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Editors

Principles of Agronomy for Sustainable Agriculture

Second Edition

Springer

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Preface to the First Edition

This textbook is the result of a long experience teaching general agronomy at the University of Cordoba (Spain). After many years of teaching the subject to agronomy engineering students in Spanish, we now offer a separate class, taught in English, and this book reflects the organization and materials used in the class.

The book reflects our vision of agronomy as a complex, integrative subject at the crossroads of many disciplines (Crop Ecology, Agrometeorology, Soil Science, Agricultural Engineering) with a strong emphasis on providing quantitative answers to specific problems. Our experience has been primarily with water-limited agriculture, hence there is an emphasis throughout the book on the role of water in the agronomy of agricultural systems. We also seek to leave behind artificial boundaries that have been created in the past among crop production areas such as Horticulture, Pomology, and Field Crops that have led to separate journals and professional careers in the past. In this book we cover all common aspects of crop management and productivity that should concern anyone dealing with the management of agricultural systems and we provide relevant examples from different cropping systems, from herbaceous to woody crops.

Our quantitative approach is based on providing the ideas and concepts needed as foundations in all the quantitative assessments required for making informed, technical decisions in farm management. Farmers operate along the philosophy of learning by doing (adaptive management) and agronomists should also follow the same path, but they should have the knowledge and tools that are needed to first correctly interpret the complex responses of the system to change, and then provide reasonable options for subsequent actions. This book does not fall in the category of those that focus on providing prescriptive agronomic recommendations or blueprints that cannot be generalized because of their empirical nature. Rather, we have tried to concentrate on the analysis of crop productivity processes which lead to identifying the main factors affecting management decisions, and on how to get quantitative answers to agronomic problems in the context of making current agricultural systems more sustainable.

From a teaching perspective the book includes two short blocks on the environment and crop productivity that could serve as an introduction for students with no background in Soil Science, Crop Ecology or Agrometeorology. The third, larger block, is devoted to specific crop production techniques (sowing, soil management, irrigation, fertilizers, etc.). A number of our colleagues have contributed to the writing all with the aim of providing future agronomists and practitioners with the quantitative tools required to calculate the adequate level of inputs (such as water, nutrients, or energy) for sustainable crop production, and to assess the yield responses as a function of climate and soil conditions, and of management options.

Preface

Agronomy is a mature discipline that integrates a set of practices, discussed in this book, required for crop production. Despite the relatively recent publication of the first edition of this book (2016), we have perceived the need to revise it and publish a second edition, less than nine years after the first one. The main reason is that over the last decade, the adoption of new tools and methods in agronomy has accelerated, contributing to the improvement of agricultural practices. This book is oriented toward the sustainability of agricultural systems, understood as maintaining or enhancing productivity over time without deteriorating the environment. Furthermore, the principles and applications described here are aligned with the sustainable intensification of agricultural production as the most logical approach to ensuring sufficient food production for a growing world population with minimal land expansion and negative consequences for nature.

As a result of climate and soil variations, crop production is variable in space and time, and coping with such variations is a fundamental challenge to modern agronomy now and in the future. In addition to revising and updating the content of the 37 chapters of the first edition, this revised version has four new chapters focused on tools and methods used in spatial analyses of soil and crop properties. As novel soil and plant sensors for assessing soil and plant water status have been developed, Chap. 21 discusses soil and plant sensors for irrigation scheduling as an alternative to the water balance, the established method. Over the last 40 years, remote sensing of crop optical properties has seen substantial advances, but the explosion of different applications has mostly occurred over the last decade. The increase in resolution and the expansion of its use to map different vegetation properties, from biomass to evapotranspiration, makes remote sensing a powerful tool to assess spatial variations, as is discussed in the new Chap. 38. Spatial variations in crop growth and soil and water properties present management challenges at field and farm scales. Heterogeneous field units treated homogeneously in pest control, mineral fertilization, and irrigation would have areas that would receive less or more inputs relative to the average needs. Site-specific input applications will result not only in higher net profits but in a reduction of pollution risks as well. This is described in a new chapter (39) on site-specific agriculture, also termed precision farming. The fourth new chapter (Chap. 40) is devoted to crop simulation modeling and its usage in decision support systems, alone or with other complementary tools such as remote sensing and soil and plant sensors for real-time simulation updates. Additionally, this edition has four new chapters dealing with issues not fully covered in the previous version. One is the energy consumption in agriculture (Chap. 37), an aspect often overlooked in the past where the focus has been on energy production by agriculture. The adaptation and mitigation of agriculture to climate change is now fully discussed in Chap. 41. Water and soil conservation topics are enriched with two new chapters: Chap. 23 on optimizing irrigation management and design, and Chap. 30 on soil improvement and reclamation. A new feature is presented at the end of this book with two new chapters (Chaps. 43 and 44) describing a practical exercise based on the book content, aimed at analyzing quantitatively most features of an irrigated agricultural system. Those using this book as a textbook could adapt the exercises proposed here to other agricultural systems that may be more relevant in their geographical locations. Overall, this second edition has been expanded and has about 25 percent more content than the original version of this book. We hope that the book will contribute to supporting science-based decisions on agricultural policies as opposed to the increasing trend of using misconceptions founded on the perceptions of part of urban societies.

Principles of Agronomy for Sustainable Agriculture is a piece of collective work, written by many co-authors (17) to whom we are extremely grateful. All of them have contributed their time and effort to distill fundamental knowledge from their specialties, and have given a diversity of agronomic perspectives to the different chapters. Particularly, we would like to remember here all the meaningful contributions that Luciano Mateos made to this book. His unique insight into the different angles of irrigation, from design to management, has been a beacon to many irrigationists around the world and has provided this book with a special focus on the irrigated agriculture of temperate climates. He passed away at the end of 2022 before he could finalize the revisions of his chapters. We dedicate this book to him.

Cordoba, Spain Francisco J. Villalobos

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Finally, we dedicate this book to our families, whose love and support has been the engine moving us forward.

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Agriculture and Agricultural Systems

1

Elias Fereres, Álvaro López-Bernal,
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Abstract

Crop ecology deals with agricultural ecosystems that are manipulated by man to funnel the maximum energy into usable products (food and raw materials). Agricultural ecosystems show generally lower biodiversity and autonomy and a shorter trophic chain than natural ecosystems. The main features of farming systems are productivity, stability, resilience, and sustainability, the latter indicating the ability to maintain a certain level of production indefinitely. Production of agricultural systems requires inputs of matter, energy, and information. Normally the economic optimum provision of inputs is below that necessary to achieve maximum production. Various parameters have been defined to characterize the productivity of agricultural systems (potential, attainable, and actual yield).

Agricultural systems may be classified according to different criteria. According to the length of the trophic chain, the higher efficiency is obtained with a system where crops are directly used by humans. However, animal husbandry allows the exploitation of areas marginal for food crop production and the use of residues. According to intensification, agricultural systems have evolved from subsistence agriculture to intensive modern systems where the main challenge is sustainability. The carrying capacity, the number of animals that can be fed by the primary production of a given area, may be also calculated for humans growing cereals taking into account that an individual requires around 300 kg grain/year to meet the energy and protein demand.

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1.1 Ecology and Ecosystems

Ecology is the discipline that studies the relationships between the organisms living in a given space, called "habitat," and their surrounding environment. Within this definition, the environment is understood as an ensemble of biotic and abiotic features that affect the growth, reproduction ability, and life span of individual organisms. Therefore, environmental factors integrate both other living organisms and purely physical features determined by weather and soil conditions that interact with the studied individual. Environmental factors can also be classified as resources when they are directly consumed by the organism (e.g., nutrients), and regulators, when they affect the rate at which resources are used (e.g., temperature).

The *ecosystem* represents the fundamental unit of study in ecology. It comprises all the living organisms and the physical environment in which they live and with which they interact. This definition does not imply any spatial scale: both the stomach of a ruminant and a large grassland where ruminants graze may be considered ecosystems. By including both the biotic and abiotic components, the ecosystem is a complex system with dynamic behavior over time. Ecosystem responses are often explained by the integration of processes at lower levels of biological organization (from molecules and cells to individual organisms) which obey basic physical, chemical, and biological laws such as those of mass and energy conservation and thermodynamics. This implies that ecology is a synthetic science that draws from several disciplines.

Ecologists aim to understand how an organism fits into its environment. In this regard, the term *ecological niche* describes all the combinations of biotic and abiotic factors that allow the population of a given species to persist over time. Some authors decompose the concept between fundamental and effective niches. The first defines the entire range of conditions in which organisms, free of interference from other species, survive and reproduce, while the latter is narrower, as it accounts for the pressure exerted by other organisms. The definition of ecological niches is relevant as they define the places where a species can be found or succeed if introduced, while also revealing the conditions in which biological interactions among different species are theoretically possible: two species will not interfere if there is not some overlap between their niches.

Box 1.1: Biological Interactions

Biological interactions among organisms living in the same ecosystem can be classified according to the impacts on the individuals involved:

- Competition: The presence of the two organisms is detrimental for both. This usually happens when both organisms exploit a resource that is in scarce availability (e.g., radiation, nutrients, water) and may involve individuals of the same (e.g., neighboring plants of a crop competing against each other) or different species (e.g., weeds vs crop plants).

(continued)

Box 1.1 (continued)

- Antagonism: The interaction is beneficial for one of the individuals and detrimental for the other. This category includes depredation, herbivory, and parasitism, although the borders among them are sometimes difficult to delimitate. Predators kill and eat other organisms, their prey. As an example, many birds and arthropods prey on pests, helping to reduce their impact on crops. Herbivores feed on living plant tissues with vegetation often being able to recover. Response to herbivory depends on the feeding habits of the animal and plant architectural traits. Finally, parasites are organisms that live on or inside another organism, the host, which decreases its fitness. Both phytophagous arthropods and pathogens causing pests and diseases, respectively, are considered crop parasites.
- Mutualism: The two organisms cooperate, and both benefit from the presence of the other (e.g., pollinators and entomophilous plants). The term *symbiosis* is also used when the two organisms live in close association. That is the case of some nitrogen-fixing bacteria living in association with legumes in root nodules.
- Commensalism and amensalism: They have positive (commensalism) or negative (amensalism) impacts on one of the organisms while the other is not affected by the presence of the first. They are of limited relevance in the context of crop ecology.

The organisms in an ecosystem are interrelated by flows of energy and materials (carbon, nutrients, and water). The dimensional characterization of the energy flows in the ecosystem is called the *trophic chain*. The primary source of energy is solar radiation, the driving force of life on Earth. The *trophic level* defines the position of an organism concerning the entry of energy into the ecosystem. The first level is integrated by autotrophs, called primary producers, which fix solar energy through photosynthesis, transforming it into usable energy that will move along the trophic chain. Higher trophic levels are numbered consecutively, including primary (organisms feeding on plants), secondary (carnivores that eat herbivores), and tertiary consumers (carnivores that eat carnivores). In practice, this picture is an oversimplification of reality, since many organisms can feed on (or be eaten by) organisms from several trophic levels. Here emerges the concept of *trophic* or *food web*, which is the natural interconnection of the different food chains in place within an ecosystem. For instance, microbial populations at the end of trophic webs use residues or dead tissues from different organisms in the ecosystem, irrespective of their trophic level.

Most wavelengths of solar radiation are of no use for photosynthesis, so most part of the incoming radiation is reflected or invested in heating the air and the soil or in evaporating water, as discussed in Chaps. 3, 4, 5, 6 and 7 in this book. In addition, an important fraction of the energy assimilated by plants through photosynthesis is not stored as biomass but consumed by respiration to provide the energy required for the growth and maintenance of metabolism. In ecology, the total amount of energy assimilated by photosynthesis in an ecosystem is known as *gross primary productivity*, while that effectively converted into the biomass of primary producers is called *net primary productivity*. On average, each transfer to higher trophic levels has a net efficiency of about 10%, with most of the energy going to metabolic processes such as growth, respiration, and reproduction. Thus, *secondary productivity*, the energy assimilated by heterotrophs in the next trophic levels, is always lower than that stored in the biomass of the primary producers in the ecosystem.

The transfer of energy through the ecosystem is unidirectional since it dissipates when moving from one trophic level to the next. By contrast, the movement of chemicals at the biosphere level is cyclical, since they can be reused. This means that the same atoms of carbon, nitrogen, phosphorous, etc., can be exchanged between different types of organisms, the soil, the oceans, or the atmosphere over the course of millennia. By decomposing dead biomass, soil microorganisms play a critical role in closing the nutrient cycles in ecosystems.

1.2 Crop Ecology and Agricultural Systems

Over millions of years, man has obtained the energy required for living from different trophic chains, by hunting and gathering edible plants until 10,000 years ago, when agriculture was invented. Farming allows man to produce food and other products by managing and manipulating the trophic webs of ecosystems. Agriculture is a set of human interventions that alter ecosystems to maximize the yield of the desired product and minimize energy losses along trophic chains. The science and technology of producing and using plants for human use is Agronomy. It deals with the exploitation by man of terrestrial ecosystems and has, therefore, its roots in ecology. The ecosystems modified by agriculture are called agroecosystems and the science that deals with their study is Crop Ecology. An agroecosystem is an ecosystem managed with the ultimate goal of producing food and other goods and services derived from agriculture. Population pressure has reduced the area of ecosystems free of human intervention. However, there are reserves, forests, and other areas that may be called natural ecosystems, which are generally characterized by higher biodiversity, longer trophic chains, and higher autonomy than agroecosystems.

The agroecosystem is characterized by the presence of a lower number of species than the natural ecosystem. This lower diversity is a result of the need to reduce energy losses along trophic chains in agricultural ecosystems, which aim to remove all unwanted energy transfers (to parasites, pathogens, or plants which compete with the crop) and is usually associated with a shortening of the trophic chain. The energy autonomy of agroecosystems is relatively low because they depend on inputs of materials, energy, and information provided by humans.

The unit of study in Crop Ecology is the field or plot. A community of plants, along with management practices (e.g., tillage method, rotation, etc.) located on a field is called a *cropping system*. At this level, one can analyze the production processes of plants, their relationships with the soil, and their dependence on the aerial environment. By observing the same plot for several years, we can analyze the effects of rotation, tillage practices, or crop residue management on soil properties and resulting yields, as they are affected by the use of resources such as water and nutrients. Economic analyses or determining manpower needs are often made at the plot scale. A farm represents a single management unit constituted by several fields or plots.

At a higher level of organization, the cropping system is part of a farming system where other elements (e.g., livestock) are also managed by the farmer providing inputs to the crops or using crop products. The different crops and management practices prevalent in a given area are called agricultural systems at a regional scale.

Agriculture, like all human activities, has known successes and failures throughout its history. Today agriculture produces enough food for the vast majority of the world population, despite the unprecedented population growth experienced over the last 50 years (see Sect. 1.6). However, it has also negative environmental impacts such as soil degradation and water pollution from the use of fertilizers and pesticides, and the reduction of biodiversity. Furthermore, other sectors of society are very sensitive to a diverse set of problems created by agriculture, notably those related to food safety and to its expansion threatening natural ecosystems.

1.3 Characteristics of Agricultural Systems

The primary objective of farming is the production of sufficient food and other goods and services so that the farm stays viable. Therefore, a key feature of farming systems is their *productivity*, defined as output per unit of resource used, commonly referred as the cultivated area, which is the primary limiting factor of agriculture. Thus, productivity is defined as the yield of usable product per unit area but can be applied to other natural or artificial inputs such as radiation, water, nutrients, or labor, which are also typically measured per unit of area. In areas of favorable climate such as the tropics, it is useful to consider the productivity per unit area per unit time, as different cropping sequences vary in productivity per unit area depending on the duration of individual crops. For instance, a sequence of three short-season rice crops is more productive than another one of two long-season rice crops. The productivity level further serves as an indirect measure of the efficiency with which these inputs are used.

When characterizing agricultural systems, the term *efficiency* is often used to define the ratios of crop productivity and certain inputs. For example, the efficiency of water use is defined as the ratio of yield to the volume of water used, but it would be more correct to speak of the productivity of water or nutrients, expressed as kg/m^3 water or kg/kg nutrient. In engineering, efficiency is the ratio between the output and the input of any entity in a system; for example, the energy supplied to an engine.

Besides productivity and efficiency, there are other important properties of agricultural systems. Yields may vary from year to year due to weather variations and other causes. The term *stability* refers to the magnitude of these oscillations. The lack of stability causes fluctuations in production that threaten the persistence of agricultural systems. This is particularly true when there are sequences of successive years of low yields that may have a catastrophic effect on their economic viability. Related to the fluctuations in productivity, there is another feature termed *resilience*, defined as the capacity of the system to recover from a catastrophic event, like a drought. High resilience is a desirable property of agroecosystems.

Another feature of farming systems is their *sustainability*, which indicates the ability to maintain a certain level of production indefinitely. This feature stems from the concept of sustainable development, a development model that proposes economic growth without adversely affecting the opportunities of future generations. A farming system is considered sustainable when it is economically viable and socially acceptable, however, one must define the time frame, because what is feasible and acceptable today may not be so in the future. Thus, in agricultural systems, it would be more correct to speak of the degree of sustainability: a system will be more sustainable when its exploitation does not degrade the quality of water and soil resources, and when current management practices do not affect the productivity and viability of the system in the future. The improvement of the sustainability should be based on two objectives: reducing or eliminating, if possible, the negative environmental effects of agriculture while maintaining high productivity. Decades of intensive production in many agricultural systems have caused negative environmental effects and have created awareness of the need to focus on the sustainability of the agricultural systems, leading to a debate about developing new forms of agriculture that can ensure economic and ecological sustainability. The need for production intensification stems from the requirement to produce sufficient food for the current and future world population, but it must be ensured that such intensification is sustainable in the long run.

1.4 Management of Agricultural Systems

The strategy of agriculture is to manipulate the environment and the plant community to optimize the yield of goods useful to mankind. This involves establishing communities (crops or pastures) dominated by species that allocate a large proportion of the primary production to usable organs or materials. In addition, the farmer tries to minimize system losses due to insects, diseases, and weeds.

Farmers have numerous management tools to control their crops, such as tillage for weed removal and seedbed preparation, choice of species and cultivars, sowing date and sowing density, application of fertilizers and pesticides, etc. External factors such as climate and markets are difficult to predict so the flexibility in managing the crop is very important to minimize the risk of crop failure or economic losses in the farm. For example, an application of fertilizer may be reduced or waived if the rainfall is very low or if the expected price of the product is also low.

In general, for many resources the response curve of yield versus input level is curvilinear and the maximum profit is obtained at a level of resources below (but not far from) that required for maximum yield. This is because of the synergies that occur among different inputs and of the addition of fixed costs, which make low-input strategies generally inefficient. The more productive and more profitable farms are those that use resource levels that are commensurate with the production target, without any input limiting yield. For example, there is little point in providing additional water as irrigation if the additional quantities of fertilizer required to realize the targeted yield are not provided.

Example 1.1
The response of wheat to N fertilizer in a rainfed Mediterranean area is shown in the table below. The selling price is 0.25 €/kg, the fertilizer cost is 0.80 €/kg N and the fixed cost is 200 €/ha. The highest yield is achieved using 250 kg N/ha. However, the economic optimum is achieved with an application of 200 kg N/ha. In this case, a very limited use of fertilizer leads to worse economic performance than the overuse.

N applied	Yield	Income	N cost	Income – N cost	Net profit
kg N/ha	kg/ha	€/ha			
0	1200	300	0	300	100
50	1929	482	40	442	242
100	2329	582	80	502	302
150	2558	640	120	520	320
200	2883	721	160	561	361
250	3020	755	200	555	355

The criteria for managing agricultural systems must take into account many factors that are affected by farmer decisions. Not only plant and animal production processes are important, as are economic objectives, but also the effects on soils, water, animal welfare and human health, landscape and biodiversity, among others, have to be considered. All these items have a different weight depending on the farming system under consideration, although, as in any other business, when the farm is not dedicated to the subsistence of the owner, it is handled essentially based on economic criteria. Nevertheless, there are many facets to the management of farming systems. In areas where the ratio of population/arable land and input prices is low (e.g., the USA and Australia), the emphasis is on maximizing profit per unit of labor. In Northern and Central Europe and in Japan, where arable land is the limiting factor and input prices and wages are high, farmers tend to maximize productivity per unit area. Similar goals are pursued in the agriculture of China and India due to the limited availability of land per farm. These situations contrast with those of many poor countries where labor is abundant and access to inputs and capital is scarce.

Crop yields are close to their maximum potential only in a few areas (as in farms in Japan and Northern Europe) so the average yields of agricultural systems are generally poor indicators of potential productivity. Actual yields lie in a broad interval from zero (crop failure) to a maximum attainable level which is only limited by the aerial environment (solar radiation and temperature regime). The maximum attainable yield level is called *potential yield*. *Actual yield* is defined as the average yield of a cultivar in all the fields of a farm or of a specific region. It represents the state of the climate and soil and the ability of farmers to apply successfully the available technology.

The potential yield of a species in an area is achieved when the technology is not limiting, that is when all inputs are used optimally. Strictly, this concept applies to the yield of a well-fit cultivar with no limitations due to water or nutrients and full control of weeds, pests, and diseases. In general, the potential yield is calculated using theoretical models based on climate and other environmental factors and the morphological and physiological characteristics of the crop in question. In practice, these estimates of potential yield should be contrasted against record yields obtained by the best farmers in the same geographical area.

There is a considerable *gap* between actual and potential yield in most agricultural systems, so sometimes other yield levels are defined for diagnostic purposes. For example, *attainable yield* is defined as the yield achieved within the environmental constraints of climate and soil of the area, using the best technology available. The yields obtained by the best farmers and research stations in the area are an indicator of attainable yield. The attainable yield in particularly favorable years results in record yields.

The concepts of potential and actual yield (and to some extent attainable and record yields) are very useful for the evaluation of farming systems and the identification of possible improvements that will help in closing the gap between what farmers are achieving and what they could achieve. These concepts are also used to define cultivation intensity. In the intensive agriculture of Japan and Northern Europe, actual yields are close to potential yields and the yield gap is small. As yields approach potential levels, there is little incentive for farmers to further intensify production thus there is always some gap between actual and potential production in all systems. As the difference between actual and potential yield increases, so do the opportunities to increase productivity.

1.5 Types of Agricultural Systems

Agricultural systems can be classified according to various criteria. An ecologically based approach is based on the type of trophic chain. The shorter chain is one in which crops are directly consumed by humans. In other chains, crops or pastures are eaten by livestock, which in turn is consumed by humans. The energy efficiency of a system is lower the greater the number of levels of the trophic chain. On average each transfer in a food chain has a net efficiency of about 10%. Thus, for a net primary productivity of 100 units, if it is consumed directly (vegetarian diet), the transfer of energy is close to 100. If cattle are employed to transfer the energy to humans, only 10 would be recovered. This does not imply that animal husbandry should be abandoned. On the one hand, animals are the only choice for exploiting marginal areas where crop production is not possible (see below). On the other hand, some animals can use materials not digestible by humans (e.g., cellulose in crop residues) or not suitable for food (e.g., food leftovers, residues from industrial processing).

Farming aims at minimizing energy flows through undesired routes (weeds, insects, etc.) that end up at the level of decomposers. As we have seen, a short food chain (crop ---> humans) is the most efficient from an energy transfer standpoint. However, in many agricultural systems, environmental conditions (for instance, very shallow/poor soils) prevent obtaining products for direct use by humans (e.g., grain) and only pastures may be grown. There is also the case of areas with semi-permanent flooding or very arid areas. In all of these situations, cattle allow the conversion of primary production to other usable forms by man, even at the cost of lower efficiency.

Agricultural systems may be characterized also according to their position within an interval that goes from *subsistence* agriculture to *intensive* agriculture. In subsistence farming, many species are used, cultivars are adapted to the specific environments, yield potential is low, and actual yields are low but stable. Subsistence farming is also very labor-intensive and livestock is a main component in nutrient management. This leads to high energy efficiency. At the opposite extreme, intensive agriculture is characterized by lower genetic diversity (both in terms of species and cultivars) in search of high yields, greater use of machinery replacing labor, as well as high use of fertilizers and pesticides, resulting in high productivity but often with low efficiency.

Historically agriculture in developed countries has undergone a transition from subsistence farming to intensive agriculture with a continuous increase in productivity and a gradual decline in energy efficiency. The routes differ depending on how land use has evolved in the different countries: For instance, Canada, Australia, and large parts of the USA and Argentina have not intensified their agriculture as much as it has occurred in Northern and Central Europe and Japan. In many Asian countries, very intensive agriculture is practiced with high use of certain inputs and low yield gaps. Therefore, in some developed countries, we may find extensive systems with low inputs, but a high level of mechanization that requires large areas for the farm to be economically viable, while in other countries (mostly developing) highly productive systems with high use of labor may coexist with subsistence agricultural systems.

The intensification of agriculture in many countries has led to major pollution episodes due to excessive use of inputs such as fertilizers and pesticides and, in some cases, to the production of agricultural surpluses due to ill-conceived subsidies. In some cases, food safety incidents have been related by the public opinion of these countries to agricultural intensification. This has led to proposals to develop alternative agricultural systems, some based on avoiding the use of mineral fertilizers and synthetic pesticides, such as in organic farming and other forms of biological or ecological agriculture that are considered to be based on agroecology, such as regenerative agriculture. Other alternatives have proposed to adopt agricultural practices that are environmentally friendly and that ensure the quality and safety of food. The term "*sustainable agriculture*" refers to farming practices that allow the indefinite maintenance (sustainability) of agricultural systems, which requires the conservation of resources and the maintenance of economically viable farms. Some experts speak of a transition from traditional agriculture (low input, low control) to intensive agriculture (high input, low control), from which we must move to a more sustainable agriculture (inputs optimized, high control), where resources are used only in the appropriate amounts for each system and where there is better control of the environment and the crop.

1.6 Carrying Capacity

The carrying capacity is the number of animals (or people) that can be maintained by the primary production of a given area of land. The main components of the human diet are the sources of energy and protein. A human requires 0.6 g of protein per kg of weight per day, although the FAO sets the minimum safety level at 0.75 g of protein per kg. These requirements are much less variable than the energy requirements that depend largely on the activity performed by the individual. If we think of an average human being, the daily requirements are 10.5 MJ of digestible energy and 50 g protein. Therefore, in one year, the energy and protein required by an individual may be calculated as:

$$10.5 \text{ MJ day}^{-1} \times 365 \text{ day} = 3800 \text{ MJ year}^{-1}$$
$$50 \text{ g protein day}^{-1} \times 365 \text{ day} = 18.2 \text{ kg protein year}^{-1}$$

The average energy content of the plant material is 17 MJ kg^{-1}, so 3800 MJ can be obtained from 224 kg of dry matter of high digestibility. Ingestion of this amount, despite a low protein content (assuming a 9% protein), ensures the need for protein (224 kg × 0.09 = 20.2 kg protein). Cereal grains contain more than 10% protein, making them an ideal source of energy and protein for human consumption. A greater diversity of the human diet is highly desirable, among other reasons, to acquire the essential vitamins and minerals.

Once we know the needs of food per individual, we can calculate the carrying capacity of a particular agricultural system (CC, individuals ha^{-1}) as:

$$CC = \frac{NP\, f_c\, f_d\, GE}{ER} \tag{1.1}$$

Where NP is the net primary production (kg dry biomass ha^{-1}), f_c is the fraction of NP that is consumed, f_d is the fraction of the energy consumed that is digested, GE is the gross energy content of the feed (MJ kg^{-1}), and ER is the annual energy requirement (3800 MJ individual^{-1} in the case of humans).

Example 1.2

Let us calculate the carrying capacity of a wheat field with a yield of 6000 kg ha^{-1} (12% moisture). The dry yield will be 5280 kg ha^{-1}. From this quantity, only 80% may be consumed as a fraction of seeds will be used for sowing in the next season and because there are losses in storage and processing. The digestibility of wheat for humans is 0.85 and its energy content is 18.5 MJ kg^{-1}. As a result, the annual amount of wheat required to sustain a human will be:

$$\frac{3800\,\text{MJ year}^{-1}}{0.80 \times 0.85 \times 18.5\,\text{MJ kg}^{-1}} = 302\,\text{kg year}^{-1}$$

And the carrying capacity:

$$CC = \frac{5280\,\text{kg ha}^{-1}}{302\,\text{kg human}^{-1}} = 17.5\,\text{humans ha}^{-1}$$

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Part I

The Crop Environment

The Soil: Physical, Chemical, and Biological Properties

2

Antonio Delgado and José A. Gómez

Abstract

This chapter provides a basic description of soil as a crucial resource for agriculture. Soil is a dynamic and living entity where complex interactions among its biological, chemical, and physical components take place. These components and their interactions determine the functioning of the soil; this functioning underlies the concept of "soil quality." Soil quality is the capacity of soil to function within ecosystem boundaries to sustain ecosystem services, between them the biological productivity, and maintaining environmental quality. Thus, any given approach to soil quality will depend on each particular ecosystem. Land use and management can have a profound impact on soil quality that results in improvements or constraints for the productivity of agricultural lands and for agricultural sustainability in the long term.

2.1 Introduction

Soil is the porous three-dimensional body developed over the Earth crust able to store nutrients and water and to exchange gases with the atmosphere. Soil is formed by the combination of mineral and organic material, air, and water. Between the organic material, soils contain living organisms that interact with other components. This leads to be not only a physical media for supporting life, but also a living

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Fig. 2.1 Soil profiles showing two different degrees of development. Shallow Calcaric Cambisol (left) and deeper Vertic soil (right)

system itself, which is continuously evolving. The arrangement, combination, or interaction between soil components determine the so-called soil properties.

Agricultural soils are vital not just for producing food and goods but also for providing other essential benefits for society. To understand how soils determine agricultural productivity it is necessary to understand how soil properties interact with plants. The aggregation state of soil components, i.e. soil structure, should be suitable for the germination of the seeds and the growth of the roots and must have characteristics that enhance the storage and supply of water, nutrients, gases, and heat to the crop. The interaction between solid components (primarily the insoluble compounds of silica, calcium, and aluminum) and the water phase determines chemical reactions in soils, i.e. the soil chemistry. Understanding soil chemistry is of paramount importance to understanding how soils provide nutrients to plants. This is the necessary knowledge basis to predict the response of crops to fertilization. Soil chemistry may have a direct impact on soil physical conditions as in the case of sodic soils with high exchangeable sodium content promoting dispersion of particles of colloidal size. The complex fauna and microbial web hosted in soils are involved in many different biological processes, which also affect its physical and chemical properties, and ultimately the productivity of agricultural ecosystems.

For a given soil, its properties depend on the history of the soil formation (Fig. 2.1) and can be substantially modified by human intervention, e.g. through agricultural practices. A proper understanding of soil properties and adequate interpretation of the magnitudes of these properties is required for proper management of agricultural soils with a view of maintaining or improving the benefits that they can provide to society, between them the production of food and goods.

2.2 Dynamics of Soil Formation and Soil Loss

Soil genesis refers to the developmental processes that take place for a long time over solid or unconsolidated material, the so-called parent material, as the result of the complex physical, chemical, and biological interactions, as described in Fig. 2.2.

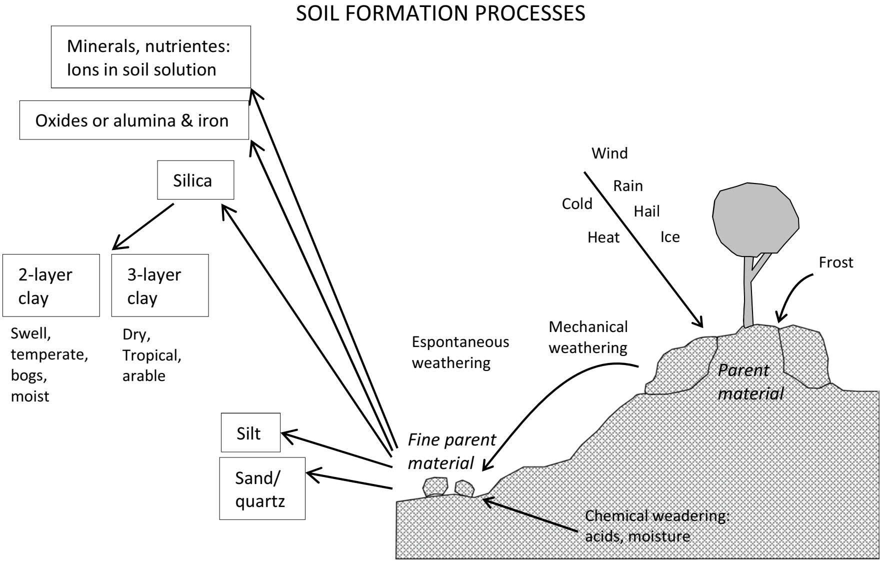

Fig. 2.2 Description of key processes in soil formation

Soil genesis involves processes of different nature, normally driven by the integrated effect of climate and living matter on the parent material. These processes include the accumulation of soil components (e.g., organic matter), formation on site of new ones (e.g., clay minerals or oxides), transport within the soil profile (e.g., clay, carbonate, or soluble salts), or changes in the aggregation state of soil particles (e.g., formation of a structure). This usually leads to the arrangement of soil material in different layers with different properties and will define the morphology of soils and their potential for providing benefits for society, in particular agricultural productivity.

The available soil depth for plant growth, i.e. the depth of the soil profile that can be explored by plant roots also termed rootable soil depth, is a determining factor in agronomy. It strongly affects overall crop development and soil productivity and is the result of the balance between soil formation and soil destruction rates as a consequence of erosion. Soil formation rates are extremely low. It is usually less than 5 mm per century, frequently ranging from 0.01 to 40 mm per century. In landscapes that are not under quick geological transformations, e.g. alpine uplifting, these soil formation rates tend to be in equilibrium with the erosion rates under natural vegetation. Natural erosion rates range between 0.005 and 60 mm per century and are mostly the result of water and wind erosion and mass movement by gravitational forces.

2.3 Soil Physical Properties: Texture and Structure

Soil physical properties determine many key soil processes mainly related to heat, gas, or water retention or flows (Fig. 2.3). Consequently, these properties are crucial for defining the agricultural productivity of a soil. *Soil texture* refers to the size distribution of the mineral soil particles composing the solid fraction of the soil (from clay <2 μm to coarse particles >2000 μm). It is perhaps the most important physical property since it determines many other physical properties (such as infiltration rate) and some chemical properties since particle size is inversely related to the chemically reactive surface of soils. Clay content and mineralogy greatly influence the physical and chemical properties of soils, one of them the swelling–shrinking behavior of the soil, e.g. vertisols, if the clay is an expansive type. *Soil structure* describes the arrangement of soil particles and organic matter in the soil, and particularly the arrangement of pores among these particles, as well as the stability of this arrangement under external forces such as traffic, rainfall drops, or runoff. In contrast to texture, soil structure can be substantially modified by soil management. The distribution of pore space and texture determines soil water retention properties (see Chap. 8) which are characterized by the relationship between soil water content and soil water potential (tension). This relation is determined by soil structure and pore size distribution when the soil is at low water tension (wet) and mostly by soil texture at high water tension (dry soil). *Bulk density* is the ratio between soil dry mass and volume that is determined by particle size and aggregation. It decreases with increased porosity. Thus, bulk density is a very important soil property influencing soil water retention, aeration, trafficability, and infiltration rate and is extremely sensitive to soil management. *Soil porosity* is the fraction of soil occupied by air and water. *Soil mechanical resistance* reflects the resistance to penetration. It is proportional to soil compaction and affected by water content, increasing sharply as the soil dries.

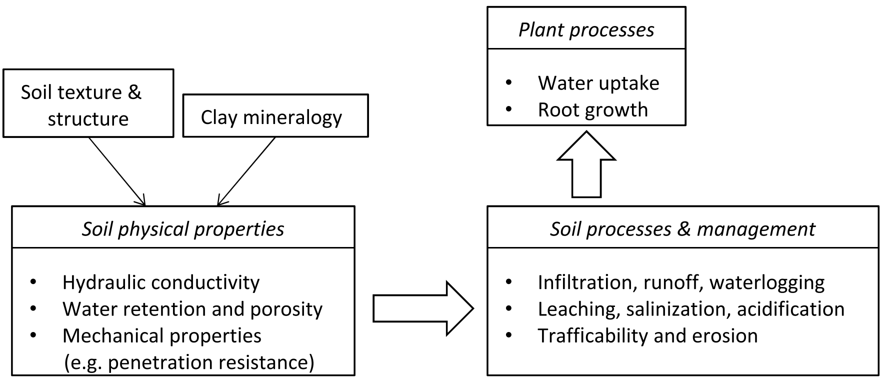

Fig. 2.3 Description of key soil physical properties and related soil processes and management issues. (Adapted from Geeves et al., 2001)

Soil permeability is a broad term used to define the ability of the soil to transmit water. It is important to understand the water dynamics and the water balance of the soil (Chap. 8) and it must be known for accurate management of irrigation (Chaps. 20 and 21). It is determined partly by texture, with sandy soils having high permeability as compared to clay soils and it can be altered by soil management (e.g., tillage, Chap. 17). Other parameters that reflect the water transmission properties of the soil are the infiltration rate, i.e. the rate of water flow through the soil surface, and the hydraulic conductivity, i.e. the ability of soil to conduct water, which decreases with increased soil water content.

Soil particles and the void spaces with their continuity and sizes are all arranged in clusters giving way to a certain structure. Soil physical, chemical, and biological properties all influence soil structure by providing means that help hold together soil particles and aggregates. Structure affects many soil properties that are relevant in agronomy. The penetration of plant roots, the movement and storage of soil water, the aeration and the mechanical resistance of soil are some of the more relevant properties influenced by the way soil aggregates are clustered together creating a given structure. Common management practices such as tillage can change soil structure very rapidly with short-term beneficial effects, e.g., increased aeration, but also might have negative side effects, e.g. loss of aggregate stability. Such short-term changes are reversible but the long-term degradation of soil structure is a serious problem as it is associated with decreased water infiltration and increased erosion risks. Organic matter plays an important role in facilitating aggregate formation and its long-term decline contributes to the loss of stability of soil aggregates.

2.4 Soil Chemical Properties

2.4.1 pH

Soil pH is that of a solution in equilibrium with soil. The soil pH is determined in the laboratory as the pH of soil suspensions in water or salt solutions (usually 0.1 M $CaCl_2$ or 1 M KCl). The degree of acidity or alkalinity of soil is very relevant affecting many other physicochemical and biological properties. Soil pH is related to the proportion of acidic or basic elements retained by soils. In nature, acidic soils are related to humid climates promoting a high degree of weathering and leaching, leading to base loss from exchange sites and replacement by H^+ and Al^{3+}. This process is faster in soil parent materials with low base content such as granites. Basic or alkaline soils are the consequence of the buffering of soil pH by base elements or by the presence of buffering compounds such as carbonates. *Calcareous soils* are those with an appreciable concentration of $CaCO_3$ that buffers soil pH near 8.5; the presence of other carbonates (Mg or Na in sodic soils) can buffer soil pH well above 8.5. The pH of a calcareous soil cannot be changed due to its high buffering capacity and its limitations for agricultural use, mainly related to restrictions in nutrient uptake and plant nutrition, may be overcome with special fertilizer products and fertilization strategies.

Some of the soil fertility features affected by soil pH include:

(a) Solubility and availability to plants of mineral elements in the soil. The solubility of Mo and P compounds is decreased in acidic soils, thus decreasing its availability to plants. On the contrary, Al concentration is increased (usually at pH <5.5) and thus its toxicity effects; the concentration of Fe and Mn, essential nutrients for plants, can be high enough at low pH to cause toxicity. In acidic soils, the risk of deficiency of base nutrients (Ca, Mg, and K) increases due to their low content. At high pH, the solubility of many metals and trace elements is decreased, including essential nutrients for plants such as Fe, Mn, Cu, or Zn. Deficiency of Fe is frequent in basic soils (typically in calcareous ones). In cereals, Zn deficiency is usually the most relevant nutritional problem when grown in calcareous soils.
(b) Biological properties: Extreme pH values decrease microbial activity in soils, which affects many soil processes (for instance, soil organic matter decomposition, nitrification, and biological N_2 fixation under acidic conditions, see Chaps. 26 and 30).
(c) Physical properties: Low Ca concentration in acidic soils is usually related to increased dispersion of colloids if Al is not present in high concentration. Thus, acidic soils can have poor soil physical properties, including poor structural stability or low permeability.

2.4.2 Redox Status

The redox status of a soil is determined by the availability of electrons that can participate in redox reactions (pE, – logarithm of the activity of electrons) and it is controlled by physical conditions (water content and porosity) and biological activity. It affects the solubility and speciation of elements with different redox states, such as N, S, Fe, Mn, some toxic trace elements (e.g., As, Se), and even C. Reducing conditions in agricultural soils usually occur at very high water content (saturation) since, under these conditions, oxygen is quickly consumed by biological activity. Redox potential becomes more negative with increased saturation time. Reducing conditions increase the loss of N to the atmosphere (NOx, N_2O, N_2) by denitrification (Chap. 26), and the solubility of Fe and Mn compounds, enhancing the uptake of these nutrients (which can become toxic) and of elements adsorbed on Fe and Mn oxides (e.g., P and heavy metals).

2.4.3 Ion Retention in Soils

Ions can be retained in soils by precipitation and adsorption processes. *Precipitation* means the formation of a new solid phase, e.g. when P fertilizer is applied to a soil with a high Ca concentration, new crystals of Ca phosphates can be formed. *Adsorption* is the accumulation of chemical species (sorbate) on the surfaces of an existing solid in the soil (sorbent). Precipitated and adsorbed species are in equilibrium with the soil solution (precipitation/dissolution and adsorption/desorption equilibria).

Adsorption can be the consequence of chemical reactions with functional groups of sorbent surface which is sorbate specific (e.g., P on hydroxylated surfaces), or electrostatic attraction by sorbent surface which is not sorbate specific. Charges associated with mineral and organic surfaces can be permanent and variable. The permanent charge arises from isomorphic substitution within a mineral. Variable charge is the result of unsatisfied bonds at the terminal ends of minerals and organic matter and is pH dependent.

2.4.3.1 Exchange Capacity

Exchangeable ions are those weakly adsorbed by soil particles that can be displaced from sorption sites by other ions in the solution. Exchangeable ions are essential for maintaining plant nutrient reserves in the soil.

Cation exchange capacity (CEC) is the total amount of cations that can be retained by a soil as a consequence of the negative charge in clay minerals, oxides, and organic matter. It is expressed in equivalents or moles of charge per unit of soil mass. CEC is usually dominated by Ca, Mg, Na, K, Al, and protons. When CEC is determined as the sum of these cations extracted with a highly concentrated non-buffered saline solution it is defined as the *effective cation exchange capacity* (ECEC), usually applied to acidic soils. The term CEC is applied to that determined in a highly concentrated saline solution with buffered pH (usually 7). The selectivity or relative affinity of a cation by sorbent surfaces is based on the ion's charge and size. The smaller the hydrated radius (cation + water molecules strongly interacting by ion–dipole interaction) the greater the affinity (ions with the same valence have a larger ionic radius the smaller the unhydrated radius), and the higher the valence the greater the exchanger preference. The affinity scale for dominant cations in soils can be summarized as:

$$Al^{3+} > Ca^{2+} > Mg^{2+} > NH_4^{\ +} \approx K^+ > Na^+$$

Base saturation is defined as the ratio of base exchangeable cations (Ca, Mg, K, and Na) to total CEC, which decreases at decreased pH in the soil. It is usually expressed as a percentage (*Percent base saturation* BSP):

$$\mathrm{BSP} = \left(\mathrm{Ca} + \mathrm{Mg} + \mathrm{K} + \mathrm{Na}\right) \cdot 100 / \mathrm{CEC}$$

where Ca, Mg, K, and Na are the exchangeable bases. On the other hand, it can be defined the *Acid saturation* such as the ratio of exchangeable acidity (H^+ and Al^{3+}) to CEC, which can be also expressed on a percentage basis (*Percent acid saturation*, ASP).

Ca, Mg, and K are plant nutrients, so a high base saturation means a greater nutrient reserve for the same CEC. Low base saturation related to soil acidity can cause Ca deficiency for plants. To guarantee good physical soil properties (soil aggregation, structure stability, good aeration and drainage) and crop nutrition, Ca must be the dominant cation in the exchange complex, ideally >50% of CEC. Ca is a divalent cation with a small hydrated radius, and this enhances the aggregation of colloidal particles. It is also desirable that the Ca/Mg ratio would be 5–10 and the K/Mg ratio 0.2–0.3 to avoid nutritional disorders (antagonisms).

2.4.4 Salinity and Sodicity

Salinity refers to the concentration of soluble salts (more soluble than gypsum) in soils. A saline soil has a soluble salt concentration high enough to impair the growth of cultivated plants. Soil salinity is quantified as the electrical conductivity (EC) of the saturation extract of the soil (EC_e). Soils are defined as saline when their EC_e is above 4 dS/m. There is ample variation among species in the responses to salinity (Chap. 24). Highly sensitive crops (e.g., carrot, bean, strawberry) are affected by EC_e slightly above 1 dS/m. On the opposite side, tolerant crops such as barley and sugar beet can tolerate EC_e above 4 dS/m. The impact of salinity on plant growth is caused by osmotic effects (decreased water potential in soil) and from specific toxicity, typically due to high Cl or Na content in saline soils.

Sodicity refers to a high exchangeable Na concentration in soils. Since Na salts are common in saline soils, both problems are usually related. Na is a monovalent cation with a big hydrated radius. Hence, high contents of Na adsorbed on soil colloids promote their dispersion, thus degrading soil physical properties. A soil is classified as sodic if exchangeable Na accounts for more than 15% of the CEC (Exchangeable Na percentage—ESP— >15). However, crops sensitive to Na toxicity are affected at ESP >7 (e.g., peach, citrus, strawberry). In crops tolerant to Na toxicity (e.g., cotton or rye) problems are usually caused by the physical degradation of soil. Soils with EC >4 dS/m and ESP >15 are classified as saline-sodic. Problems derived from sodic soils can also be related to their very high pH (usually >8.5 if the soil is not saline).

Chapter 24 expands on the salinity problem in agriculture and describes the approaches for its management and control.

2.5 Soil Biological Properties

Soils host a complex *web of organisms* (Fig. 2.4) which can influence soil evolution and specific soil physical and chemical properties. For instance, earthworm activity increases infiltration rate or microbial activity decreases soil organic matter due to mineralization.

Soil biological properties are also interconnected with other soil physical and chemical properties; e.g. aeration, soil organic matter, or pH affect the activity of many microorganisms in soils which in turn perform relevant activities in carbon and nutrient cycling. Examples of this interconnection are given in Sect. 2.4. Thus, changes in soil properties due to management can significantly affect biological

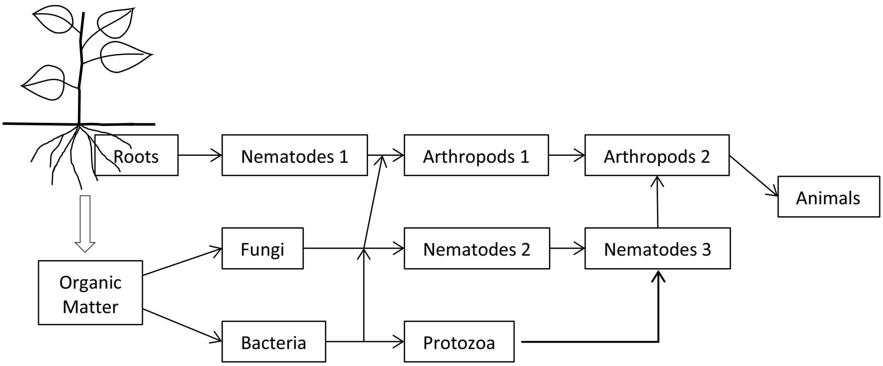

Fig. 2.4 Soil food web

properties in soils, some of them being extremely sensitive to soil management; e.g. soil microbial activity can be greatly increased by improved drainage, liming, or organic amendments.

Soil organic matter is a key factor affecting biological activity in soils. It is the carbon source for many organisms, including soil microbiota. Not only the amount but also the type of organic compounds in the soil determines its biological activity; e.g., microbial activity is greatly increased by incorporating fresh organic residues (such as green manure or crop residues), which can be readily mineralized by microbes. On the other hand, stable forms of organic matter (humic and fulvic compounds), which constitute most of the organic matter of soils in temperate regions, are not easily mineralized by soil microbiota, which explains the long half-life of these compounds in soils (usually > centuries). Therefore, stable organic compounds do not contribute significantly to soil microbial activity but constitute a stabilized stored soil C pool which is very relevant to the C global cycle, partially buffering the consequences of increasing C emissions to the atmosphere.

The **rhizosphere** is the volume of soil altered by the root system and is the part of the soil profile where the concentration of suitable C sources for many microorganisms is greatest. Organic compounds exuded by plant roots (including organic anions of low molecular weight) alter soil chemical properties and greatly increase the biological activity in comparison to the bulk soil. The rhizosphere is a space of intense interaction of plant roots with soil microorganisms. Rhizospheric microorganisms can significantly affect plant development through the production of growth regulators, by decreasing the incidence of plant diseases, and by increasing nutrient availability to plants.

Understanding soil biological properties is important for soil management but also for the prevention and control of crop pests and diseases. Many of the properties indicated in Table 2.1 are a description of the diversity and activity of parts of the soil food web, or of closely related properties such as soil respiration rate or organic matter content.

Table 2.1 Some soil biological properties

Property	Indicators of the property
Respiration rate	CO_2 evolution under standard laboratory conditions or at the field
Potential C, N, or P mineralization	Increase in mineral N or C content under standard laboratory conditions Enzyme activities related to nutrient cycle: e.g., $\beta-$ glucosidase, urease or phosphatase activities
Earthworms	Density of earthworms
Microbial biomass	C, N, or P in soil microbial biomass Total content in fatty acids related to microbial phospholipids
Microbial community structure and diversity	Physiological profiles for phenotyping (e.g., Biolog®) Phospholipid-derived fatty acids (PLFAs) Genomic sequencing
Presence of pathogens	By different techniques, bioassays, cultures, or DNA profiling

2.6 Nutrient Cycles and Balances in the Soil

Nutrients in soils are present in different chemical forms that can remain in solution or bound to soil particles. The exchange of nutrients between different forms or "soil pools" is governed by a combination of physical, chemical, and biological processes that form the soil *nutrient cycle*. Since the soil is not a closed system, gains or losses of nutrients from the soils occur to/from the atmosphere or water courses (leaching or erosion), which links the soil nutrient cycle with the global nutrient cycle in the Earth's crust. The soil and global nutrient cycles are affected by human activities. In agricultural soils, fertilization alters the cycle, introducing nutrients into the system. Without this supply, the natural input of nutrients in soils would be much lower than typical crop extractions, thus inducing a progressive depletion of nutrients, i.e. a loss of soil fertility and a decrease in yields.

A general nutrient cycle is represented in Fig. 2.5. The flux of nutrients to plant roots comes from the soil solution, mainly as dissolved ions. The *labile nutrient pool* is the one readily equilibrated with the solution, as adsorbed ions described in Sect. 2.4.3.1, those precipitated as soluble salts or those present in organic compounds that are readily mineralized. The *available pool* of nutrients is the amount in solution plus that readily equilibrated with the solution (labile forms); for a given nutrient, it is the amount that can be extracted by successive crops until severe deficiency. Chemical (e.g., adsorption/desorption or precipitation/solubilization) and biological (immobilization/mineralization) interactions affect nutrient equilibria and exchange rates between the labile fraction of the soil solid and solution phases. This exchange ultimately determines the solution ionic activities and the transport of nutrients to plant roots.

Accurate estimation of fertilizer requirements in modern agriculture is based on the knowledge of nutrient cycles and the precise estimation of available nutrient pools in soils through chemical methods. *Mobile nutrients* are those not bound to soil particles. Nitrogen, despite ammonium being adsorbed, is readily transformed

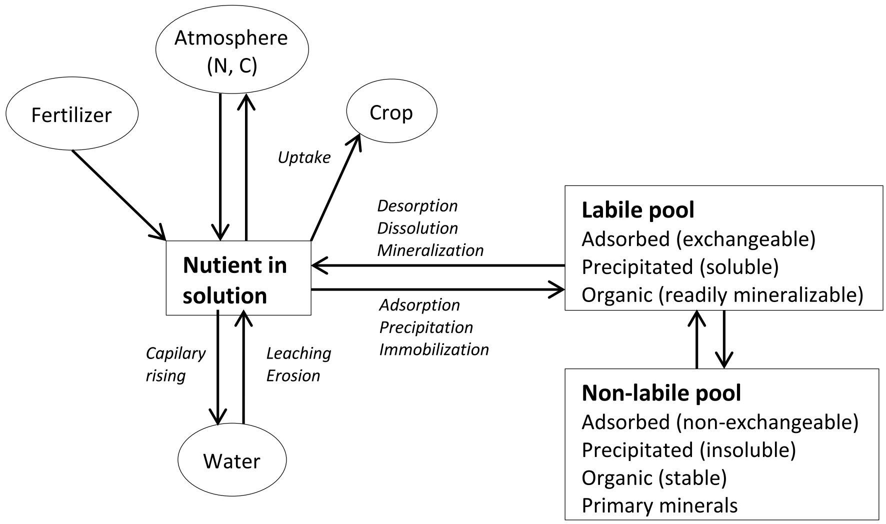

Fig. 2.5 General nutrient cycle in the soil. In italics physical, chemical, or biological processes. Residue incorporation involves nutrient recycling: not only in soluble forms (e.g., K), but most in organic forms or organic bound forms that can become part of the labile or non-labile pool. Exchange between labile and non-labile forms implies the same processes that those involved in the equilibria between labile forms and solution

to nitrate, which is not adsorbed to soil particles. In agricultural systems, where the contribution to the available nutrient pool by organic matter mineralization is usually low, the major contributors to the available pool of mobile nutrients are inorganic ions in the soil solution. *Immobile nutrients* are those that are bound to soil particles through adsorption or precipitation processes, while the labile pool is the major contributor to the available pool. Immobile nutrients, such as P, K, Ca, or Mg, are less susceptible to leaching; on the other hand, the nature of chemical reactions involved in their retention limits the availability of the nutrients supplied as fertilizer.

2.7 Soil Quality

Ecosystem services are the benefits for humans obtained from ecosystems and are the basis for human well-being (Fig. 2.6). Many essential ecosystem services depend on soils. These services are known as "soil functions." The soil functions related to agricultural systems involve (1) primary productivity, (2) water purification and regulation, (3) carbon sequestration and other aspects of climate regulation, (4) provision of a habitat for functional and intrinsic biodiversity, and (5) nutrient cycling and provision. Traditionally, in agricultural systems, the focus has been put on primary productivity. However, the other functions of soil in agricultural systems are also relevant for society. The concept of soil quality addresses this multifunctionality of soil, and it has been traditionally defined as the capability of soil to

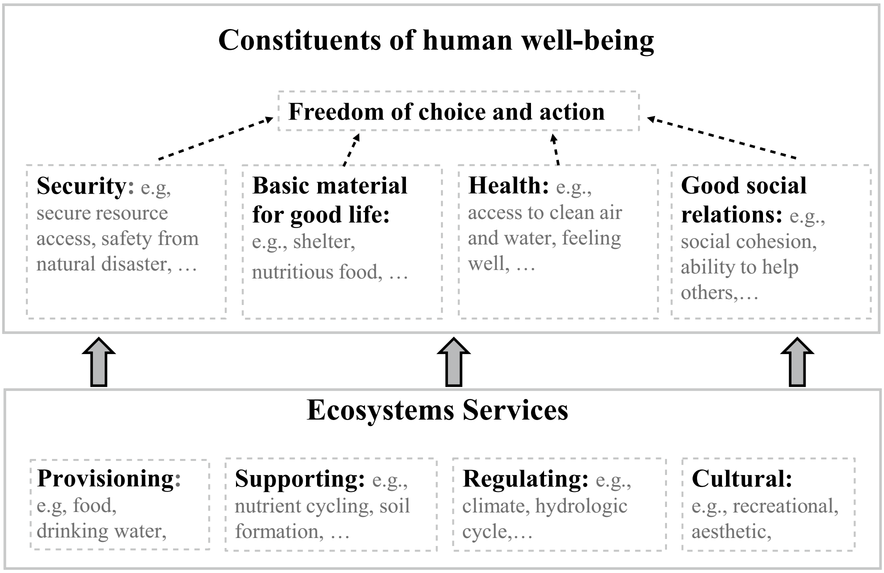

Fig. 2.6 Overall view of ecosystem services and human well-being. (Adapted from Millennium Ecosystem Assessment, 2005)

perform its functions within the ecosystem boundaries. Soil quality should be interpreted according to how relevant are those functions for society. This quality is related to soil properties and processes. As an example, texture and structure (properties) determine water infiltration (process) which may affect different soil functions such as primary productivity or water purification and regulation. Not only natural processes involved in soil formation but also agricultural practices can affect soil properties and consequently modify soil quality.

The main threats to soil quality, which constraints the performance of ecosystem services derived from soils, are:

2.7.1 Soil Erosion

Erosion is the loss of land surface by water, wind, ice, gravity, or other natural or human agents that abrade, detach, and remove soil particles. Human interventions mainly by removing the protective plant cover can result in accelerated erosion rates under inappropriate land use or soil management practices. These accelerated erosion rates can reach up to 50 mm per year, resulting in a reduction of the soil profile depth and its degradation. Achieving sustainable erosion rates is a major goal of the so-called soil conservation practices. Sustainable erosion rates are defined as those that are either close to the soil formation rates or at least below a given safe rate (customarily below 10–100 mm per century) that extends far into the future the impact of the imbalance between soil formation and soil erosion rates. The use of soil conservation techniques aims at reducing erosion rates within the range of 0.003 to 60 mm per century to achieve a more sustainable agriculture.

2.7.2 Degradation of Soil Physical Properties

The degradation of soil physical properties is mainly related to the loss of aggregate stability or dispersion of soil particles. This leads to the loss of porosity and subsequent increased bulk density, compaction, and soil crust formation. In the soil surface, soil crusting and sealing after wetting or impact of rainfall/irrigation drops leads to reduced water infiltration, thus increasing runoff and soil erosion. In addition, soil crusting may hinder seedling emergence, leading to yield loss. Soil compaction implies a decreased porosity and increased bulk density, leading to lower infiltration, less aeration, and reduced root growth. Intensive tillage, in particular with moldboard plows or disk harrows, the traffic of heavy machinery such as harvesters and poaching cause soil compaction. A specific case of compaction is the plow pan provoked by particular tillage devices (e.g., disk harrows, rotatory harrows) or intensive tillage. The degradation of soil properties may be related to changes in chemical properties. In this regard, acidification and sodification (see Sect. 2.7.3) may cause colloidal particle dispersion, reducing infiltration and aeration. The loss of organic matter may reduce aggregate stability.

2.7.3 Degradation of Soil Chemical Properties

Although the soil forming process involves changes in chemical properties, human intervention may have a direct impact on these properties, thus affecting soil quality. The main threats to soil chemical properties are:

Acidification is the increase in hydrogen ions in the soil. When components such as carbonate cannot buffer soil pH, there is a trend toward acidification in the long term because rain is usually slightly acidic due to the dissolution of CO_2 and the dissociation of the resulting H_2CO_3. Also, CO_2 resulting from microorganisms and root respiration leads to an increased H_2CO_3 concentration in the soil solution contributing to natural acidification. Besides this natural trend, agricultural management increases acidification risks. Plants' roots release H^+ when cation uptake is higher than that of anions to balance the charge. This is particularly relevant in legumes since the fixation of atmospheric N_2 results in the formation of NH_4^+ within the root nodules and the uptake of an excess of cations. This increased positive charge needs to be balanced by a net release of protons. The use of urea and ammonium N-fertilizers is considered the most important cause of acidification in agricultural soils since the oxidation of ammonium to nitrate implies the release of hydrogen ions (2 moles of H^+ per mol of NH_4^+). However, if nitrate is absorbed by a crop, there is no net acidification since its absorption is coupled with that of hydrogen ions. Acidification occurs when nitrate formed from ammonium fertilizer is leached since there is no consumption of hydrogen ions involved in the absorption of this nitrate and also occurs by the leaching of cations (mainly bases) to maintain electrical balance. Finally, the emission of nitrogen and sulfur compounds from industrial processes is the origin of the deposition of nitric and sulfuric acids in soils contributing to its acidification. As mentioned above, acidic soils may suffer structure degradation, decreased microbial activity and may promote deficiency or toxicity problems in plants.

Salinization is the accumulation of soluble salts in soils. It may occur by natural causes such as saline parent material, hydrologic conditions, or capillary rising of saline underground water. However, irrigation is the main cause for salinization when soluble salts supplied with irrigation water are higher than those lost by leaching. This risk is increased with the use of poor-quality irrigation water. The management of irrigation involves leaching to decrease or maintain the soluble salt content in the soil (Chap. 24). It is important to anticipate what will happen to the soil if the irrigation is abandoned in the future, since all the salts will remain in the soil and it will condition the future land use.

Sodification is the increase in exchangeable Na in soil. It is frequently related to salinity since Na salts are one of the most frequent in saline environments. However, sometimes if soluble salts disappear from soils a high content of exchangeable Na remains. Irrigation water can also be a source of Na. In sodic soils (non-saline) there is a dispersion of colloids degrading physical properties, possible Na toxicity and reduced nutrient availability due to high pH. The control of sodicity is discussed in Chap. 30.

Exhaustion is the progressive depletion of nutrients and soil organic matter (SOM). The decrease in SOM has implications for other chemical, biological, and physical properties. Organic matter exhaustion is the consequence of scarce organic residue incorporation that does not compensate the losses by mineralization and erosion. This SOM loss contributes to the physical deterioration of soil since it is an aggregating agent; also, chemical properties are negatively affected since organic matter has a charge (pH dependent) that contributes to nutrient retention. Organic matter also contributes to the soil pH buffering capacity and it is a nutrient reserve made available by mineralization. SOM decay also reduces the activity of soil microbes as it is an essential energy source for them. C/N ratios range from around 80 in some fresh residues such as cereal straw to around 10 in humic substances. Values below 10 indicate that the major contributor to SOM is microbial biomass (C/N around 8) and reveal the urgent need of organic amendments to the soil.

Contamination is the accumulation of pollutants in soil coming from fertilizers, pesticides, or the application of other products such as compost, or sewage sludge that may contain trace elements or organic pollutants. Atmospheric deposition of pollutants coming from industrial or large urban areas may also pollute the soil. Fertilizers obtained from mines, such as P, may contain trace elements (typically Cd) depending on the origin of the phosphate rock, which may accumulate in animals or humans. New threats associated with the recycling of different residues in agriculture are gaining attention, such as microplastics. From a microbiological point of view, the presence of genes of resistance to antibiotics threatens animal and human health.

Table 2.2 Some soil properties normally used in evaluating soil quality

Soil property				
Physical	Soil texture	Soil structure	Bulk density	Infiltration rate
Chemical	CEC and exchangeable cations	Organic C concentration	Salinity	pH
Biological	Earthworms presence	Soil respiration	Microbial biomass (e.g., C or N in microbial biomass)	Microbial activity[a] and biodiversity

[a]e.g., Biological indicators such as enzyme activities related to microorganisms

2.7.4 Soil Quality Indicators

Soil physical and chemical properties can be used in the assessment of soil quality. Some examples are shown in Table 2.2. However, most threats to soil quality negatively affect soil microorganisms, promoting changes in the structure of the communities, in the biomass and their activity. As some examples, reduced soil porosity and water infiltration negatively affect aerobic microorganisms and typically decrease organic matter mineralization rates. Extreme pH values (acidic or sodic soils) imply a decreased microbial activity negatively affecting essential processes such as nitrification. Organic matter exhaustion favors oligotrophic organisms over eutrophic, with an overall decreased diversity and activity. That is why some soil biological properties can be used as indirect indicators of appropriate soil management and good soil quality, like soil respiration rate or some enzymatic activities that can be derived from living organisms in the soil.

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The Radiation Balance

3

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Abstract

Solar radiation (short wave) is the energy source for photosynthesis, warming, and evaporation in agricultural systems. Its value can be calculated as a function of latitude, time of year, and cloud cover. Fifty percent of solar radiation is available to photosynthesis and is called Photosynthetically Active Radiation (*PAR*), although only a very small fraction is actually used in this process. Net radiation is obtained by discounting the reflected solar radiation (which depends on the albedo) and longwave losses that depend on air temperature, humidity, and cloud cover. Plants intercept all types of the radiation fluxes. Radiation interception is modulated by leaf angle distribution that varies with leaf area index (*LAI*) and plant type. The fraction of radiation intercepted by trees can be calculated assuming simple geometrical forms (e.g., spheroids).

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3.1 Introduction

Electromagnetic radiation is the basic physical phenomenon determining the environment of crops. Solar radiation, which is shortwave radiation, constitutes the primary energy source for crop production. In addition, we have to consider the longwave thermal radiation emitted by any object on the planet, including soil, crops, water, and the atmosphere. Moreover, light quality, i.e., its composition in different wavelengths, plays a key role in many developmental processes of plants, as discussed in Chap. 11.

The total energy emitted for the whole electromagnetic spectrum is calculated by the Stefan–Boltzmann Law:

$$E = \varepsilon \sigma T^4 \tag{3.1}$$

where ε is the emissivity (or effectiveness of the body in the emission of radiation), σ is the Stefan–Boltzmann constant (5.67 10^{-8} W/m^2/K^4), and T is the absolute temperature of the surface of the emitting body. This law applies to any object, including the surface of the sun or the earth. The emissivity of plant surfaces is between 0.97 and 0.99, thus very close to that of the "black body," which by definition is 1.

3.2 Solar Radiation

The flux density of solar radiation in the limit of the atmosphere (extraterrestrial radiation), on a surface perpendicular to the beam, when the sun and the earth are at an average distance apart, is called the "solar constant" and its value varies between 1350 and 1400 W/m^2, with an average value of 1361 W/m^2.

Considering a horizontal surface, if the ray and the normal to the surface are not parallel, flux density can be calculated by Lambert's cosine law:

$$I = I_p \cos\theta \tag{3.2}$$

where θ is the zenith angle (angle between the radiant beam and the vertical) and I_p is the flux density in the direction of the beam.

The zenith angle for a horizontal surface on the planet depends on the latitude (λ_s), the solar declination (δ_s), and the time of day (expressed as hour angle, h_a, that varies from 0 to 360°, taking the value of 0° at solar noon):

$$\cos\theta = \sin\lambda_s \sin\delta_s + \cos\lambda_s \cos\delta_s \cos h_a \tag{3.3}$$

The solar declination ranges from +23.45° at summer solstice (Northern hemisphere) to −23.45° at winter solstice and may be calculated (in degrees) as:

$$\delta_s = 23.45 \cos\left[\frac{360(DOY - 172)}{365}\right] \tag{3.4}$$

where DOY is day of the year (DOY = 1 for January 1 and 365 or 366 for December 31).

Example 3.1
On February 1 (*DOY* 32) in Cordoba, Spain (λ_s = 37.85°), the solar declination is

$$\delta_s = 23.45\cos\left[\frac{360(32-172)}{365}\right] = 23.45\cos(-138°) = -17.4°$$

At 3 h after solar noon: h_a = (15−12) 15 = 45°, thus:

$$\cos\theta = \sin(37.85)\sin(-17.4) + \cos(37.85)\cos(-17.4)\cos(45) = 0.35$$

and then θ = arc cos(0.35) = 69.5°.

Legal time is obtained by adding or subtracting a certain number of hours to standard time, plus a daylight savings time (usually one hour) in summer. For instance, in most Western Europe (France, Germany, and Spain) there is a one-hour difference in the fall-winter period and two hours in spring and summer (daylight savings). To calculate actual solar time, we must take into account the longitude of the place as the path of the sun to the west has an apparent speed of 15° per hour. However, we will ignore other phenomena related to the rotation of the Earth that can change up to 16 min from our predictions of solar time.

Example 3.2
Santiago de Compostela (Spain) is located at 42.9°N and 8.43°W. We will calculate solar time at 1500 h (legal time) on May 1.

As the date corresponds to spring-summer, solar time at the standard meridian (in this case, the Greenwich meridian) will be:

15−2 = 13 h

Then we subtract 1 h per 15° longitude to the West:

13−8.43 1/15 = 12.44 h, which means that actual solar time is 12:26.

In crop ecology and agronomy, we are especially interested in three major bands in the spectrum of solar radiation reaching the upper atmosphere. The infrared and visible wavebands represent approximately 51% and 40% of the solar constant, respectively, while the ultraviolet waveband is approximately 9%. The visible waveband, which ranges from 400 to 700 nm, is also the Photosynthetically Active Radiation (*PAR*), although a very small fraction of this radiation is used in this process. *PAR* may be expressed as radiation flux density (W m^{-2}) or as photon flux density (mol m^{-2} s^{-1}).

As the sun's beams travel through the atmosphere, the radiation is altered in quantity, quality, and direction by absorption and scattering. The absorption, which is a change from radiant energy to heat, results in the heating of the atmosphere and a reduction of the amount of radiant energy that reaches the ground. Absorption is mainly due to ozone and oxygen, especially in the ultraviolet waveband, and water vapor and carbon dioxide, in the infrared waveband. Some aerosols are also important absorbers of shortwave radiation. The scattering occurs when photons hit against the molecules composing the air and airborne particles and aerosols, causing changes in the direction of radiation, but without removing energy from the radiation. In the visible region of the spectrum, absorption by molecules of the atmosphere is less important than scattering while in the infrared waveband, the opposite occurs. Solar radiation on the earth's surface, normal to the sun's rays, rarely exceeds 75% of the solar constant, due to absorption and scattering.

3.3 Solar Radiation at Ground Level

As a result of atmospheric attenuation, solar radiation reaching the earth's surface is no longer only beam radiation coming directly from the sun (direct solar radiation). We have a second component, diffuse solar radiation, i.e., the radiation scattered in the atmosphere that reaches the surface, coming from the entire sky hemisphere. The sum of direct and diffuse solar radiation, measured on a horizontal flat surface, is called global radiation, total radiation, or simply solar radiation. On average, *PAR* represents 50% of the global radiation flux, while, in extraterrestrial radiation, it represents only about 40%.

In general, the ratio of diffuse over total radiation increases with latitude and zenith angle as the path of the rays through the atmosphere increases. This implies that both at sunrise and at sunset, the diffuse/total ratio is higher than at noon. Cloudiness also increases the ratio up to 1 when the sky is completely overcast (all solar radiation is diffuse). However, the absolute maximum of diffuse radiation is reached when cloud cover is around 50%.

Global radiation (R_s) is measured with pyranometers. On clear days, during the daytime, it follows approximately a sinusoidal curve (Fig. 3.1), and, on a daily time step, it can be estimated from extraterrestrial radiation (R_A) and the ratio of the actual number (n_s) and the maximum possible number (N_s) of sunshine hours:

$$R_s = \left(0.25 + 0.50\frac{n_s}{N_s}\right)R_A \tag{3.5}$$

Alternatively, when no data on sunshine duration is available, we may use the Hargreaves–Samani equation to calculate solar radiation as a function of air temperature and extraterrestrial radiation as follows:

$$R_s = K_{RS}\, R_A \sqrt{T_{\max} - T_{\min}} \tag{3.6}$$

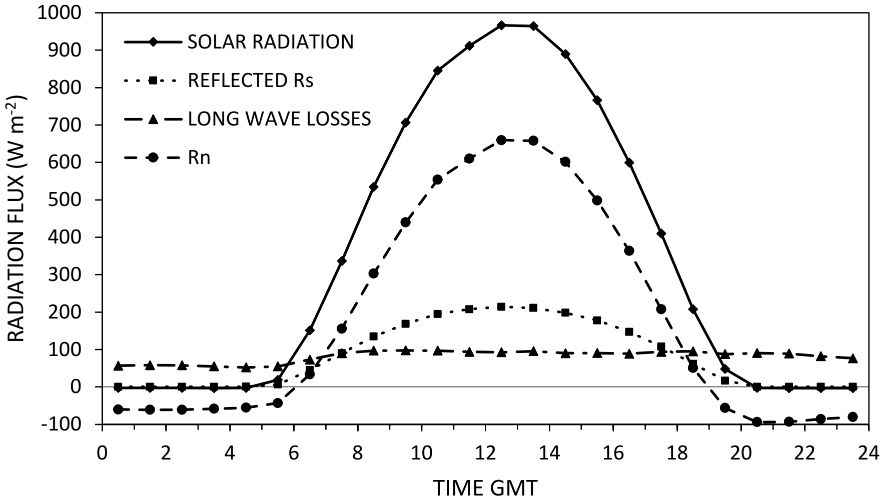

Fig. 3.1 Daily time course of solar radiation, reflected shortwave radiation, longwave losses, and net radiation over a cotton crop in Cordoba (Spain) on June 27, 2003

where T_{max} and T_{min} are the daily maximum and minimum air temperature, respectively.
K_{RS} varies between 0.16 and 0.19 $K^{-0.5}$ for interior and coastal locations, respectively.

Daily extraterrestrial radiation (MJ/m²/day) may be calculated by integrating the cosine law from sunrise to sunset:

$$R_A = 37.4\, d_r \left[\sin\lambda_s \sin\delta_s \, h_s \frac{\pi}{180} + \cos\lambda_s \cos\delta_s \sin h_s \right] \tag{3.7}$$

where h_s is half the daylength (degrees):

$$h_s = \text{arc}\cos\left[-tg\lambda_s \;\; tg\delta_s\right] \tag{3.8}$$

And d_r is the correction for changes in the distance between the earth and the sun, which depends on the day of the year:

$$d_r = 1 + 0.033\cos\left[\frac{360\, DOY}{365}\right] \tag{3.9}$$

From Eq. 3.8, we may deduce day length, i.e. the maximum duration of sunshine, as:

$$N_s = \frac{2\,h_s}{15} = \frac{1}{7.5}\text{arc}\cos\left[-tg\lambda_s \;\; tg\delta_s\right] \tag{3.10}$$

On the other hand, Eq. 3.5 indicates that on clear days solar radiation is around 75% of extraterrestrial radiation. On the average, solar radiation on overcast days is only 25% of extraterrestrial radiation.

Example 3.3

We will calculate day length and solar radiation for clear days on December 21 at Grand Rapids, Michigan (42.9°N) and South Hobart, Australia (42.9°S).

Solar declination and the correction d_r depend on the day of the year only:

December 21: $DOY = 355$

$$\delta_s = 23.45\cos\left[\frac{360(355-172)}{365}\right] = 23.45\cos(180) = -23.45°$$

$$d_r = 1 + 0.033\cos\left[\frac{360\cdot 355}{365}\right] = 1.033$$

Grand Rapids:

$$h_s = \arccos\left[-tg(42.9)\cdot tg(-23.45)\right] = 66.23°$$

Day length: $N_s = 2\,h_s/15 = 8.82$ h

$$R_A = 37.4\,d_r\left[\sin\lambda_s \sin\delta_s\, h_s \frac{\pi}{180} + \cos\lambda_s \cos\delta_s \sin h_s\right] = 11.66\,\mathrm{MJ\,m^{-2}\,day^{-1}}$$

Clear day: $R_s = 0.75\,R_A = 8.74$ MJ m^{-2} day^{-1}

South Hobart:

$$h_s = \arccos\left[-tg(-42.9)\,tg(-23.45)\right] = 113.8°$$

Day length: $N_s = 2\,h_s/15 = 15.17$ h

$$R_A = 37.4\,d_r\left[\sin\lambda_s \sin\delta_s\, h_s \frac{\pi}{180} + \cos\lambda_s \cos\delta_s \sin h_s\right] = 44.5\,\mathrm{MJ\,m^{-2}\,day^{-1}}$$

Clear day: $R_s = 0.75\,R_A = 33.4$ MJ m^{-2} day^{-1}

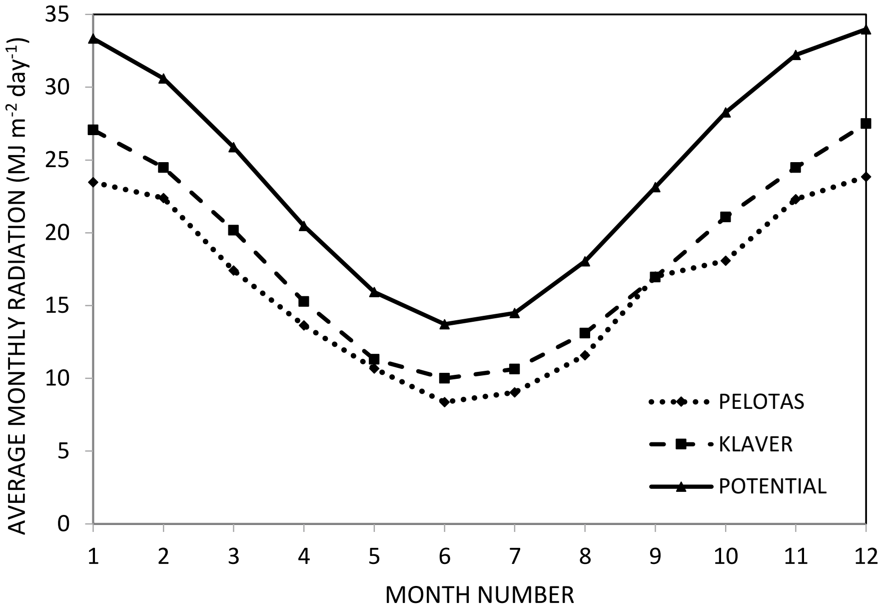

Fig. 3.2 Annual time course of the mean monthly solar radiation for two locations, Pelotas (Brazil) with mean annual rainfall of 1395 mm and Klawer (South Africa) with mean annual rainfall of 174 mm

The annual time course of global radiation also follows a sinusoidal pattern, with an amplitude that depends on the site's latitude and cloudiness. For example, Fig. 3.2 shows the annual curves of average and maximum solar radiation at two sites with very high and low rainfall. On the other hand, Fig. 3.3 shows the annual curves of solar radiation for 3 dry locations differing in latitude. As we move away from the Equator the amplitude of the annual radiation curve increases.

Mean annual solar radiation is usually between 15 and 22 MJ m^{-2} day^{-1} for latitudes from 30°S to 30°N and decreases for higher latitudes (Fig. 3.4).

Once the solar radiation reaches the earth's surface, part of the radiation is reflected. We use the term albedo (α) to express the ratio of reflected to incident radiation in the range of 0.3 to 3 µm. Some values of albedo of different surfaces are shown in Table 3.1.

Therefore, the short-wave radiation remaining on the surface of the earth can be calculated as $(1-\alpha)\ R_s$. The vegetation albedo is usually between 0.15 and 0.20 for forests and between 0.20 and 0.25 for field crops at full ground cover. The main factors that determine the soil albedo soil are its color and its surface water content. A dry soil gets darker after wetting. For example, the soil of the Agricultural Research Center of Cordoba (Spain) (sandy loam, low in organic matter) has an albedo of 0.16 when wet and 0.23 when dry.

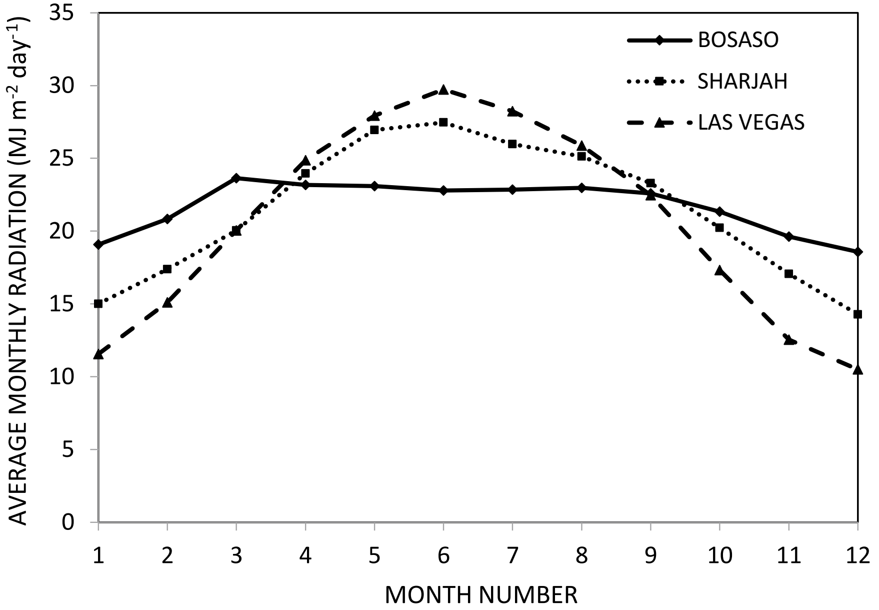

Fig. 3.3 Annual time course of the mean monthly solar radiation for three dry locations: Bosaso (Somalia) (11.28°N), Sharjah (United Arab Emirates) (25.33°N), and Las Vegas (NV, USA) (36.08°N)

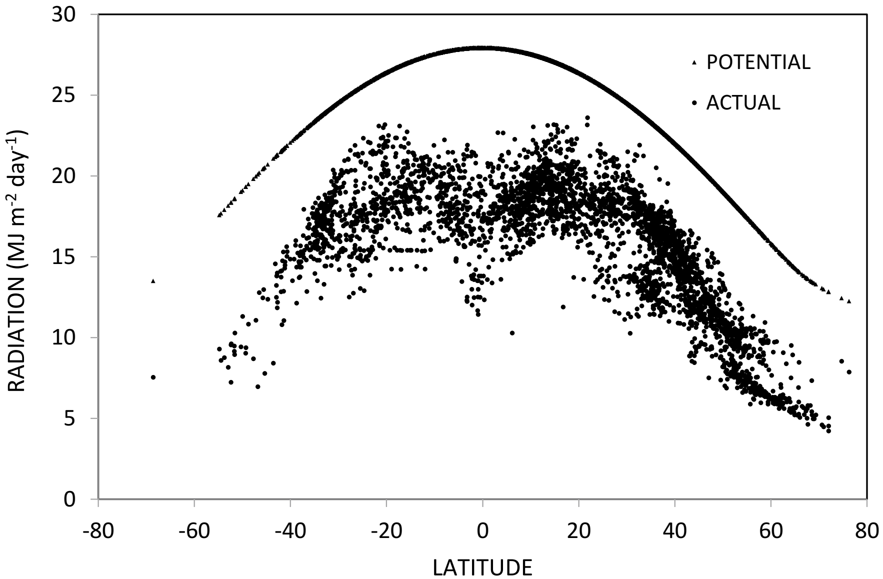

Fig. 3.4 Mean annual solar radiation for different locations as a function of latitude

Table 3.1 Albedo for daily solar radiation of different surfaces

Surface	Albedo
Fresh snow	0.80–0.95
Dry sand	0.35
Soil, wet, dark when dry	0.08
Soil, dry, dark when dry	0.13
Soil, wet, light when dry	0.1
Soil, dry, light when dry	0.35
Water bodies	0.05–0.14
Annual crops	0.16–0.26
Orchards, deciduous forests	0.10–0.20
Coniferous forests	0.05–0.15

3.4 Longwave Radiation

All surfaces are emitters of longwave radiation following the law of Stefan–Boltzmann (Eq. 3.1). Under clear skies, most of the radiation emitted by the earth's surface (i.e., *terrestrial radiation*) is absorbed by the molecules composing the atmosphere, mainly water vapor and carbon dioxide, although nitrous oxide (N_2O) and methane (CH_4) are also important absorbers. Radiation in the waveband 8–12 µm (i.e., the *atmospheric window*) is almost not absorbed by these gases due to the small size of its molecules. Under cloudy skies, cloud droplets, however, when present, contribute extensively to the absorption of the longwave radiation, thus "closing" this atmospheric window. The remainder that is not absorbed is lost into the extraterrestrial space. The radiation absorbed can be re-emitted to the earth's surface, thus constituting *atmospheric radiation*. This downward flux originates mainly from the first kilometer of the atmosphere, from the emissions of those constituents mentioned above that are highly selective absorbers (thus highly selective emitters) of longwave radiation. For practical purposes, since the average temperature of the air in the lower atmosphere is related to the air temperature near the ground, but much colder, it is possible to apply the Stefan–Boltzmann law with a fitted apparent emissivity. This parameter depends on the difference in temperature of the lower atmosphere and the ground, the amount of cloud cover, and the actual emissivity of the lower atmosphere. Terrestrial radiation is higher than atmospheric radiation and that results in net losses of longwave radiation.

Daily losses of longwave radiation (R_b, MJ m^{-2} day^{-1}) can be calculated as:

$$R_b = \left(0.9\frac{n_s}{N_s} + 0.1\right)\left(0.34 - 0.14\sqrt{e_a}\right)4.9 10^{-9}\,T^4 \qquad (3.11)$$

where 4.9 10^{-9} is the Stefan–Boltzmann constant expressed in MJ m^{-2} K^{-4}, e_a is the air vapor pressure (kPa), T is the air temperature (K), and n_s/N_s is the ratio of actual sunshine duration (n_s) and day length (N_s).

Equation 3.11 indicates that longwave losses will be greater under clear skies (high n_s/N_s), with lower humidity and higher air temperature. Cloud cover has a dramatic impact on losses of longwave radiation, as for given air temperature and humidity, longwave losses under an overcast sky are only 10% of those when the sky is clear. As sunshine duration is rarely measured, it can be estimated by inverting Eq. 3.5:

$$\frac{n_s}{N_s} = 2\frac{R_s}{R_A} - 0.5 \tag{3.12}$$

3.5 Net Radiation

The net balance of radiation that remains on a surface of albedo α is expressed by:

$$R_n = (1-\alpha)R_s - R_b \tag{3.13}$$

Net radiation is thus the difference between the flux of radiation toward the surface and from the surface of the Earth. It is therefore the energy available on the surface for evaporation, heating of the air, the soil, and the crop and to a lesser extent, for photosynthesis.

Example 3.4

Let us calculate the net radiation over short grass ($\alpha = 0.23$) in South Hobart (42.9°S) for a clear day on December 21 if the average air temperature is 25 °C and the air vapor pressure is 1.8 kPa. Solar radiation was already calculated in Example 3.3.

Longwave loss:

$$R_b = \left(0.9\frac{15.17}{15.17} + 0.1\right)\left(0.34 - 0.14\sqrt{1.8}\right)4.910^{-9}\left(273+25\right)^4 = 5.88\,\mathrm{MJ\,m^{-2}\,day^{-1}}$$

Net radiation:

$$R_n = (1-0.23)33.4 - 5.88 = 19.8\,\mathrm{MJ\,m^{-2}\,day^{-1}}$$

Figure 3.1 represents the daily time course of solar radiation, net radiation, and reflected solar radiation on a summer day on a cotton field in Cordoba, Spain. Curves of R_s and R_n have similar shapes but while the solar radiation flux is always positive during the day and nil during the night, the net radiation is negative at night.

The daily values of net radiation in summer are usually positive and decrease as the nights get longer in the fall. At higher latitudes, daily net radiation reaches negative values during winter. For example, in Cordoba (Spain), solar and net radiation are highest in July although extraterrestrial radiation peaks in June. This is explained by the higher average cloudiness and air humidity of June as compared to July.

3.6 Intercepted Radiation

Leaf area is a good indicator of the ability of the crop to intercept radiation. To characterize the leaf area of a crop canopy, we use the leaf area index (*LAI*), defined as the ratio of total green leaf surface area (one side) and the ground surface.

According to Monsi and Saeki (1953, as cited in Rosenberg et al. 1983), radiation transmitted through the canopy is an exponential function of *LAI*:

$$I = I_0\, e^{-k\,LAI} \tag{3.14}$$

where I_0 and I are the flux densities above and below the canopy, respectively, and k is the extinction coefficient.

Intercepted radiation will be the difference between incoming radiation and that reaching the soil surface. Therefore:

$$I_0 - I = I_0\left(1 - e^{-k\,LAI}\right) \tag{3.15}$$

The above equations may be applied to any type of radiation in terms of wavelength (e.g., PAR or Near Infrared, NIR), directional properties (direct or diffuse), or time scale (instantaneous or daily) by taking the appropriate extinction coefficient.

The extinction coefficient depends on the angle of elevation of the sun and the leaf angle distribution. The most useful approach is given by the ellipsoidal leaf angle distribution of Campbell (1986) that uses a single parameter of leaf inclination (X). For daily time step computations, the extinction coefficient is a parameter that may be fixed for the whole growing season or for specific phenological phases. Example values of k and X are given in Table 3.2.

Table 3.2 Daily extinctions coefficients (k) of PAR and X parameter of the ellipsoidal inclination angle distribution for some crop canopies

Crop	k (PAR)	X parameter	Source
Beans, Pea	0.4–0.5		2, 3
Bell pepper	0.72	2.5–2.9	7
Cassava, peanut, cotton	0.80–0.87		5, 6
Forage and pasture (legumes)	0.8–0.9	1.5–3.3	3
Maize, sorghum, millet	0.57–0.70	1.40	1, 4, 5, 6
Oil palm	0.48		5
Oilseed rape	0.84	1.9–2.1	1, 2, 6
Potato	0.64	1.7–2.5	1, 6
Soybean, cowpea, pigeon pea	0.7–0.8		3, 5, 6
Sugar beet, pepper (bell)	0.68	1.5–1.9	1, 2, 6
Sugar cane	0.46		6
Sunflower	0.90	1.8–4.1	1, 6
Sweet potato	0.60		6
Wheat, barley, rice	0.44–0.52	1–1.2	1, 2, 6

Sources: (1) Campbell and Norman (1998). (2) Hough (1990). Eur Commission Report EUR 13039 EN. (3) Jeuffroy and Ney (1997). Field Crop Res. 53:3–16. (4) Kanton and Dennett (2008). West Afric J Appli Ecol13:55–66. (5) Squire (1990). The Physiology of Tropical Crop Production. CAB Int. (6) van Heemst (1988). Simulation Report CABO-TT 17, Wageningen. (7) Vieira et al. (2009). Sci Horticul 121:404–409

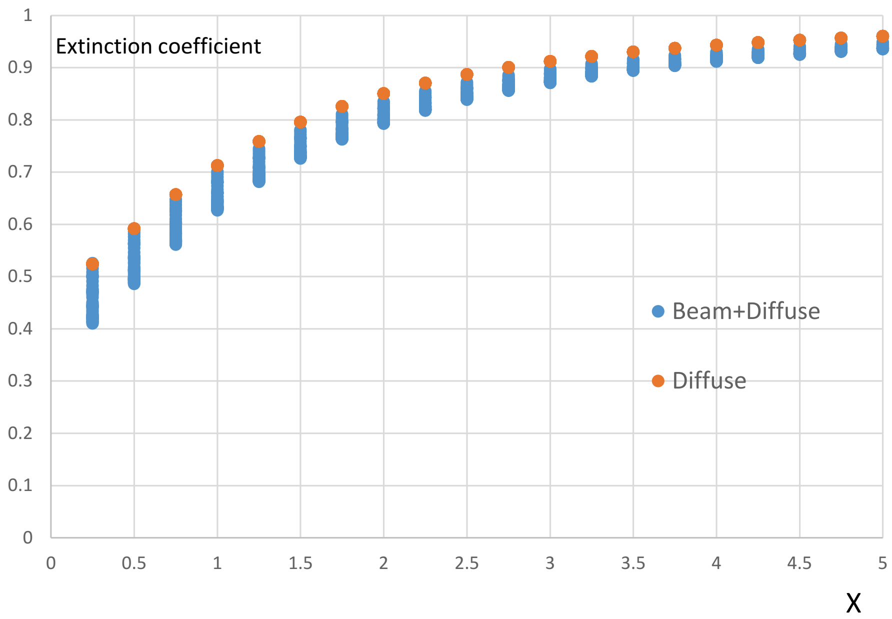

Fig. 3.5 Extinction coefficients for daily solar radiation using the ellipsoidal model of Campbell

The extinction coefficient may be related to the inclination angle of the leaves as shown in Fig. 3.5. Vertical leaves ($X = 0$) have extinction coefficients around 0.4 while horizontal leaves ($X \rightarrow \infty$) approach 1.

The leaf angle distribution has agronomic and ecological implications. Small plants with horizontal leaf distributions (i.e., higher *k* values) intercept more radiation than those with erect leaves. The drawback is that when LAI is high, the light distribution is very unequal, the lower leaves receive too little light, which usually accelerates their senescence. On the contrary, more vertical leaf angle distributions (i.e., lower *k* values) may be advantageous to intercept radiation when the zenith angle is large (winter or high latitudes) and leads to a more homogeneous distribution of radiation within the canopy when LAI is high. Therefore, the maximum LAI that may be sustained will be higher for low extinction coefficient values. Ideally, for optimal radiation interception, the upper leaves should be more erect and the lower ones more horizontal. Modern maize canopies have such leaf angle distribution.

Leaf-level photosynthesis saturates with high irradiance (Chap. 13) but irradiance decreases as we move down into the canopy, so that a large fraction of the leaves will be below the irradiance saturation level. This results in crop carbon assimilation increasing linearly with irradiance at the canopy level, as will be shown in Chap. 13.

When leaf area cannot be determined, the degree of intercepted radiation may be estimated by calculating the fraction of the ground area covered by the crop canopy (horizontal projection). This can be easily assessed in the field using photography and the appropriate software and is expressed as a percentage of full cover (100%). The ground cover is a useful parameter for characterizing canopy size from remote sensing.

3.7 Radiation Interception of Trees

We consider the tree crown as a spheroid with constant Leaf Area Density (μ_l, m^2 m^{-3}), horizontal radius r, and height h_t.

For any isolated tree, radiation interception for rays with zenith angle θ is the product of incoming radiation flux in the direction of the beam (I_p), Projected Envelope Area in the θ direction ($PEA(\theta)$), and the mean interception over PEA:

$$I_i = I_p\,PEA(\theta)\left[1 - t_c(\theta)\right] \tag{3.16}$$

where $t_c(\Theta)$ is the mean transmissivity of the crown in the direction of the sun rays.

For spheroids:

$$PEA(\theta) = \pi r^2 \sqrt{\cos^2(\theta) + \left(\frac{h_t}{2r}\right)^2 \sin^2(\theta)} \tag{3.17}$$

Note that PEA is related to the area of the shadow envelope (S_s) projected by the tree on the horizontal plane ($PEA = S_s \cos(\theta)$). The average transmissivity of the spheroid may be calculated as:

$$t_c(\theta) = 2\frac{1-(1+A)e^{-A}}{A^2} \tag{3.18}$$

where

$$A = G(\theta)\frac{3}{2}\frac{\mu_l V}{PEA(\theta)} \tag{3.19}$$

$G(\theta)$ is the projection function in the θ direction and V is the tree volume (m^3). Similar equations may be written for other solids of revolution like semi-spheroids.

Daily radiation interception of isolated trees may be calculated using interception for zenith angle 1 rad (PEA_1). For spheroids and semi-spheroids, of height h and horizontal radius r, the intercepted radiation equivalent area (REA, units m^2), i.e., the ratio of radiation intercepted by the tree (MJ) and incoming radiation on a horizontal surface (MJ/m^2), may be calculated as:

$$REA = 0.95\left(1 - t_{c1}\right) PEA_1 \left[1 - \alpha' + \alpha' \frac{0.0036\, R_{sn}\, N_s}{0.75\, R_A}\right] \quad (3.20)$$

where R_{sn} (W m^{-2}) is the average solar radiation normal to the sun beams for clear sky conditions, which can be calculated as:

$$R_{sn} = -0.0013\, x^2 + 2.19\, x - 79.7 \quad (3.21)$$

where $x = 0.75\ 10^6\ R_A/(3600\ N_s)$. The previous equations can be simplified to:

$$REA = c_1\ PEA_1 \left[1 - \alpha' + \alpha' \left(1.84 - \frac{0.75\, R_A}{3.6\, N_s}\right)\right] \quad (3.22)$$

N_s is the day length (hour) while R_A is the daily extraterrestrial radiation (MJ m^{-2} day^{-1}). The factor α' reflects sky conditions, being 0 for completely overcast skies and 1 for clear sky, and may be calculated using measured radiation:

$$\alpha' = 2\frac{R_s}{R_A} - 0.5 \quad (3.23)$$

The factors related to the trees are, in the first place, the projected envelope area for 1 rad:

$$PEA_1 = \pi\, r^2 \left(a_p + b_p\, h/r\right) \quad (3.24)$$

The parameter c_1 of Eq. 3.2 is the mean interception of the tree envelope for 1 rad:

$$c_1 = 1 - t_{c1} = 1 - \exp\left[-c_p A + d_p\, A^2\right] \quad (3.25)$$

where

$$A = \frac{\mu_l\, \pi\, r^3 h}{2\, PEA_1} \quad (3.26)$$

The coefficients depend on tree shape:

For spheroids: $a_p = 0.3$, $b_p = 0.35$, $c_p = 0.64$, $d_p = 0.026$
For semi-spheroids: $a_p = 0.36$, $b_p = 0.4$, $c_p = 0.646$, $d_p = 0.047$

The equations presented here require knowing the value of leaf area density, the ratio of leaf area and crown volume. We may take values as low as 0.5 m^{2}m^{-3} for very sparse crowns up to 2–3 m^{2}m^{-3} for dense crowns.

Example 3.5
We have an olive orchard in Cordoba, Spain. Plant spacing is 7 × 3.5 m. The trees have horizontal radius 0.5 m, height 1.5 m, and Leaf Area Density 2 m^2 m^{-3}. Let us calculate radiation interception on 21 March, under clear sky conditions. For that day and location: R_A = 29.8 MJ m^{-2} day^{-1} and N_s = 12 h.

Using Eqs. 3.24, 3.25, and 3.22:

Assuming a spheroid:

PEA_1 = 1.06 m^2 and c_1 = 0.49, so *REA* = 0.69 m^2 and intercepted PAR is 7 MJ day^{-1}.

Assuming a semi-spheroid:

*PE*A1 = 1.2 3 m2 and c1 = 0.44, so REA = 0.71 m2 and intercepted PAR is 7.2 MJ day−1.

If we want to express radiation interception at the orchard level to get the fraction of intercepted radiation, we divide the value of REA by the area per tree (7 × 3.5 = 24.5 m2):

fPI = 0.69/24.5 = 0.03

The same orchard would have REA = 0.79 m2 on January 1 and 0.65 m2 on June 21. This illustrates the fact that isolated trees will intercept a higher fraction of radiation in winter than in summer.

As in herbaceous crops, the degree of radiation interception by a tree may be estimated by determining the ground cover as the horizontal projection on the ground of the tree shade at solar noon divided by the tree spacing. Given the wide diversity of tree architecture, this is only a first approximation of the intercepted radiation as calculated above. For a given ground cover, the fraction of intercepted radiation will increase with crown height.

3.8 Radiation Interception of Hedgerows

We used a model of radiation interception of tree hedgerows to develop a summary model as follows:

The fraction of diffuse interception is given by:

$$Q_d = 1 - \exp\left[-\left(0.86 - 0.17\,\mu_l\right) V_u\,\mu_l\right] \tag{3.27}$$

where V_u is the canopy volume per unit land area ($m^3 m^{-2}$). Then, the fraction of *PAR* intercepted on clear days is:

$$Q_t = Q_d\left[a - b\cos\left(\lambda_s - \delta_s\right)\right] \tag{3.28}$$

where λ_s is the latitude (degree) and δ_s is the solar declination (degree). Note that $\lambda_s-\delta_s$ is equal to the zenith angle at solar noon. The coefficients a and b are 1.22 and 0.28 for North-South and 1.72 and 0.94 for East-West orientations, respectively. This model is valid for ground cover between 25% and 50%.

For other orientations, daily radiation interception is calculated using:

$$Q_t = Q_t^{NS}\cos^2(\alpha) + Q_t^{EW}\sin^2(\alpha) \tag{3.29}$$

where Q_t^{NS} and Q_t^{EW} are the calculated values of Q_t for NS and EW orientations, respectively, and α is the angle between North and tree rows (absolute value).

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Wind and Turbulent Transport

4

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Abstract

The wind flow over crop canopies causes a momentum transfer from the air to the canopy. That transfer generates turbulence, which enhances the exchange of matter and energy between the atmosphere and crops. Turbulence increases with wind velocity and aerodynamic roughness, proportional to crop height. Wind speed (U) varies logarithmically with height. This profile can be described mathematically by two parameters related to crop height. Turbulence can also be expressed as an inverse function of aerodynamic resistance, which reflects the difficulty of turbulent transport and is therefore very high when U is low and for smooth (short) crops. Inside the canopy layer, the wind speed acquires profiles more dependent on the architecture of the canopy than on the wind vector over it. Wind speed changes considerably over space and time, generally lower at night and attaining a maximum in the afternoon; over the long term, higher average wind speeds are often registered at higher latitudes.

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4.1 Transport of Mass and Energy from Crops

The partition of net radiation over a crop surface takes place in several forms. Part is spent in convection, thereby increasing the air temperature within the crop and the atmosphere above (sensible heat). The rest is used in conduction leading to an increase in the soil (and the crop) temperature, or as latent heat associated with evaporation. A small fraction of the energy is also used for the reduction of CO_2 (photosynthesis).

The transfer of mass (e.g., water vapor) or energy (e.g., sensible heat) is expressed by analogy of Ohm's Law as (Cs – Ca*)/R,* where Cs and Ca are the concentrations of material or energy levels at the surface and in the atmosphere, respectively, and *R* is the resistance to the exchange. This resistance may refer to different processes (e.g., conduction, convection, etc.). In the case of heat transport by convection, which is very similar to the transfer of chemicals between the crop and the atmosphere, fluxes are enhanced by turbulence, which in turn depends on wind speed.

4.2 Wind and Exchange of Matter, Energy, and Momentum

Crops are subject to the mechanical action of wind, which moves and bends their leaves, stems, and branches. But wind has another essential effect on crops, as it enhances the turbulent transport of water vapor, CO_2, and heat. This flux is characterized by turbulent air currents or eddies of many different sizes and variable directions and is very effective as a transport mechanism. If the heat and the gases were transported just by diffusion, the surface conditions on earth would not be suitable for plant life due to the high temperatures that would be reached and the limitation on the downward flux of CO_2 required for photosynthesis.

Wind speed profiles are determined by the transport of eddies in the surface boundary layer, i.e. the layer of atmosphere closer to the crops and the soil. If air flows parallel to a flat surface, the profile of wind speed is logarithmic (exponential increase with height) and velocity tends to zero as we approach the surface. This profile is due to a frictional force between the surface and the air, transmitted to the upper air layers through the intermediate layers. The friction force per unit area is called the shear stress (τ_s) and is proportional to the gradient of wind speed:

$$\tau_s = \mu_a \frac{dU}{dz} \tag{4.1}$$

where μ_a is the dynamic viscosity of the air, U is the wind speed, and z is the height. The dimensions of τ_s are the same as those of momentum per unit area and unit time (momentum flux). This variable allows an analogy between heat (or mass) transport and vertical momentum transfer. The magnitude of the momentum flux is indicative of the amount and size of eddies that are formed.

The transfer of momentum and other entities between uniform, extensive horizontal surfaces is similar, but differs in the effectiveness of the exchange and its formulation.

4.3 Profiles of Wind Speed Above Crop Canopies

Flat surfaces are very rare in nature, especially on land. When obstacles such as stones or crop canopies are present, the wind profile is affected. The obstacles hinder air movement in comparison to an ideal flat surface. First, the wind velocity is not zero at the surface as shown in Fig. 4.1; extrapolated zero wind velocity lies somewhere between the surface of the ground and the plane at the height of the obstacles. This level is called the *zero plane displacement* (d_z). It indicates the level above which momentum is absorbed, namely the virtual level where the crop exerts friction forces.

Another feature that influences the aerodynamics of a surface is the *roughness length* (z_0). This is a parameter used to quantify the distortion of the real wind profile over a rough surface from the ideal logarithmic profile if the surface were smooth; it is thus a measure of the aerodynamic surface roughness. Like the zero-plane displacement, it has also the dimensions of a length and its value ranges from 10^{-6} m for smooth ice to 0.3 m for orchards and 1 m for forests. Both d_z and z_o are related

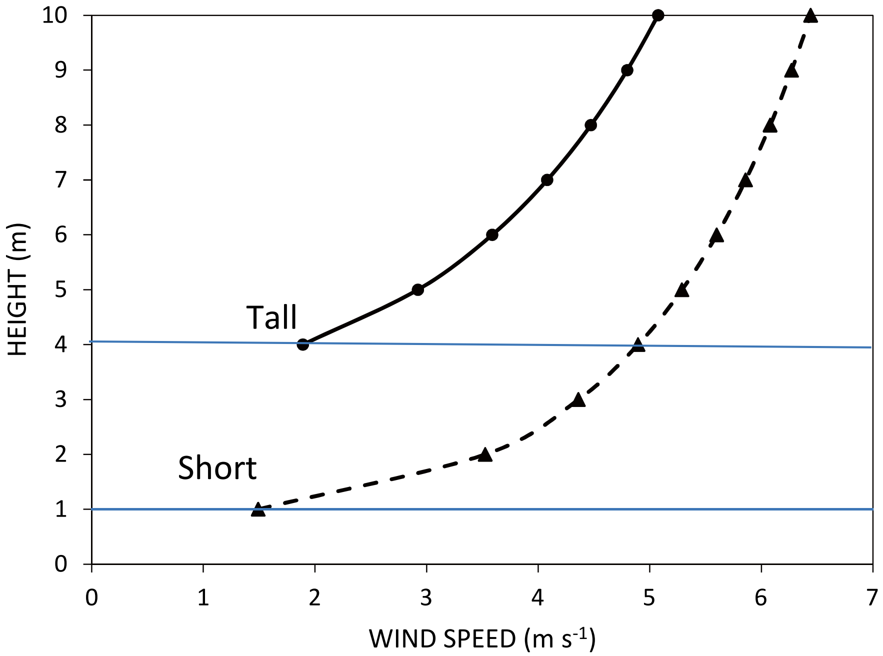

Fig. 4.1 Wind profiles over a medium height (1.0 m) and tall height (4.0 m) canopy

to the form of the crop canopy. Obviously, z_o depends on the roughness of the crop (uniformity of height among plants, distance between plants or between rows, amount of ground cover, etc.). The parameter d_z also depends on the height and flexibility of the plants and on foliage density. A simple approximation for the two parameters for different crops is to calculate d_z as 0.65 h and z_o as 0.13 h, where h is the crop height.

Typical profiles of mean horizontal wind speed above crops are shown in Fig. 4.1. These profiles may be calculated for neutral conditions (see Chap. 5) as:

$$U(z) = \frac{u_*}{k_k} \ln\left(\frac{z - d_z}{z_0}\right) \tag{4.2}$$

where $U(z)$ is the mean wind speed at height z, k_k is the von Karman's constant (0.4), and u_* is the friction velocity, which is related to momentum flux:

$$u_* = \sqrt{\frac{\tau_s}{\rho_a}} \tag{4.3}$$

where ρ_a is the air density (kg m^{-3}) that depends on air temperature (T in K) and atmospheric pressure (P_{at} in kPa) (the effect of air humidity is neglected):

$$\rho_a = 3.484 \frac{P_{at}}{T} \tag{4.4}$$

Applying the above equations, once z_o and d_z are known, we may generate the whole profile of wind speed as a function of wind speed measured at a reference height (z_m):

$$U(z) = U(z_m) \frac{\left[\ln(z - d_z) - \ln z_0\right]}{\left[\ln(z_m - d_z) - \ln z_0\right]} \tag{4.5}$$

Example 4.1

Figure 4.1 shows the wind profiles of two crops with height 1 m (e.g., wheat) and 4.0 m (e.g., olives), respectively. To construct this curve, we assumed that the wind speed at 100 m height is 10 m/s in both cases. The wind speed above olive is significantly lower than above grass. The olives slow down the wind more, or, in other words, they take more momentum away from the wind. Friction velocities are 0.60 m/s and 0.76 m/s, for grass and olive, respectively, which correspond to values of momentum transfer of 0.43 and 0.70 N/m^2.

Often, the only available information on wind speed comes from a nearby weather station where the wind is measured at a standard height ($z = 2$ m in agrometeorological stations). However, we may need U at a height z over a canopy of height h. We can use Eq. 4.5 to calculate first U_{100}, the speed at a height of 100 m, which we may assume that does not vary spatially, i.e. it is the same above the weather station and above the crop. If the station is located over grass ($h = 0.12$ m) then:

$$U_{100} = U_{2g} \frac{\left[\ln\left(100-0.078\right)-\ln\left(0.0156\right)\right]}{\left[\ln\left(2-0.078\right)-\ln\left(0.0156\right)\right]} = 1.82\,U_{2g} \tag{4.6}$$

where U_{2g} is the wind speed measured at 2 m over grass.

And then we can calculate $U(z)$ above our crop of height h:

$$U\left(z\right) = 1.82\,U_{2g} \frac{\left[\ln\left(z-0.65h\right)-\ln\left(0.13h\right)\right]}{\left[\ln\left(100-0.65h\right)-\ln\left(0.13h\right)\right]} \tag{4.7}$$

Example 4.2

Wind speed at z = 2 m above grass (U_{2g}) is 2.5 m/s. We will calculate U at z = 5 m over a 4-m olive orchard.

$$U\left(z\right) = 1.82\cdot 2.5 \frac{\left[\ln\left(5-0.65\cdot 4\right)-\ln\left(0.13\cdot 4\right)\right]}{\left[\ln\left(100-0.65\cdot 4\right)-\ln\left(0.13\cdot 4\right)\right]} = 1.33\,\text{m/s}$$

4.4 Aerodynamic Resistance

The equation describing the flux of momentum in terms of the gradient of horizontal wind speed (Eq. 4.1) can be written using the Ohm's Law analogy, by introducing an aerodynamic resistance to momentum transfer between heights z_1 and z_2. Therefore, if

$$\tau_s = \rho_a \frac{U_2 - U_1}{r_{aM}} \tag{4.8}$$

and using Eqs. 4.2 and 4.3, then the aerodynamic resistance between a height z where wind speed is $U(z)$ and height $d + z_o$ (where the extrapolated wind speed is zero) will be:

$$r_{aM} = \frac{\left[\ln\left(\frac{z-d_z}{z_0}\right)\right]^2}{k_k^{\,2}\,U\left(z\right)} = \frac{U\left(z\right)}{u_*^{\,2}} \tag{4.9}$$

This equation indicates that the aerodynamic resistance to momentum flux will be higher for short than for tall crops. Short, smooth surfaces are less effective in slowing the wind that flows above them, thus less energy is transferred from the wind to the surface for a given wind flow. The resistance decreases as wind speed increases. In theory, the resistance tends to infinity as U tends to 0. However, that does not occur during the daylight hours in the atmosphere because of buoyancy, which will be treated in Chap. 5. Suffice it to note here that as U decreases, the lack of turbulence reduces the exchange of heat between the crop and the atmosphere thereby increasing the temperature of the canopy and the air in contact therewith. This heated air tends to rise because of its lower density causing turbulence. This type of turbulence is called "thermal" as opposed to "mechanical" turbulence, which is due to friction of the wind on the crop. Both types of turbulence coexist although mechanical turbulence prevails when U is high and thermal turbulence is enhanced during the daytime when U is low.

Example 4.3

Let us calculate the aerodynamic resistance for $z = 5$ m in the two cases mentioned in Example 4.1 (olive orchard with $h = 4$ m and wheat with $h = 1$ m) if the wind speed at 2 m height over grass (U_{2g}) is 2.5 m/s.

We need to know first $U(z)$ for $z = 5$ m in both cases.

We saw in Example 4.2 that U(z = 5) = 1.33 m/s for olive

For wheat, using Eq. 4.5:

$$U(z) = 1.82 \cdot 2.5 \frac{\left[\ln\left(5 - 0.65 \cdot 1\right) - \ln\left(0.13 \cdot 1\right)\right]}{\left[\ln\left(100 - 0.65 \cdot 1\right) - \ln\left(0.13 \cdot 1\right)\right]} = 2.41\,\mathrm{m/s}$$

then applying Eq. 4.9 for the two surfaces:

Olive:

$$r_{aM} = \frac{\left[\ln\left(\frac{5 - 0.65 \cdot 4}{0.13 \cdot 4}\right)\right]^2}{0.4^2 \cdot 1.33} = 11.0\,\mathrm{s/m}$$

Wheat:

$$r_{aM} = \frac{\left[\ln\left(\frac{5 - 0.65 \cdot 1}{0.13 \cdot 1}\right)\right]^2}{0.4^2 \cdot 2.41} = 32.0\,\mathrm{s/m}$$

4.5 Wind Speed and Turbulence at Canopy Height

The mathematical analysis of wind profiles above crops presented above should allow the calculation of wind speed at canopy height as a function of crop height. However, the existence of the so-called Roughness Sub-layer, which extends up to 2–2.5 times canopy height has not been taken into account. In that layer, the profiles of temperature and wind are distorted due to the proximity of vegetation.

Including this effect, the following equation allows calculating wind speed at canopy height as a function of wind speed measured at 2 m height over grass:

$$U_h = \frac{2.6U_{2g}}{6.6 - \ln(h)} \tag{4.10}$$

This equation indicates that for most agricultural crops, with heights between 0.2 and 3 m, wind speed at canopy height ranges between 0.32 and 0.46 times the wind speed at 2 m over grass.

In the previous sections, we have defined turbulence as an ensemble of eddies of different sizes and properties (temperature, humidity, CO_2 concentration) moving up or down and following, on average, the direction of wind speed. This vertical exchange of eddies is responsible for the fluxes between the crop and the atmosphere. For instance, the convective transport of heat is due to warm eddies moving up and cooler eddies moving down. We can characterize this turbulent exchange using the average velocity of eddies going up, which is equal to that of those going down (as the mean vertical velocity is close to zero). This upward velocity, accompanied by a downward velocity of the same magnitude may be seen as a mean renovation rate (w_r) for the air located below. The renovation rate is proportional to horizontal wind speed (U). For neutral conditions, we can write:

$$w_r = 0.14U \tag{4.11}$$

Note that w_r has dimensions of velocity. By combining Eqs. 4.10 and 4.11, we can calculate the renovation rate of air in contact with a canopy of height h:

$$w_r = 0.14\ \frac{2.6U_{2g}}{6.6 - \ln(h)} \tag{4.12}$$

And the relative renovation rate with dimensions T^{-1} would be obtained by dividing w_r by canopy height h.

Example 4.4

When wind speed over grass is 2 m/s the renovation rate of a maize canopy with height 2 m is:

$$w_r = 0.14\ \frac{2.6 \times 2}{6.6 - \ln(2)} = 0.123\,\mathrm{m/s}$$

And the relative renovation rate is 0.123/2 = 0.0615 s^{-1}

This means that the air in contact with the canopy would be completely renovated in 16.3 s (inverse of the relative renovation rate). The concept of renovation rate is applied to greenhouses as a measure of ventilation and is usually expressed as the number of renovations per hour. In this example, the relative renovation rate is equivalent to 0.0615 s^{-1} × 3600 s/h = 221.4 renovations h^{-1}.

4.6 Wind Speed Within Canopies

If the wind profiles are complicated above the canopy, they are even more complicated inside it. In simple terms, the canopy height is divided into two or three zones. The top layer (above d_z) absorbs most of the momentum. In this layer, the wind speed decreases logarithmically as we enter the canopy and has the same direction as the average wind over the canopy. This is seen in Fig. 4.2 for a hedgerow olive orchard down to 2.5 m height. Below that height, wind speed is almost constant and rather small (35–40% of that at the top of the canopy in the example of Fig. 4.2).

4.7 Daily and Seasonal Variation of Wind Speed and Direction

Both the daily and the seasonal time courses of wind speed are highly variable. The predominant winds have traditionally been characterized by the wind rose, which is a representation of the frequencies of occurrence of each wind direction. The seasonal time course, besides being highly variable from year to year, is often site-specific. As an example, Fig. 4.3 shows the wind speed in Fuente Palmera (Spain) during the year. In this case, the highest values of U occur in spring and summer and

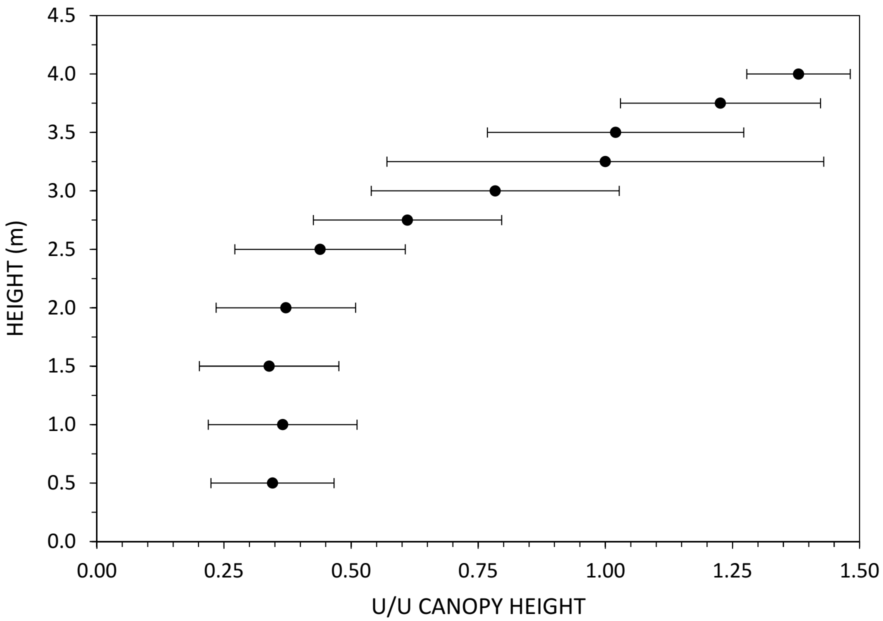

Fig. 4.2 Profile of wind speed (relative to that at canopy height 3.25 m) measured in an olive orchard close to Cordoba (Spain) in the summer of 2012. Horizontal segments represent twice the standard deviation

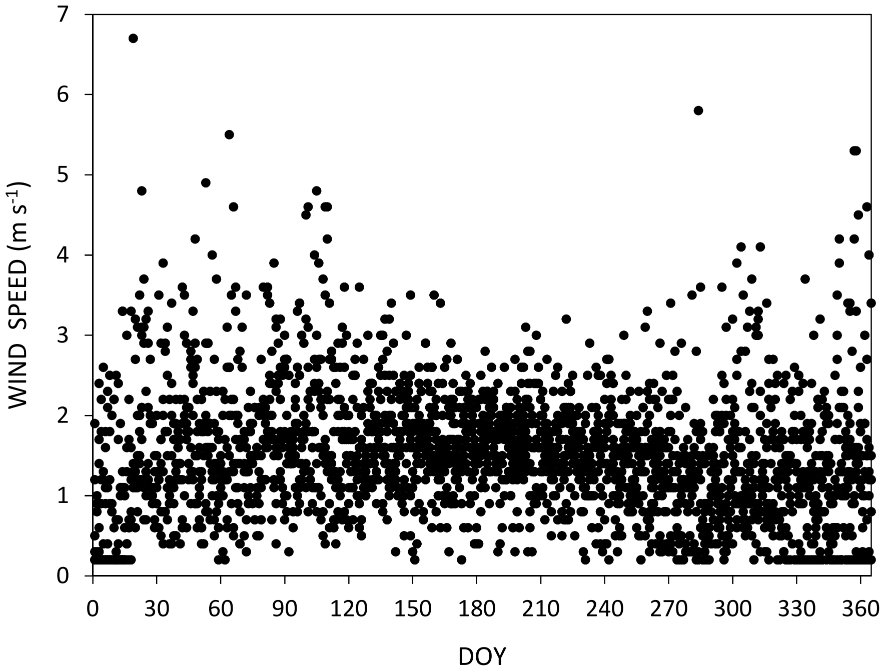

Fig. 4.3 Mean daily wind speed at 2 m height at Fuente Palmera (Spain) 2007–2013

lower values occur in autumn and winter. The large differences between locations in wind patterns are evident in Fig. 4.4, which shows the monthly average values of *U* in Bangui (Central African Republic), Cordoba (Spain), and Amarillo (Texas). The large variation among locations in wind speed is illustrated in Fig. 4.5, which plots mean annual wind speed for many locations as a function of latitude. Both mean wind speed and its variability increase as we move away from the Equator.

In the diurnal time course, we usually observe that calm conditions predominate at night while the maximum wind speed occurs during the day. Figure 4.6 shows the diurnal time course of wind over grass at Cordoba in June: *U* is low at night, especially at dawn, and *U* increases during the day.

A wind rose is a graphical representation of the distribution of wind speed and direction at a given site over a specific period. Presented in a circular format, the wind rose shows the frequency of winds blowing from each direction, typically classified in 16 cardinal directions, such as north (N), NNE, NE, etc., where North corresponds to 0°, East to 90°, South to 180° and West to 270°. The distance from the center represents the frequency of that particular direction, which may be also given for different wind speed classes (see example in Fig. 4.7).

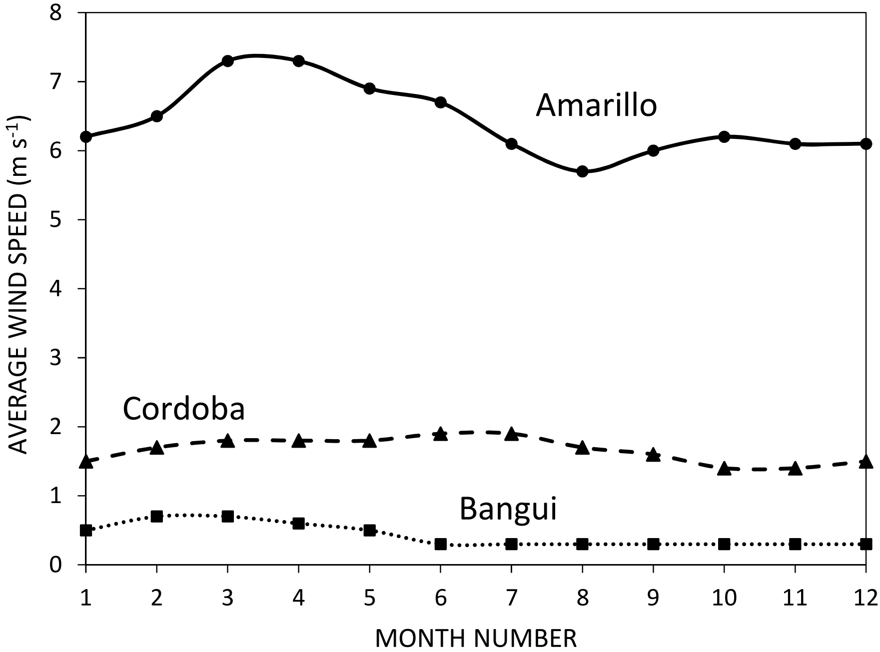

Fig. 4.4 Time course of monthly mean wind speed in Bangui (Central African Republic), Amarillo (Texas, USA), and Cordoba (Spain)

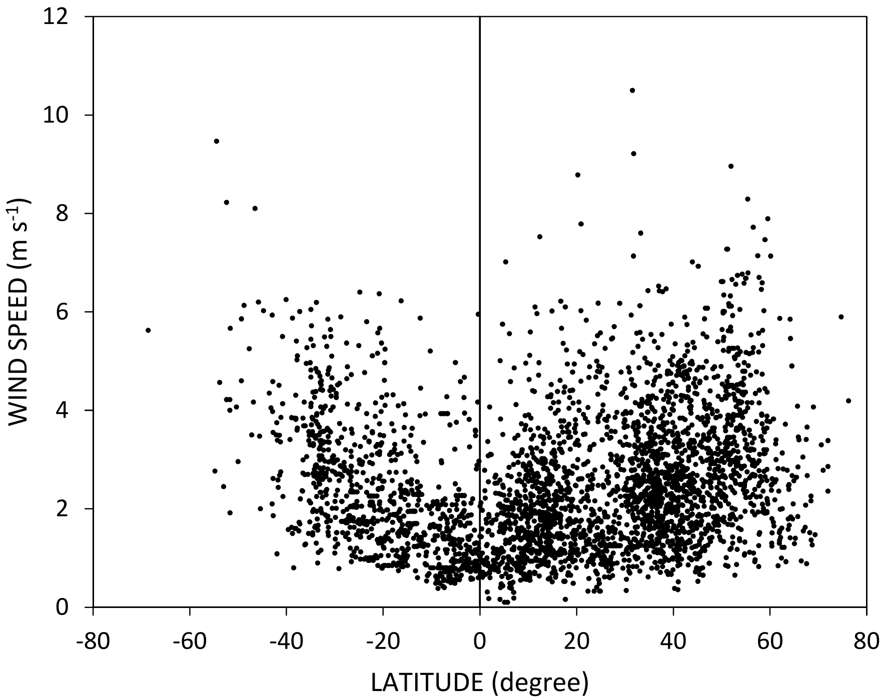

Fig. 4.5 Mean annual wind speed for different locations as a function of latitude. (Source: Climwat-FAO)

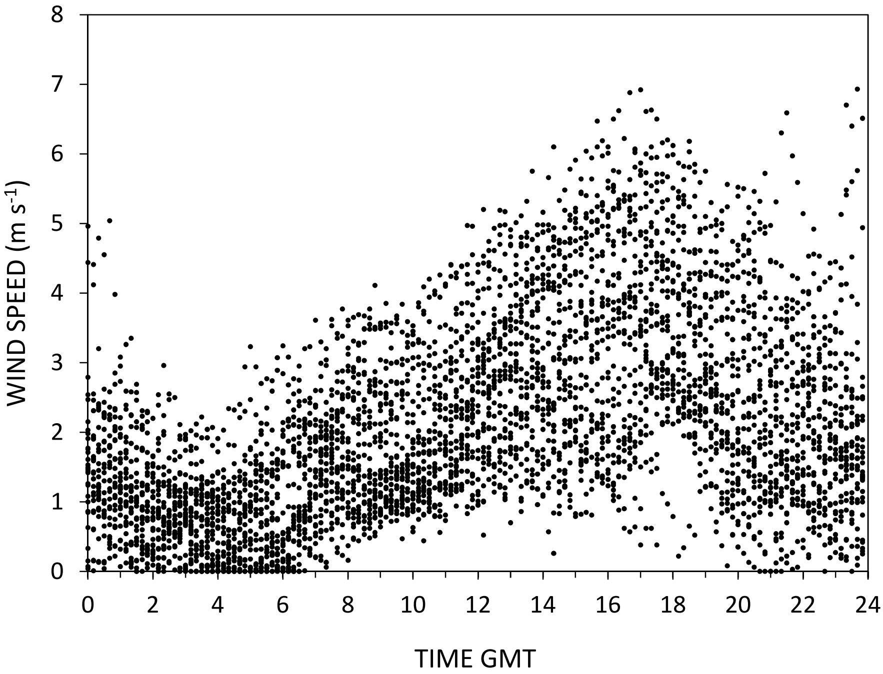

Fig. 4.6 Wind speed at Cordoba (Spain) in June 2003 plotted as a function of time during the day. Each point is the 10-min average wind speed

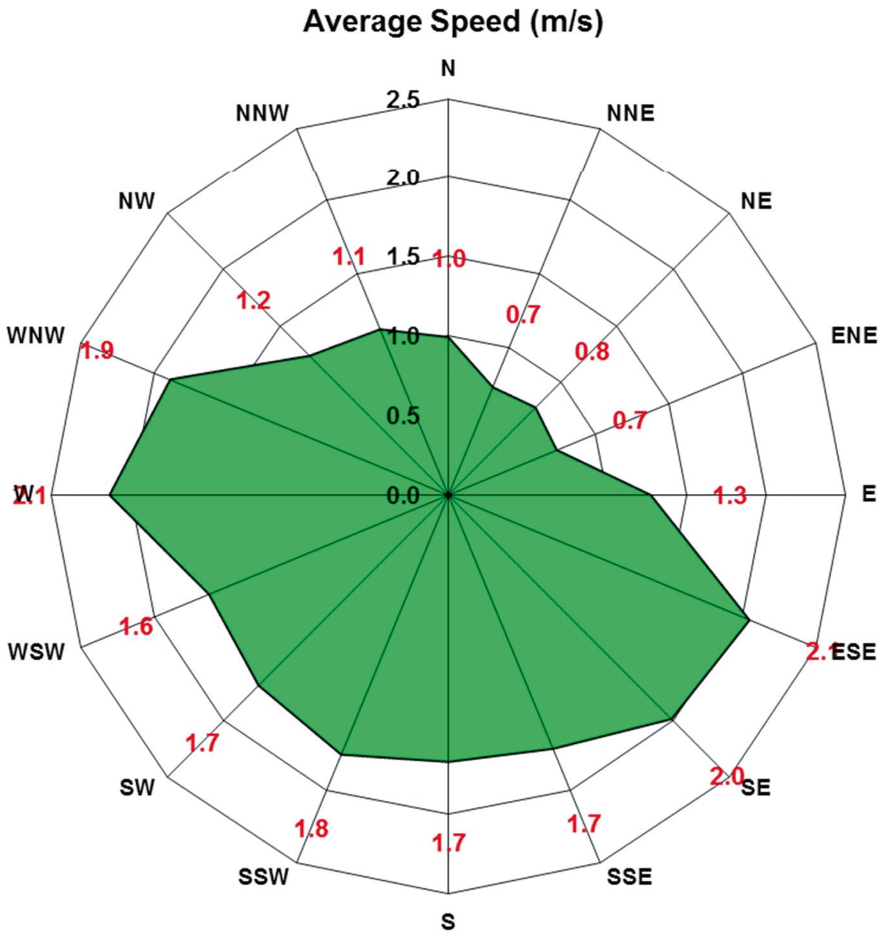

Fig. 4.7 Wind rose at finca "Villazulina," Espiel (Spain) 2003–2012

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Air Temperature and Humidity

5

Francisco J. Villalobos, Luciano Mateos, Luca Testi,
Elias Fereres, and José Paulo De Melo-Abreu

Abstract

Air temperature shows unstable profiles during the day and stable profiles during the night. Therefore, canopy temperature is generally higher than air's during the day and lower at night. Heat transfer between the crop and the atmosphere is sustained by turbulence and increases with wind speed, i.e. as aerodynamic resistance decreases. In situations of unstable atmosphere, turbulence is enhanced (by added thermal turbulence) while in a stable condition, turbulence is reduced. The atmosphere water vapor content can be expressed by different variables (vapor pressure, relative humidity, vapor pressure deficit, mixing ratio, and vapor density). The flow of water vapor (equivalent to energy spent as latent heat) between the crop and the atmosphere is directly proportional to the vapor pressure difference and inversely proportional to the sum of the canopy and aerodynamic resistances.

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5.1 Introduction

Air temperature controls the functioning of terrestrial ecosystems. Crop temperature affects photosynthesis, growth and development rates, transpiration, etc. Crops are heated by radiation absorption. Part of the absorbed energy is used to heat the air (sensible heat) which, in turn, determines the air temperature above the crop.

Air humidity is important in crop production for two main reasons. First, water and/or humidity are essential for living organisms in the agricultural ecosystem to grow and complete their life cycle. Secondly, moisture plays an important role in energy exchange. Changing water from liquid to vapor state, i.e. evaporation, requires 2.45 MJ/kg. When 1 kg of water vapor condenses and then freezes, 2.8 MJ is released. The first process relates radiation absorption to water use by crops and the second process occurs when white frost is formed.

5.2 Atmospheric Stability

In an adiabatic process, there is no heat exchange between a parcel and its environment. If a parcel of air moves fast enough, the heat exchange between the parcel and the surrounding air is practically nil, allowing for the assumption of an adiabatic process.

An air parcel that rises adiabatically (see Box 5.1) from one level to a higher one expands and cools at a rate of 0.01 °C/m, before it reaches the condensation level. On the contrary, if the parcel is pushed downward if warms up at the same absolute rate. The rate of change of temperature of the air parcel with elevation (±0.01 °C/m) is termed the *dry adiabatic lapse rate*. Figure 5.1 shows the dry adiabatic rate

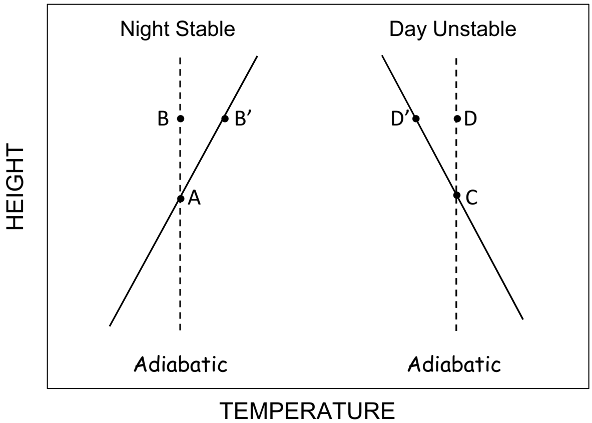

Fig. 5.1 Typical temperature profiles during the day and during the night

(dashed line) and the environmental lapse rates in two contrasting stability conditions of the atmosphere. Figure 5.1 (right) illustrates an *unstable atmospheric condition*. In this case, by raising a parcel of air adiabatically from point C to D, that parcel of air will have a higher temperature than the surrounding air (D′), will be less dense, and will tend to continue rising. The initial push of the air parcel may be mechanical or of thermal origin.

Conversely, Fig. 5.1 (left) illustrates a *stable atmospheric condition*. In this adiabatic process, if an air parcel is given a push upward (/downward), its temperature will be lower (/higher) than the surrounding air and its density will be higher (/lower), so the parcel will tend to return to its original position.

If the environmental lapse rate coincides with the dry adiabatic rate, the atmospheric condition is neutral.

Box 5.1: Adiabatic Processes

A process (change of state) that occurs without gain or loss of heat is called adiabatic. If the pressure of an air volume changes adiabatically from P_1 to P_2, the change of temperature (from T_1 to T_2) is given by:

$$\left(T_2 / T_1\right) = \left(P_2 / P_1\right)^{1-Cv/Cp} \tag{5.1}$$

where C_p and C_v .are the specific heats of air at constant pressure and constant volume, respectively.

The above equation means that a mass of air at a pressure 100 kPa and temperature 30 °C will cool down to 20.8 °C if it rises adiabatically to a height where the pressure is 90 kPa. This temperature drop as height increases is called adiabatic lapse rate. Its value for dry air is about 0.01 K/m while it is lower for moist air, depending also on temperature (approx. 0.006 K/m).

5.3 Basic Principles on Air Humidity

According to Dalton's Law, the air pressure in the atmosphere is the sum of the partial pressure of water vapor (e_a) and the partial pressure of dry air (P_d). Both partial pressures may be expressed as the product of their respective molar fractions by the atmospheric pressure (P_{at}).

From a water surface, some molecules escape in the evaporation process while others return to the liquid state. When the number of molecules escaping equals that of those returning, the system has reached a steady state and the atmosphere is saturated. In this state, the vapor pressure has reached its saturation value (e_s).

For a given temperature, there is a single value of e_s, and the relation between the two variables is an exponential function:

$$e_s = 0.6108 \exp\left(\frac{17.27\,T}{237.3+T}\right) \tag{5.2}$$

where e_s is expressed in kPa and T is temperature (°C). The atmosphere is usually not saturated, thus *actual vapor pressure*, e_a is lower than e_s for that temperature.

Relative humidity (%) indicates the degree of saturation as:

$$RH = 100\frac{e_a}{e_s} \tag{5.3}$$

However, as it depends on the temperature, it is not a good indicator of the amount of water vapor in the air.

Another interesting measure of air humidity, widely used in crop ecology, is the *vapor pressure deficit* (*VPD*) which is the difference e_s–e_a. It reflects the drying power of the atmosphere and is therefore a key factor in determining the rate of evaporation and transpiration.

Air humidity may also be quantified by the *dew point temperature* (T_d), the temperature at which a given parcel of humid air must be cooled, at constant pressure, to reach saturation. If the air temperature falls below T_d, condensation will start. This explains the film of water that covers the soil or plants at sunrise, after nights of intense radiative cooling, which is called *dew*.

The *mixing ratio* is the ratio of mass of water vapor per unit mass of dry air and can be calculated (in g/kg) as:

$$X_v = 622\frac{e_a}{P_{at}-e_a} \tag{5.4}$$

where P_{at} is the atmospheric pressure (kPa) and e_a is the vapor pressure (kPa). Finally, air humidity may be expressed as vapor density (ρ_v), also known as *absolute humidity*, which is the mass of water vapor per unit volume of air and can be calculated (g water vapor m^{-3}) as:

$$\rho_v = \frac{1000\,e_a}{0.4615(T+273)} \tag{5.5}$$

where T is air temperature (°C).

Example 5.1
Air temperature is 20 °C and relative humidity is 80%. We will calculate vapor pressure, *VPD*, mixing ratio, vapor density, and dew point temperature. We will assume standard atmospheric pressure (101.3 kPa).

First, we calculate saturation vapor pressure:

$$e_s = 0.61078 \exp\left[17.269\,20 / \left(20 + 237.3\right)\right] = 2.338\,\text{kPa}$$

Therefore: $e_a = (HR/100)\ e_s = 80/100 \times 2.338 = 1.87$ kPa

$$VPD = e_s - e_a = 2.338 - 1.87 = 0.467\,\text{kPa}$$

Mixing ratio: Xv = 622 × 1.87/(101.3–1.87) = 11.7 g/kg

Vapor density: ρv = 1000 × 1.87/(0.4615 × 293) = 13.83 g m–3

Dew point temperature may be deduced by equating Eq. 5.2 to 1.87 kPa, the actual vapor pressure, and then solving for temperature as:

$$T_d = \frac{237.3 \ln\left(\dfrac{e_a}{0.6108}\right)}{17.27 - \ln\left(\dfrac{e_a}{0.6108}\right)} = 16.44°\text{C}$$

If this air is cooled down to 16.4 °C, we will reach saturation. This may be checked by putting T = 16.44 °C into Eq. 5.2, yielding 1.87 kPa.

5.4 Temperature Profiles Within and Above Crop Canopies

The soil or crop surface undergoes cooling at night as solar radiation is zero and longwave radiation emission continues (R_n negative). The air in contact with the surface transfers heat to the surface, cools and its density increases. If radiative cooling is high enough and the wind is calm, a temperature inversion develops and the atmospheric condition is stable (Fig. 5.2).

During the day the opposite occurs. The surface absorbs radiation that, in part, serves to heat the lower layers of the atmosphere. The temperature now decreases with height and the atmospheric condition is unstable (this can be seen in the afternoon in Fig. 5.2).

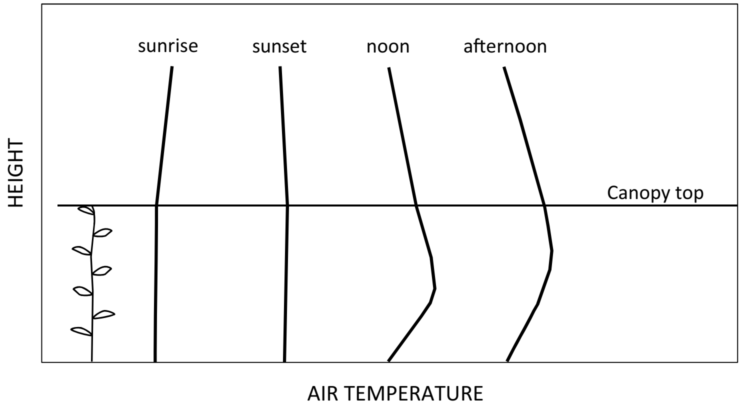

Fig. 5.2 Typical temperature profiles above and within a crop canopy

The shape of the temperature profiles has important implications for the temporal and spatial distribution of temperature on crops. As we approach the crop surface, thermal oscillation (the difference between maximum and minimum temperature) increases as higher maximum and lower minimum temperatures are observed.

Moreover, during the day, inverted profiles can be observed due to cooling as a result of crop evapotranspiration. This situation is typical of summer when hot-dry air blows over irrigated crops. The phenomenon is called sensible heat advection and is explored in more detail in Chap. 7.

Both the day and night profiles are often highly variable and are affected by other factors, particularly wind speed. When wind speed is very high, the temperature profile above the crop tends to be uniform with height, so the air and the crop temperature are similar. In contrast, during calm conditions, the temperature profile is very sharp and the crop is much hotter than the air (during the day) or much colder (overnight). The temperature profiles (stable or unstable) have an important effect on turbulence (Box 5.2).

Box 5.2: Effects of Atmospheric Stability on Turbulence

The mathematical treatment of stability effects lies outside the scope of this book. However, some remarks should be made on the importance of stability. During the daytime, turbulent transport is assured, as wind speed is higher. If wind speed is low, buoyancy increases and turbulence will be sustained. Therefore, only in rare cases, the lack of turbulence in the daytime may restrict the vertical transport of energy or matter. The opposite will occur at night as wind speed is usually lower and the temperature profile is typically inverted. In this case, there is a layer above the crop where turbulence is almost absent, thus resulting in small values of transfer of heat or water vapor.

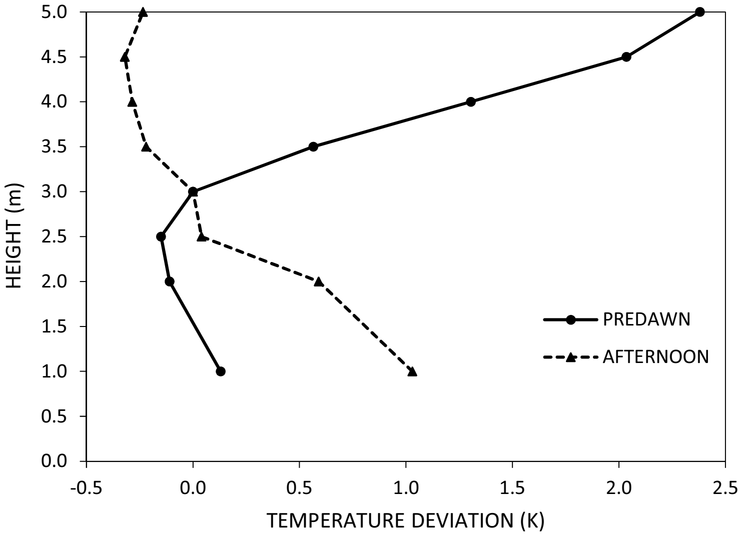

Fig. 5.3 Air temperature profiles above and within an olive canopy of 3.25 m height on a summer day (July 30, 2011) near Cordoba (Spain). The values are shown as departures from the temperature measured at 3.0 m height

The temperature profiles within the crop canopy contrast with those observed above the canopy. During the day, temperature reaches a maximum at the level where leaf density is highest. A high leaf area density allows greater radiation absorption and therefore higher temperature. Above this level, the daytime temperature profile is generally unstable and below, it is usually slightly inverted. During the night, the profile within the canopy is usually isothermal as the crop traps and re-emits radiation emitted from the soil (Fig. 5.3).

5.5 Air Humidity Profiles Above Crop Canopies

During the day, due to evapotranspiration, the vapor pressure is high near the crop surface and decreases with height. Water vapor is removed more effectively with increasing wind and turbulent transport. Therefore, the more pronounced profiles occur at noon when evapotranspiration is higher and the water vapor is removed promptly. The vapor pressure profile at night is more uniform and may even increase with height on nights when dew deposition occurs.

5.6 Time Course of Air Temperature and Humidity

The time course of air temperature along a clear day follows a sine function with a minimum around sunrise and a maximum that occurs 2–3 h after the radiation peak (Fig. 5.4). The delay of air temperature relative to radiation is due to the balance

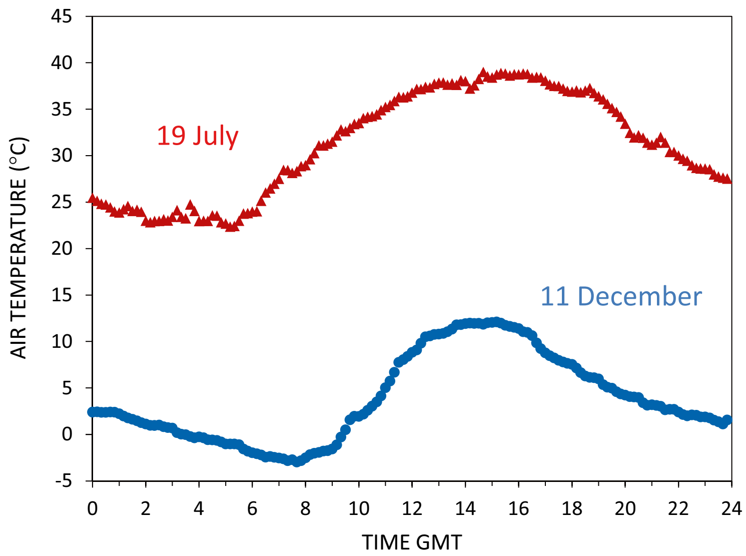

Fig. 5.4 Time course of air temperature throughout the day on a summer (19 July 2012) and a late fall day (11 December 2012) in Espiel (Spain)

between the energy reaching the surface and the energy being used. Part of the radiation in the morning is used in heating the soil and the crop. Once these surfaces have been heated, there will be sensible heat transfer to the air that will then be heated. Furthermore, other factors (such as advection) can contribute to rising air temperature in the afternoon.

Vapor pressure varies relatively little compared to other variables that measure air humidity. For example, variations in *VPD* during the day are mainly due to variations in air temperature. In any case, vapor pressure close to the canopy is proportional to the evaporation rate, thus it will be higher during midday (Fig. 5.5).

In contrast with the vapor pressure, the maximum relative humidity occurs during the night because, although the atmosphere water vapor content is somewhat lower, the temperature is much lower. Although the vapor pressure can be slightly higher after noon, minimum relative humidity occurs typically sometime after noon, due to higher temperature.

To calculate the average daily vapor pressure as a function of maximum and minimum *RH* we can use the following equation:

$$e_{\mathrm{avg}} = 0.5\left(e_{sx}\frac{RH_n}{100} + e_{sn}\frac{RH_x}{100} \right) \tag{5.6}$$

where RH_n and RH_x are minimum and maximum *RH*, respectively and e_{sx} and e_{sn} are saturated vapor pressure for the maximum and minimum temperature, respectively. Therefore, the average *VPD* will be:

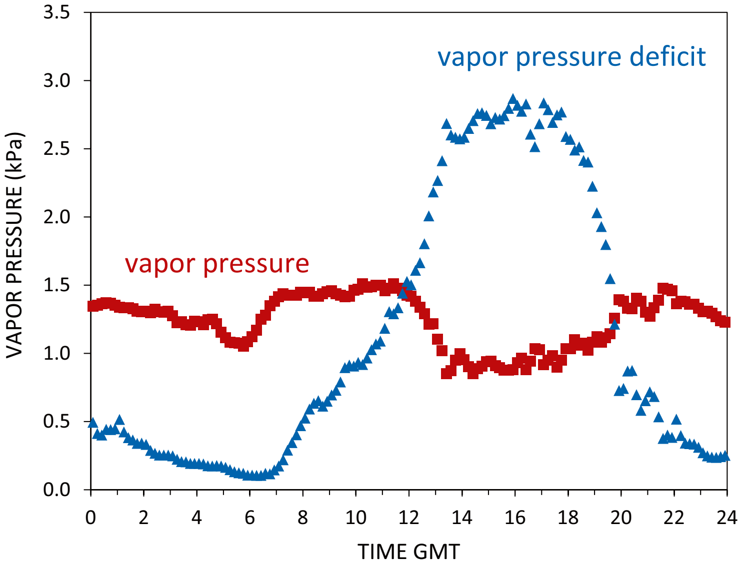

Fig. 5.5 Time course of vapor pressure (red) and vapor pressure deficit (blue) throughout the day on a spring day (5 May 2013) in Cordoba (Spain)

$$VPD_{\text{avg}} = 0.5\left[e_{sx}\left(1-\frac{RH_n}{100}\right)+e_{sn}\left(1-\frac{RH_x}{100}\right)\right] \tag{5.7}$$

The annual time courses of the air maximum and minimum temperatures follow a pattern very similar to the daily pattern (Fig. 5.6). Something similar occurs for vapor pressure.

Figure 5.7 shows the mean monthly vapor pressure in two locations with the same latitude (31.8°S) but with low (Klawer, South Africa) and high rainfall (Pelotas, Brazil). In both locations, vapor pressure is maximum in summer and minimum in winter, but the two curves reflect clearly the difference in rainfall.

On average, the minimum and the maximum temperature occur with a certain delay compared to the minimum and maximum radiation, respectively. This is presented in Fig. 5.8 that shows the annual curves of average radiation and temperature in Cordoba. The causes for the delay between the temperature and radiation waves are similar to those described for the daily curve. During the spring, part of the radiation is used to heat the soil. As the soil temperature rises above the air temperature, more energy will be available to be converted into sensible heat. A similar reasoning can be applied to explain when the minimum winter temperature occurs.

The amplitudes of the waves of air temperature, both for daily and annual cycles, depend largely on the partitioning of energy between evaporation and heating of the soil and air above, as we will see in the following sections. Therefore, the amplitude will be higher in arid than in wet areas (or near the sea).

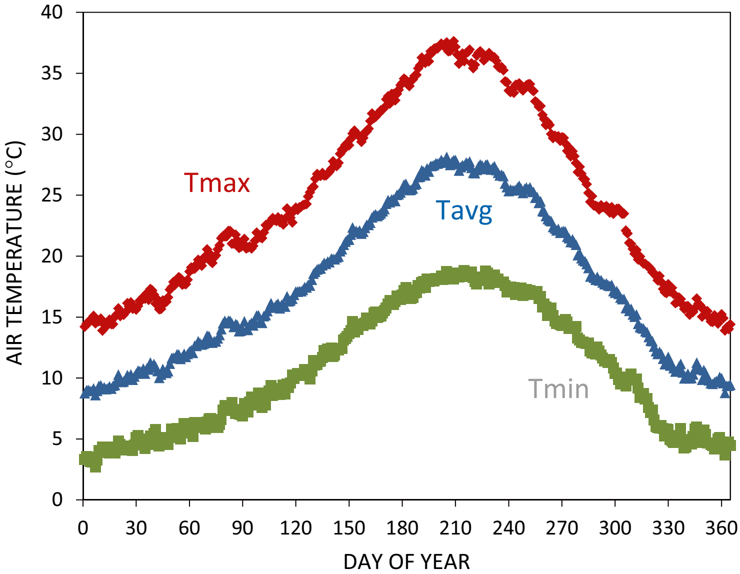

Fig. 5.6 Time course of average maximum, minimum and mean air temperature. Cordoba (Spain). 1964–2002

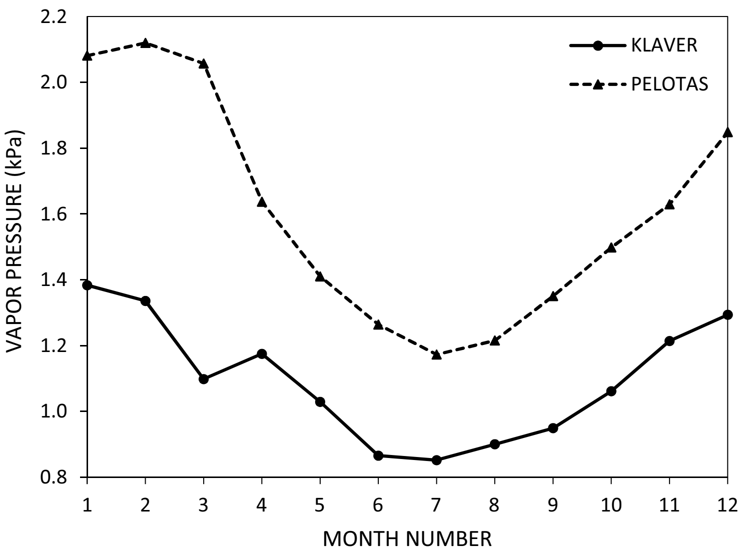

Fig. 5.7 Time course of mean monthly vapor pressure for two locations, Pelotas (Brazil) with mean annual rainfall of 1395 mm and Klawer (South Africa) with mean annual rainfall of 174 mm

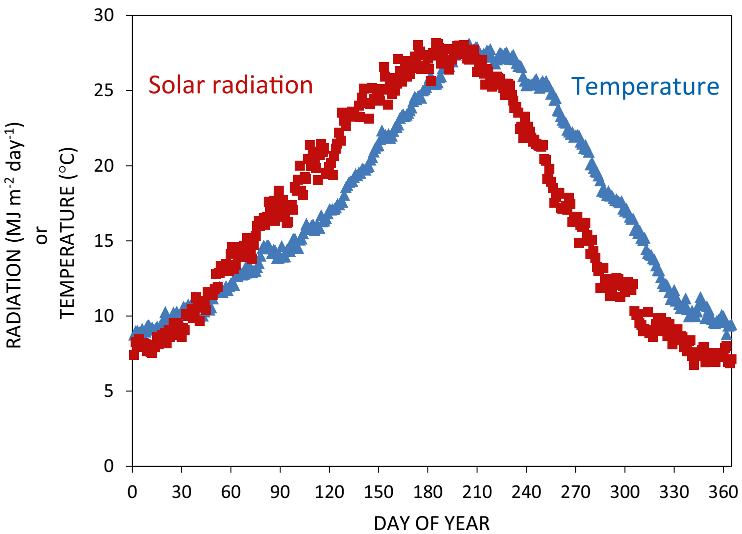

Fig. 5.8 Time course of mean air temperature and solar radiation. Cordoba (Spain). 1964–2002

The maximum temperatures expected in summer are typically between 30 and 45 °C with larger values occurring at mid-latitudes (Fig. 5.9). Minimum winter values are around 20 °C for zero latitude locations and decrease as we move North or South (Fig. 5.10). The variation of mean annual vapor pressure parallels that of minimum temperature in winter (Fig. 5.11).

5.7 Sensible Heat Flux

One consequence of the temperature gradients that occur over canopies will be a sensible heat flux (convective heat transfer) from the layers of higher temperature to those of lower temperature. Normally, the flux is directed toward the crop at night and from the crop to the atmosphere during the day. The term "sensible" means that this flux has an effect that can be detected as it involves changes in air temperature.

The sensible heat transfer is mainly accounted for by turbulence. The sensible heat flux (H) between the canopy and the atmosphere at height z where the temperature is T_a may be calculated as:

$$H = \rho C_p \frac{T_c - T_a}{r_{aH}} \tag{5.8}$$

where ρ is the air density, C_p is the specific heat of air at constant pressure, T_c is the canopy temperature, and r_{aH} is the aerodynamic resistance for heat transport (s m^{-1}).

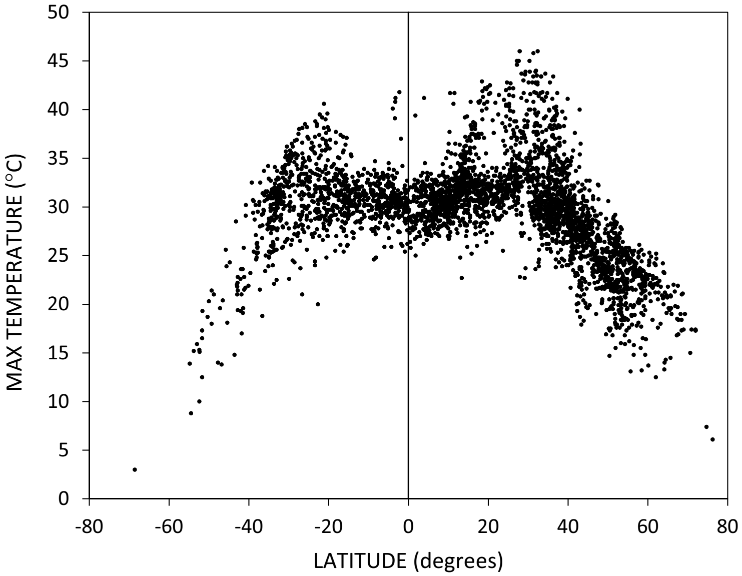

Fig. 5.9 Mean maximum temperature in July (Northern locations) or January (Southern locations) as a function of latitude. Only locations with altitude lower than 1000 m have been included

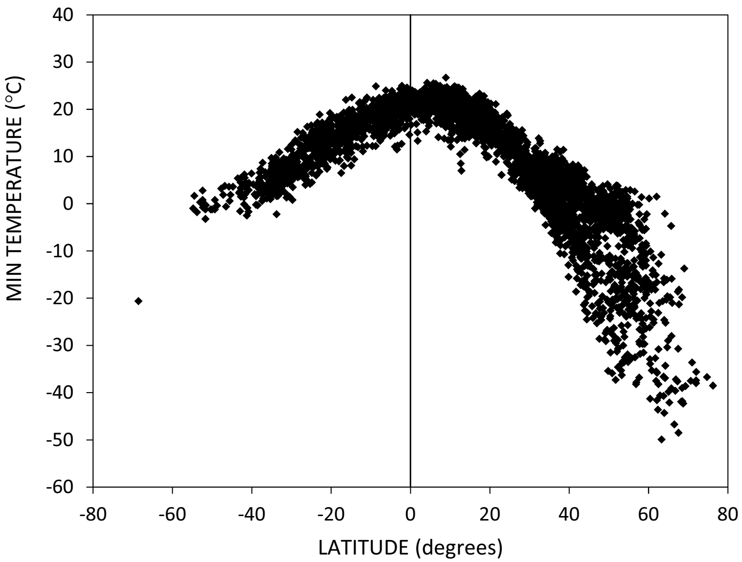

Fig. 5.10 Mean minimum temperature in February (Northern locations) or August (Southern locations) as a function of latitude. Only locations with altitude lower than 1000 m have been included

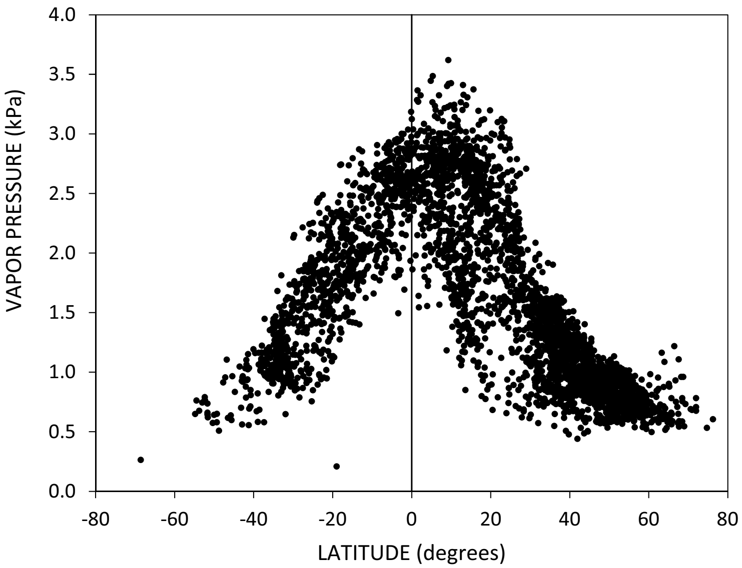

Fig. 5.11 Mean annual vapor pressure for different locations as a function of latitude

The product $\rho\, C_p$ (units J K^{-1} m^{-3}) can be calculated as:

$$\rho\, C_p = \rho_a \left(1.01 + 1.88 \frac{X_v}{1000}\right) = \frac{29 \cdot 10^3 P_{at}}{8.31(273+T)} \left(1.01 + 1.88 \frac{0.622\, e}{P_{at} - e}\right) \tag{5.9}$$

where T is the air temperature (°C), ρ_a is the dry air density (g m^{-3}), X_v is the mixing ratio (g kg^{-1}), e is the vapor pressure (kPa), and P_{at} (in kPa) is the atmospheric pressure, which can be calculated as a function of altitude (AL, m) as:

$$P_{at} = 101.3 \left(1 - \frac{AL}{44{,}308}\right)^{5.2568} \tag{5.10}$$

The calculation of r_{aH} is not straightforward as it depends on atmospheric stability. For neutral conditions, the following equation may be applied:

$$r_{aH} = \frac{\ln\left(\frac{z - d_z}{z_0}\right) \ln\left(\frac{z - d_z}{z_{0H}}\right)}{k_k^2\, U(z)} \tag{5.11}$$

where z_{oH}, the roughness length for heat exchange, may be estimated as 0.2 z_o.

5.8 Latent Heat Flux

Water vapor flows normally from the surface of the soil or the crop to the air above the crop. This involves a latent heat flux required for the evaporation of water. A downward water vapor flow and therefore a negative latent heat flux can be observed during dew deposition. Similar to the fluxes of momentum or sensible heat, the latent heat flux (*LE*) is expressed as:

$$LE = \frac{\rho C_p}{\gamma} \frac{e_{sc} - e_a}{r_{aW} + r_c} \tag{5.12}$$

where γ is the psychrometric constant (around 0.067 kPa/K), e_{sc} is the saturation vapor pressure at canopy temperature, r_c is the canopy resistance, and r_{aW} is the aerodynamic resistance to water vapor flux, which should be equal to aerodynamic resistance for heat transport (Eq. 5.11). In writing this equation, we are considering the gradient of vapor pressure between the inside of the leaves, namely in the sub-stomatal cavities (where the air is saturated and at the same average temperature as the crop canopy) and the air above. Therefore, water vapor transfer will be subjected to two resistances in series, one due to the stomata and the second due to aerodynamic conditions. The canopy resistance is thus related to stomatal closure and will be discussed in more detail in Chap. 9. Typical values of r_c are 40–80 s/m for well-watered annual crops and 100–200 s/m for forests and some fruit crops (e.g., olives) with good water supply. Under water deficit conditions, r_c can reach much higher values than those indicated above.

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Soil Temperature and Soil Heat Flux

6

Francisco J. Villalobos, Luca Testi, Luciano Mateos, and Elias Fereres

Abstract

The soil temperature regime depends on its thermal properties (specific heat, thermal conductivity, thermal diffusivity, and thermal admittance). The main factors affecting the thermal regime are water content, soil texture, and compaction. The rate of heating (or cooling) of the soil is proportional to its diffusivity which is higher in sandy soils. The amount of energy stored in the soil is proportional to its thermal admittance. Soil heating occurs as a wave train with the amplitude decreasing with depth and a phase shift that increases with depth.

6.1 Introduction

The heat flux in the soil is an important component of the energy balance of the crop. The soil is a large energy accumulator that stores heat during the day and releases it at night. Something similar happens in annual terms. The balance of these exchanges determines the time course of soil temperature. Soil temperature is important in crop growth and development processes such as seed germination, root growth and distribution in the soil, nutrient uptake, root respiration, microbial activity, etc.

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6.2 Soil Thermal Properties

The specific heat of the soil is the heat required to raise the temperature of the unit mass (specific heat per unit mass, C_M) or unit volume (specific heat per unit volume, C_V) of soil by 1 K. C_M and C_V are related through the actual soil density ($C_V = \rho\, C_M$). Using the definitions of bulk density (ρ_b = mass of solids/volume) and gravimetric moisture content (θ_g = mass of water/mass of solids), the relationship between C_V and C_M can also be expressed as:

$$C_V = \rho_b \left(1+\theta_g\right) C_M \tag{6.1}$$

C_V can be computed as the sum of specific heats of the soil components (air, water, and solid fraction), weighted by the volumetric mass densities of each of these components:

$$C_V = \frac{M_{\text{solid}}}{V} C_{M\,\text{solid}} + \frac{M_{\text{water}}}{V} C_{M\,\text{water}} + \frac{M_{\text{air}}}{V} C_{M\,\text{air}} \tag{6.2}$$

where M and C_M refer to mass and specific heat per unit mass, respectively, for each component. Neglecting the third term due to the small specific heat of air, assuming that $C_{M\,\text{solid}}$ = 0.85 J/g/K and reorganizing:

$$C_V = \rho_b \left(C_{M\,\text{solid}} + \theta_g\, C_{M\,\text{water}}\right) = \rho_b \left(0.85 + 4.18\,\theta_g\right) = 0.85\,\rho_b + 4.18\,\theta_v \tag{6.3}$$

This equation shows that soil specific heat per unit volume increases linearly with volumetric water content (θ_v) and with soil bulk density.

6.3 Soil Heat Flux

Applying Fourier's law of heat conduction, the flux of heat in the soil (J) can be expressed as:

$$J = k\frac{dT}{dz} \tag{6.4}$$

where dT/dz is the temperature gradient and k is the thermal conductivity of the soil. At the soil surface ($z = 0$), the flux is denoted as G.

The thermal conductivity has units of W/m/K and depends on the porosity of the soil, water content, and organic matter content. The dependence of k on soil water content is complex. The thermal conductivity of dry soil increases twofold when a rather small amount of water is added. This is because relatively large amounts of energy can be transferred by evaporation and condensation of water in the pores of the soil. For example, for sandy soils, k can increase from 0.53 to 1.1 W/m/K when its water content increases from the permanent wilting point (PWP) to field capacity. A further increase of the soil water content to saturation implies a smaller gain in k since the water vapor diffusion is restricted as pores are filled with water

Table 6.1 Thermal properties of soils and soil components (based on Monteith and Unsworth, 2013)

Component	Density t/m³	Specific heat: Unit mass MJ/t/K	Specific heat: Unit volume MJ/m³/K	Thermal conductivity W/m/K	Thermal diffusivity 10^{-6} m²/s	Thermal admittance J/K/m²/s$^{0.5}$
COMPONENT						
Air at 20 °C	0.0012	1.01	0.001212	0.025	20.63	5.5
Water	1	4.18	4.18	0.57	0.14	1544
Soil minerals	2.65	0.87	2.31	2.5	1.08	2403
Quartz	2.66	0.8	2.13	8.8	4.14	4327
Clay	2.65	0.9	2.39	2.92	1.22	2639
Granite	2.64	0.82	2.16	3	1.39	2545
Organic matter	1.3	1.92	2.5	0.25	0.1	790
SOILS						
Sandy PWP	1.53	0.93	1.43	0.53	0.37	871
Sandy FC	1.59	1.06	1.68	1.1	0.65	1359
Sandy SAT	1.87	1.52	2.85	1.8	0.63	2265
Loam PWP	1.52	1.13	1.72	0.65	0.38	1057
Loam FC	1.67	1.41	2.35	0.8	0.34	1371
Loam SAT	1.84	1.66	3.06	1.1	0.36	1835
Clay PWP	1.57	1.44	2.26	0.7	0.31	1258
Clay FC	1.7	1.65	2.8	0.8	0.29	1497
Clay SAT	1.77	1.8	3.18	0.9	0.28	1692

We have assumed bulk densities of 1.5, 1.4, and 1.3 t/m³ for sandy, loam, and clay soils, respectively. For each soil type, the table shows the thermal properties at soil water contents of Wilting Point, Field Capacity, and Saturation

(Table 6.1). Therefore, the thermal conductivity of wet soils is affected very little by water content variations in that range.

The change with time of the stored heat in a soil layer of thickness Δz has to equal the difference between the heat flow going in, $J(z)$, and the heat flow going out, $J(z+\Delta z)$ so, using Eq. 6.4 we may write:

$$\rho\, C_M \Delta z \frac{\partial T}{\partial t} = \Delta z \frac{\partial J}{\partial z} = \Delta z \frac{\partial}{\partial z}\left(k \frac{\partial T}{\partial z} \right) \tag{6.5}$$

and assuming that k does not vary with depth, we obtain:

$$\frac{\partial T}{\partial t} = D \frac{\partial^2 T}{\partial z^2} \tag{6.6}$$

where D is the thermal diffusivity (m²/s), defined as k/C_v, which characterizes how fast a soil warms or cools (Eq. 6.6).

By adding water to a dry soil, k initially increases faster than C_V so D increases with the water content. However, in a wet soil, k increases more slowly than C_V, so that D becomes constant or even may decrease. As shown in Table 6.1 the diffusivity of a sandy soil is higher than that of a clay soil especially when wet. Diffusivity varies little with changes in water content in the clay soil and more in the sandy soil.

6.4 Spatial and Temporal Variations of Soil Temperature

When the soil surface is exposed to solar radiation, part of it is reflected and the rest absorbed, increasing its temperature during part of the daytime. The temperature will decrease at night when no energy input is present and the heat is transferred to the rest of the soil and irradiated into the atmosphere. Soils are subjected to the cycling intensity of input energy at a daily or annual frequency.

To analyze the cyclic behavior of soil temperature, we will use $T(z,t)$ to denote temperature at depth z and time t. Then we will assume that the temperature of the soil surface follows a sine function:

$$T(0,t) = T_m + A(0)\sin(\omega t) \tag{6.7}$$

where T_m is the time-averaged temperature of the surface, $A(0)$ is the amplitude of the temperature wave at the surface, $\omega = 2\pi/P_o$ and P_o is the period of the temperature oscillations (86,400 s for daily cycles and 31,536,000 for annual cycles). With this boundary condition, we can integrate the differential Eq. 6.6 for T:

$$T(z,t) = T_m + A(0)e^{-z/M}\sin(\omega t - z/M) \tag{6.8}$$

where $M=(2D/\omega)^{0.5}$ (m) is called the damping depth which determines how much the amplitude of the wave is attenuated with depth and how much the phase is shifted in time.

The above equation indicates that the amplitude of the temperature wave decays exponentially with depth in the soil. Furthermore, the wave is shifted in proportion to depth, i.e. the maximum temperature occurs later as the depth increases. Both deductions are reflected in Figure 6.1 that represents the daily time course of the measured soil temperature at various depths. The annual trend shows a similar pattern (Fig. 6.2).

The depth where most soil heat exchange occurs is called *effective depth* and is equal to $2^{0.5}M$. The heat flux density at the soil surface may be deduced by differentiating Eq. 6.8, applying Eq. 6.4 and setting $z = 0$, which leads to:

$$G = \sqrt{2}\,A(0)\frac{k}{M}\sin(\omega t + \pi/4) \tag{6.9}$$

This equation indicates that the temperature wave on the surface (Eq. 6.7) and the heat flow are offset by $\pi/4$, i.e. the maximum temperature occurs 3 h after the maximum G (daily cycle) or 46 days (annual cycle). If maximum G occurs at the time of maximum radiation, (1200 h, solar time), then the surface temperature should reach its maximum at 1500 h (solar time) for daily cycles. For annual cycles

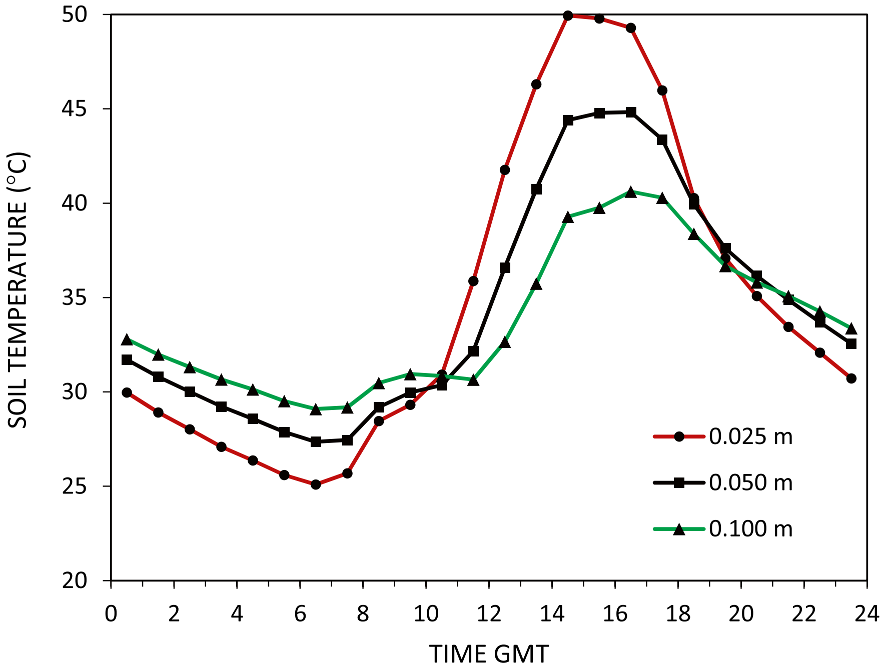

Fig. 6.1 Daily time course of soil temperature at various depths (0.025, 0.050, and 0.10 m) in an olive orchard. Cordoba (Spain). July 19, 2004

the maximum temperature should occur on day 216 (August 5) in the Northern Hemisphere and on day 36 (February 5) in the Southern Hemisphere.

Soil heat flux at the surface may be integrated over a half-cycle to determine the total heat input into the soil:

$$\int G = \sqrt{2}\, M\, A(0) C_v = \sqrt{\frac{2\,P_0}{\pi}} \sqrt{k\, C_v}\, A(0) \tag{6.10}$$

This total flux that enters the soil in one half-cycle will be equal to that going out in the other half-cycle since we start from a sinusoidal model of temperature, i.e. the temperature at the end of the period is equal to the initial temperature. According to Eq. 6.10, the amount of heat stored in the soil (and released by the soil) will be proportional to $(k\, C_V)^{0.5}$, which is called the thermal admittance (units J K^{-1} m^{-2} $s^{-0.5}$). For sandy soils, thermal admittance increases dramatically with water content from less than 1000 at PWP to more than 2000 J K^{-1} m^{-2} $s^{-0.5}$ at saturation (Table 6.1). In clay soils, admittance changes little with water content.

The amplitude of the temperature wave decreases with soil texture in the order sandy-loam-clay. This order is due to differences in thermal admittance. In Mediterranean climate conditions, in late winter, soils are often wet. Sandy soils have a higher diffusivity than clay soils, thus they will warm up more rapidly in

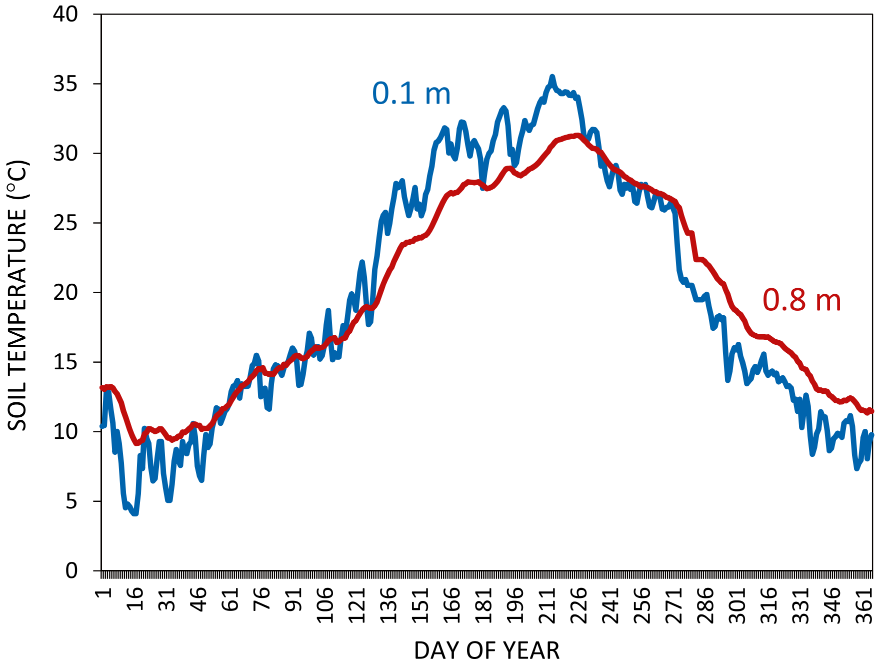

Fig 6.2 Annual time course of soil temperature at 0.10 and 0.80 m depths in an olive orchard. Cordoba (Spain). 2003

spring. If the water content is high in autumn, sandy soils will also cool faster, which has agronomic implications in the decision about planting date. Conversely, if the soil is dry, the diffusivity of sandy and clay soils is similar, so we should not expect significant differences in their thermal regime.

The temperature profile in the soil changes significantly over the day (Fig. 6.3). In the early morning, the soil surface is the coldest zone and in the afternoon, it becomes the hottest. The profile along most of the daytime indicates downward heat flux while the flow is toward the surface at night.

6.5 Effects of Evaporation and Wind on Soil Temperature

Predicting soil temperature at a given time and depth is important for some agronomic decisions. The practical importance of understanding the soil heat flux will become more evident when we address the energy balance at the earth's surface in Chap. 7.

For a dry soil surface with no evaporation, the ratio of soil heating and atmospheric heating may be written as:

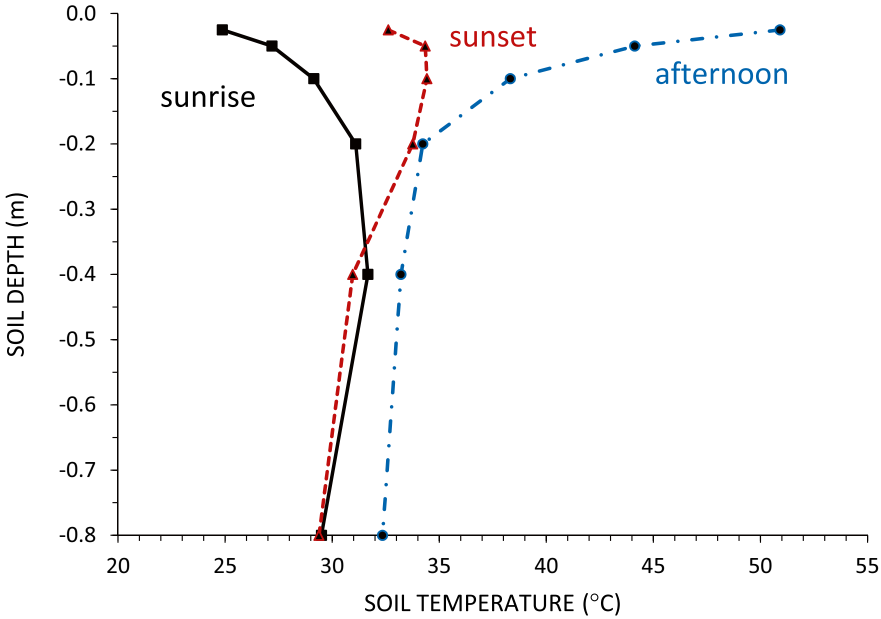

Fig. 6.3 Profiles of soil temperature in an exposed area of an olive orchard. Cordoba (Spain) 3 August 2002

$$\frac{G}{H} = \frac{\sqrt{k\,C_v}}{\mu_{\text{atm}}} \tag{6.11}$$

where μ_{atm} is the atmospheric admittance which increases with wind speed and may vary from 2000 for a calm atmosphere to 10,000 J K^{-1} m^{-2} $s^{-0.5}$ for windy conditions. This implies that dry soils will show ratios of *G/H* between 0.5 and 0.1 as wind speed increases, i.e. the soil warms faster with no wind.

The soil thermal regime may be evaluated using Eq. 6.8, which requires knowledge of the amplitude at the soil surface. Using Eq. 6.10, we may write:

$$A(0) = \sqrt{\frac{\pi}{2\,P_0}}\,\frac{\int G\,dt}{\sqrt{k\,C_v}} \tag{6.12}$$

The integral of *G* during the daytime depends on wind speed (Eq. 6.11) and the amount of energy spent in soil evaporation. For wet soils, evaporation takes a large fraction of net radiation (say 70–80%) while for dry soils, it may be negligible. Table 6.2 shows an example of calculated values of surface temperature amplitude for wet or dry clay and sandy soils on clear winter and summer days in Cordoba (Spain). The amplitude is large when the soil is dry and for calm conditions. The

Table 6.2 Calculated temperature amplitude at the soil surface for winter and summer days in sandy and clay soils

Conditions		Soil surface	Soil type	*G* integral MJ/m^2	Admittance J/K/m^2/s$^{0.5}$	*T* amplitude K
Winter	Calm	Dry	Sandy	2	870	9.8
	Windy	Dry	Sandy	0.55	870	2.7
	Calm	Wet	Sandy	0.4	1300	1.3
	Windy	Wet	Sandy	0.1	1300	0.3
Winter	Calm	Dry	Clay	2	1200	7.1
	Windy	Dry	Clay	0.55	1200	2.0
	Calm	Wet	Clay	0.4	1500	1.1
	Windy	Wet	Clay	0.1	1500	0.3
Summer	Calm	Dry	Sandy	4.7	870	23.0
	Windy	Dry	Sandy	1.3	870	6.4
	Calm	Wet	Sandy	0.9	1300	3.0
	Windy	Wet	Sandy	0.3	1300	1.0
Summer	Calm	Dry	Clay	4.7	1200	16.7
	Windy	Dry	Clay	1.3	1200	4.6
	Calm	Wet	Clay	0.9	1500	2.6
	Windy	Wet	Clay	0.3	1500	0.9

sandy soils always show a larger oscillation than the clay soil due to the smaller admittance. Equation 6.12 may be used to calculate the expected minimum and maximum soil temperatures.

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The Energy Balance

7

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Abstract

The main components of the energy balance are net radiation, latent heat flux (*LE*), sensible heat flux (*H*), and soil heat flux (*G*). These can be manipulated through changes in net radiation, *LE*, *H*, or *G*. The relative importance of the components depends mainly on the water availability for evaporation. The extreme cases will be the humid environment (*LE* approaches R_n) and the desert environment (R_n is partitioned between *H* and *G*). Agricultural systems capture only a small fraction of incoming solar energy while the rest is spent in evaporation and heating of the soils and the atmosphere.

7.1 Introduction

The exchange of matter and energy between the canopy and the atmosphere determines the variations in air temperature, humidity, and soil temperature as seen in the previous chapters. Turbulence facilitates heat, water vapor, and carbon dioxide fluxes which are all key factors in crop production. It also affects the transport of contaminants, pesticides, spores, or pollen. Understanding the partitioning of

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available energy among the different processes is required for manipulating the crop's aerial or soil environment, which not only affect the plant community but the whole ecosystem (weeds, insects, pathogens, and other soil microorganisms).

7.2 The Energy Balance Equation

According to the principle of conservation of energy, the equation of the energy balance of a crop canopy may be written as:

$$R_n = H + LE + G + P + S \tag{7.1}$$

where all terms have been defined in previous chapters except for P, the flux of energy consumed in photosynthesis, and S, the flux of heat stored in the crop biomass and the surrounding air. P is usually negligible compared to the others (Chap. 13). S may be significant only in very tall plant communities (e.g., forests) but can be neglected in the case of crops (Box 7.1). In Equation 7.1, fluxes are considered positive when they involve a loss of energy from the crop, i.e. when moving away from the canopy.

Changes in net radiation may be accomplished by variations in the shortwave or longwave radiation balances:

(a) Shortwave radiation: Incoming irradiance may be reduced using shades or changing the slope and orientation of the soil surface. Reflected irradiance is changed manipulating the albedo of the soil (e.g., mulches) or the plants (e.g., whitewash or kaolinite).
(b) Longwave radiation: It is usually manipulated by blocking losses with glass, plastic covers, or nonsolid barriers (e.g., smoke).

Soil heat flux may be changed by artificial soil heating or altering the thermal admittance by applying irrigation or compacting the soil.

Latent heat flux is mainly determined by water availability, so rainfall or irrigation management will affect greatly LE. If the soil is wet, important reductions in LE may be achieved using plastic impermeable mulches (Box 7.2).

The only alternative for manipulating sensible heat flux in the field is using barriers (windbreaks) to reduce wind speed. In controlled environments (greenhouses), we may add or remove heat or increase turbulence with fans.

Box 7.1: Calculation of Energy Spent in Heating the Canopy
The maximum standing biomass of annual crops usually does not exceed 20 t/ha (dry matter).

Assuming water content of 70 g water/100 g fresh mass (e.g., maize for silage), we may calculate the energy term S for an increase in canopy temperature of 20 K in 9 h, typical of summer in mid-latitudes.

(continued)

Box 7.1 (continued)

The water mass can be calculated based on dry biomass (B):

$$\text{mass water} = 20\frac{\text{t dm}}{\text{ha}} \times \frac{0.7\frac{\text{t water}}{\text{t fresh}}}{(1-0.7)\frac{\text{t dm}}{\text{t fresh}}} = 46.67\frac{\text{t water}}{\text{ha}} = 4667\frac{\text{g water}}{\text{m}^2}$$

The specific heat of water (C_{Mw}) and organic matter (C_{Mo}) are 4.18 and 1.92 J/g/K, respectively.

The amount of heat stored for a temperature rise of 20 K is:

$$\begin{aligned}\Delta Q &= \Delta T\left(BC_{Mo} + m_w C_{Mw}\right) = 20\left(2000\,1.92 + 4667\,4.18\right) \\ &= 466{,}961\,\text{J}\,\text{m}^{-2} = 0.47\,\text{MJ}\,\text{m}^{-2}\end{aligned}$$

The average heat flux for 9 hours will be obtained by dividing 0.47 10^6 J m^{-2} by the duration (9 × 3600 s) which yields 14.4 W m^{-2}, which is very small (about 2%) as compared to typical values of solar irradiance under those conditions (600–800 W m^{-2}).

Box 7.2: Analyzing the Effect of Black Plastic on the Energy Balance of Bare Soil

The plastic sheet creates a barrier that suppresses evaporation (LE = 0) so all the energy is spent in G and H. A small variation in R_n may be expected as the albedo is reduced and long wave loss may increase when the plastic gets hot.

The partitioning between H and G will depend on the contact between the plastic sheet and the soil as any air layer between them will reduce flux into the soil. On the other hand, aerodynamic resistance is reduced as the temperature profile over the hot plastic is very unstable. Therefore, sensible heat flux is enhanced.

In summary, covering the soil with black plastic suppresses LE and reduces the G/H ratio, which promotes a higher temperature in the aerial environment.

7.3 Relative Importance of the Components of the Energy Balance

As water availability is the main factor determining LE, two extreme conditions can be distinguished:

(a) Humid/well-watered areas where water availability does not limit evaporation. Most of the net radiation is used in LE. It is the case of large water bodies (seas, lakes), wetlands, large irrigation schemes with abundant water or any area after widespread rainfall.

(b) Dry/arid environments where no water is available: *LE* is negligible and therefore net radiation is partitioned only into heating the air and the soil.

A special case is that of the oasis, a small well-watered area surrounded by arid lands. Here, horizontal transport of sensible heat from the arid surrounding area enhances *LE* in the oasis, so it may exceed R_n. This process of horizontal energy transport from dry to wet areas is called advection.

The energy balance of crops is usually between the two extremes (wet and desert) depending on the availability of water and the presence of vegetation. This issue will be further explored in Chap. 9. Four different situations are analyzed below.

Figure 7.1 represents the daily time course of R_n, *LE*, *H*, and *G* on an irrigated cotton field measured in June 2003 in Cordoba (Spain). This would be a typical well-watered environment. The R_n presents typical values of clear days at this time of the year in Cordoba. Most of the energy is spent in *LE* which is less than R_n during the morning and higher during the afternoon. The sensible heat flux is small and reaches its maximum during the morning. From 14:00 the *H* flux is reversed, being then directed toward the surface. The soil is heated for most of the daytime, although *G* is very small as the crop covers the soil. The balance for 24 h shows that net radiation was spent mostly in evaporation. In this case, the heating of the air and the soil in the daytime is offset by their cooling during the night.

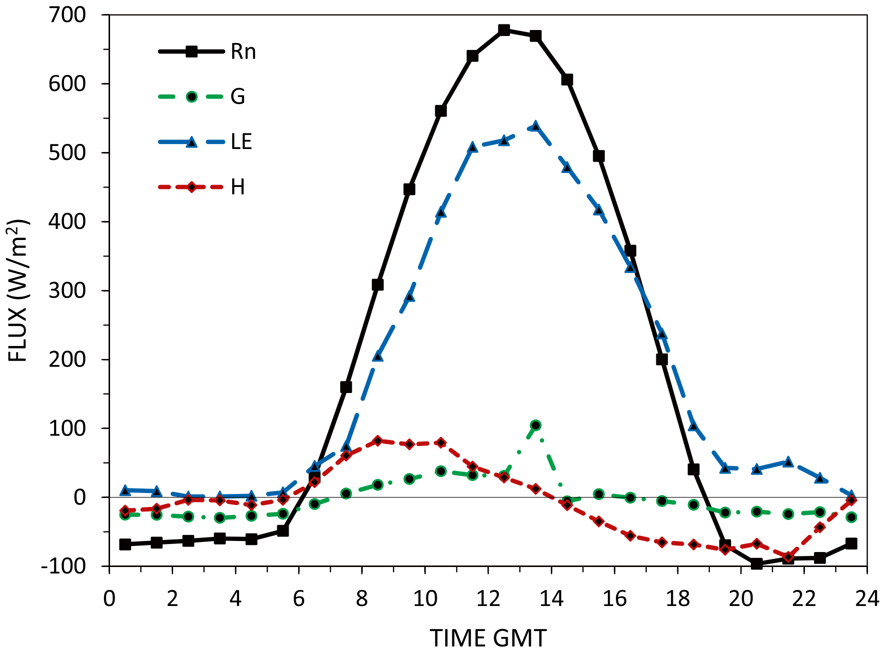

Fig. 7.1 Energy balance components over an irrigated cotton crop. Cordoba (Spain). June 27, 2003. For the 24-h period, the total fluxes were R_n = 15.9, *G* = −0.2, *LE* = 16.7, and *H* = −0.6 MJ m^{-2} day^{-1}

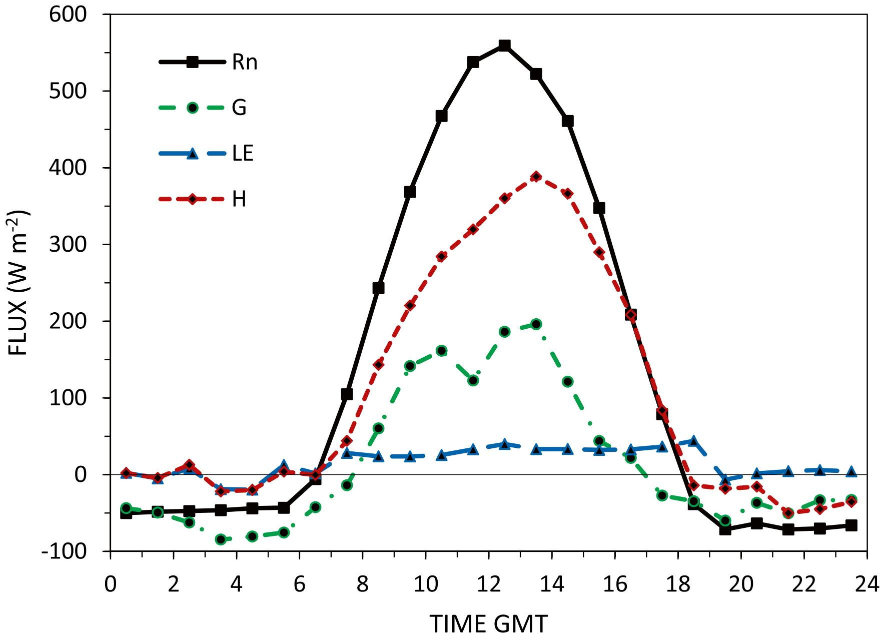

Fig. 7.2 Energy balance components on a severely stressed wheat crop. Cordoba (Spain). April 19, 1999. For the 24-h period, the total fluxes were R_n = 11.6, G = 1.2, LE = 1.4, and H = 9 MJ m^{-2} day^{-1}

An example of water-stressed crop is represented in Fig. 7.2 for wheat in spring around flowering after a dry winter in Cordoba (Spain). The soil was almost dry and consequently, crop transpiration was very low. As a result, latent heat flux is very small during most of the day while *H* and *G* use most of the energy during the daytime. For 24 h, the percentages of energy invested in *LE*, *H*, and *G* are 12, 78, and 10%, respectively.

Contrasting with the well-watered crop is the case of wheat stubble shown in Fig. 7.3. Around the measurement date (June 17), extraterrestrial solar radiation peaks in the northern hemisphere. However, the maximum R_n is slightly lower than in the case of Fig. 7.1, which is explained by the high albedo of stubble and straw covering the soil. The availability of water in this case is zero (the crop had extracted all soil water) which explains the absence of *LE*. The sensible heat flux parallels R_n throughout the day, peaking around noon. The soil heat flux is now larger than for grass and decreases during the afternoon. Considering the 24-h period, 90% of the energy is spent in heating the air and 10% in heating the soil. Note that the straw and stubble covering the soil serve as thermal insulation.

Finally, Fig. 7.4 presents an intermediate between the wet and dry cases. It is a drip-irrigated olive orchard at Cordoba, where the trees cover only a fraction of the ground. At the time of the measurements, the tree canopy represented 40% of ground cover and the soil surface was dry. In the daytime, the three fluxes (*LE*, *H*,

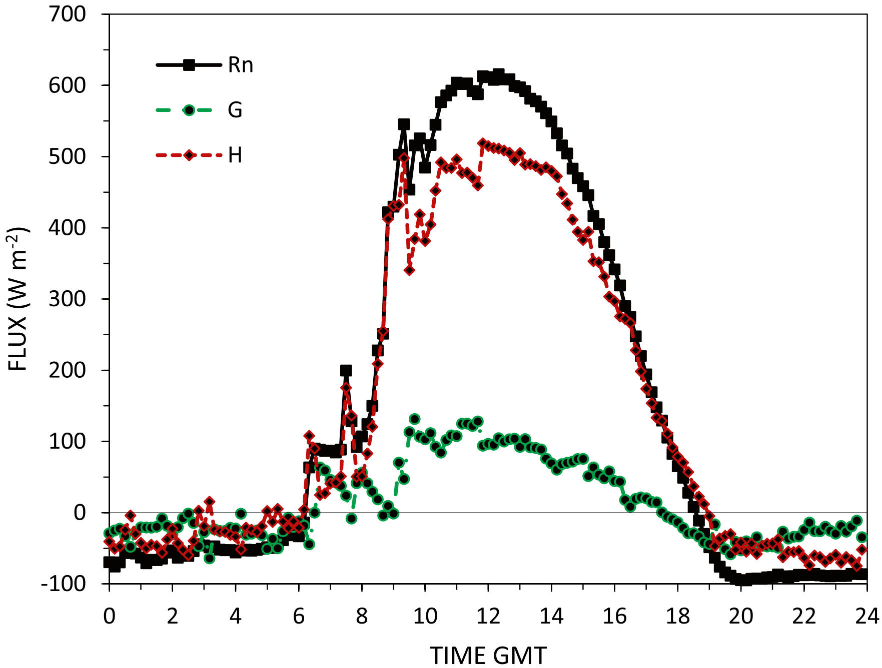

Fig. 7.3 Energy balance components on wheat stubble. Cordoba (Spain). June 17, 1995. For the 24-h period, the total fluxes were $R_n = 13.7$, $G = 1.3$, and $H = 12.4$ MJ m^{-2} day^{-1}

and G) are important but LE predominates (Fig. 7.4). The H flux peaks at noon and is small at night. G presents a pattern similar to the cases above; the maximum occurs at noon because the percentage of soil exposed to direct radiation is maximum. For 24 h, the percentages of energy invested in LE and H are 79 and 21%, respectively, while G gets no share.

We have seen that the relative importance of the components of the energy balance varies throughout the day and that when summed for 24-h periods, G is usually small as compared to H and LE, whose relative magnitudes depend on the availability of water (or the presence of vegetation) on the soil surface. The impact of the fluxes on the oscillations of air and soil temperature depends on the absolute value of H and G. The difference between the maximum and the minimum temperature will be greater when positive fluxes are higher and negative fluxes are smaller.

7.4 Energy Balance and Nocturnal Cooling

Combining the equations of heat flux in the soil (Chap. 6) and longwave radiation loss (Chap. 3), Brunt proposed a simple model to calculate the variation of surface temperature (T_s) during the night assuming (a) R_n is constant during the night, (b) $LE = 0$, $H = 0$, and (c) soil temperature is constant with depth at sunset.

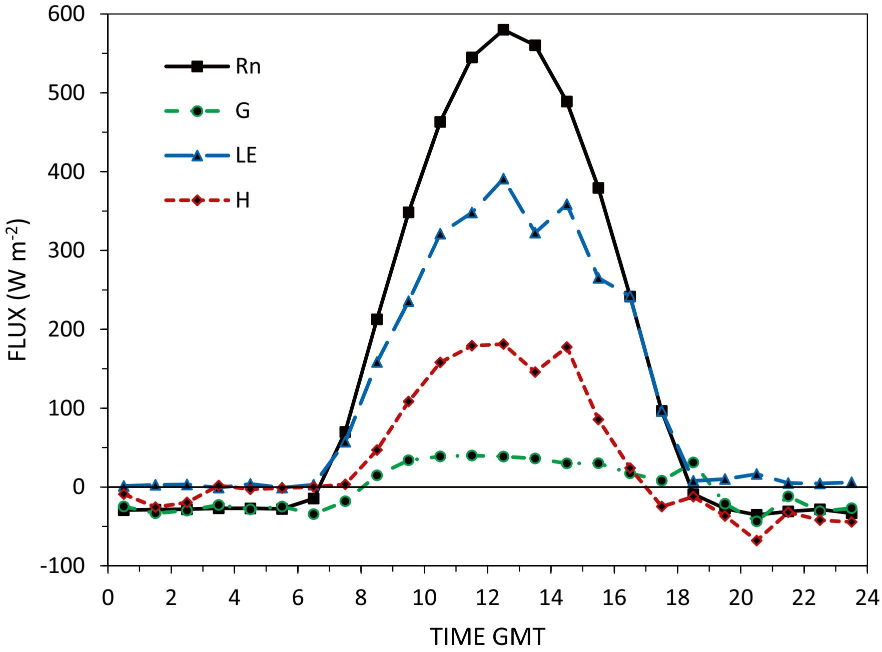

Fig. 7.4 Energy balance components in an olive grove. Agricultural Research Center of Cordoba (Spain). September 8, 1997. For the 24-h period, the total fluxes were R_n = 13.1, G = −0.1, LE = 10.3, and H = 2.9 MJ m^{-2} day^{-1}

The analytical solution for T_s is:

$$T_s - T_{s0} = \frac{2}{\sqrt{\pi}} \frac{1}{\sqrt{kC_v}} R_n \sqrt{t} \tag{7.2}$$

where T_{s0} is the surface temperature at sunset, C_V is the specific heat of the soil per unit volume (J/m^3/K), k is the thermal conductivity (W/m/K), and t is the time (s) elapsed after sunset. The function $(k\ C_v)^{0.5}$ is the thermal admittance (Chap. 6). This equation implies that temperature during the night will decrease in proportion to longwave radiation loss and the square root of time after sunset. Soils with low admittance (sandy, dry) will cool faster.

Example 7.1
The admittance of a loam soil at Permanent Wilting Point is 1057 W m^{-2} s$^{1/2}$ K^{-1} (Table 6.1). For R_n = −70 W/m^2, the temperature drop after sunset would be 10, 14.2, and 17.4 K after 5, 10, or 15 h, respectively. If the soil were at saturation (thermal admittance 1835 W m^{-2} s$^{1/2}$ k^{-1}) the temperature would decrease only 5.8, 8.2, and 10 K.

Table 7.1 Annual available energy (MJ/m^2) at different levels and losses (partitioning of energy) at each stage for an irrigated olive orchard with 40% ground cover in Cordoba (Spain)

	Available energy MJ/m^2	Losses MJ/m^2	
		Reflection	**Emission**
Solar radiation	5975	1100	2065
		LE	***H***
Net radiation	2810	1570	1124
		Respiration	
Energy photosynthesis	40	20	
		Vegetative	
Energy fixed	20	8	
		Residues	
Energy harvested	12	5	
Energy in olive oil	7		

7.5 Seasonal Energy Balance

The partitioning of energy for annual periods is also governed by the availability of water. Table 7.1 shows the energy available at different levels and the losses (partitioning of energy) at each stage, for an irrigated olive orchard with 40% ground cover in Cordoba (Spain). Starting from an incoming solar radiation of around 6000 MJ m^{-2}, the energy produced by the crop is equivalent to 7 MJ m^{-2} as oil (2000 kg oil ha^{-1}). About 50% of the incoming radiation is lost by reflection and emission of longwave radiation. Then, net radiation is allocated to evaporation (56%), heating of the atmosphere (40%), and photosynthesis (only 4%). Note that the soil-heating component is zero for annual periods as long as the mean soil temperature does not change in the long run. Around 50% of energy converted by photosynthesis is lost as respiration, leaving another 50% fixed in tree biomass (shoots, roots, and fruits). Only 60% of fixed energy is harvested. After oil extraction, the energy captured is just 7 MJ m^{-2}. The actual efficiency would be even lower as we are not taking into account other energy inputs required for the production of olives (machinery, fertilizers, pumping of irrigation water) (Chap. 37). In the same environment, an intensive, irrigated wheat-maize rotation in about the same period (as a double crop, maize planted after wheat is harvested) could yield up to 19,000 kg $ha^{-1}$of grain, which would be equivalent to about 26 MJ m^{-2}, still a minute fraction of the incoming solar radiation of 6000 MJ m^{-2}.

Appendix: Practical Exercises on the Energy Balance

This section shows a set of solved problems dealing with the components of the energy balance. Calculations revisit some of the concepts introduced in Chaps. 3, 4, 5, 6 and 7.

Example A7.1

Pesticide applications must be performed at periods of low wind speed to avoid drift. Evaluate whether the conditions are suitable for the application of a fungicide for a crop with plant height of 0.3 m if wind speed at a height of 6 m above the surface is 2.8 m s^{-1}. Consider that the application height is 1.2 m above the crop.

Equation 4.5 provides a mathematical description of the profile of wind speed above a crop (U_z) as a function of the wind speed measured at a reference height (z_m = 6 m) above the same surface (U_6 = 2.8 m s^{-1}). Here we will apply that equation to calculate the wind speed at a height (z) of 0.3 + 1.2 = 1.5 m for a crop with plants of 0.3 m high (h = 0.3 m):

$$U_{1.5} = 2.8 \times \frac{\ln\left[(1.5 - 0.65 \times 0.3)/(0.13 \times 0.3)\right]}{\ln\left[(6 - 0.65 \times 0.3)/(0.13 \times 0.3)\right]} = 1.96 \mathrm{m s}^{-1}$$

Pesticide applications are not recommended when wind speed exceeds 2.5 m s^{-1}, so in terms of wind, the conditions are suitable for spraying the fungicide.

Example A7.2

In a maize plot, an old anemometer has been installed at 4 m high. The plants are 2 m high and the instrument records 2.4 m s^{-1}. Evaluate whether the instrument works properly if a wind speed of 3.2 m s^{-1} is measured at the same time in a weather station nearby.

Applying Eq. 4.7 we may deduce the expected wind speed at 4 m height in our plot:

$$U_4 = 1.82 \times 3.2 \times \frac{\ln\left[(4 - 0.65 \times 2)/(0.13 \times 2)\right]}{\ln\left[(100 - 0.65 \times 2)/(0.13 \times 2)\right]} = 2.3 \mathrm{m s}^{-1}$$

This value is very similar to that recorded by the anemometer (2.3 versus 2.4 m s^{-1}), so our calculations suggest that the anemometer provides good estimates.

Example A7.3

The probability of infection by many fungal diseases is strongly related to the time during which the canopy remains wet after rainfall, sprinkler irrigation, or dew deposition. For the afternoon of a winter day in Cordoba, 14.8 °C temperature and 40.4% relative humidity were recorded. Considering that the variation in the actual vapor pressure is negligible, evaluate whether dew deposition will occur if air temperature is expected to reach 3.5 °C at the end of the night.

The saturation (e_s) and actual vapor pressure (e_a) in the afternoon of the first day were:

$$e_s = 0.61078 \exp\left[\frac{17.27 \times 14.8}{237.3 + 14.8}\right] = 1.68 \,\text{kPa}$$

$$e_a = 1.68 \times 40.4 / 100 = 0.68 \,\text{kPa}$$

The dewpoint temperature (T_d) for this vapor pressure can be calculated by inverting Eq. 5.2:

$$T_d = \frac{237.3 \times \ln(0.68 / 0.61078)}{17.27 - \ln(0.68 / 0.61078)} = 1.49\,°\text{C}$$

As T_d (1.49 °C) is lower than the expected temperature (3.5 °C), dew deposition will not occur.

Example A7.4

A wheat crop with leaf area index of 4 m^2 m^{-2} and plants of height 0.5 m has been irrigated with sprinklers. In the hours following irrigation, average values of temperature, wind speed, and relative humidity at 2 m height were 32 °C, 1.5 m s^{-1}, and 40%, respectively. Estimate the time required for the canopy to dry assuming a canopy temperature of 30 °C and a volumetric specific heat of air of 1220 J m^{-3} K^{-1}.

Under full cover conditions, the maximum capacity of rainfall interception is around 0.25 mm per unit of leaf area index (Chap. 9). Accordingly, the water intercepted by our canopy will be 0.25 mm m^{-2} × 4 m^2 m^{-2} = 1 mm. We will apply Eq. 5.12 to deduce the evaporation rate from the wetted canopy.

(continued)

Example A7.4 (continued)

The specific heat of air (ρC_p = 1220 J m^{-3} K^{-1}) and psychrometric constant (γ = 0.067 kPa K^{-1}) are given or known. Saturation (e_s) and actual vapor pressures (e_a) at 2 m high are calculated as:

$$e_s = 0.61078\exp\left[\frac{17.27\times 32}{237.3+32}\right] = 4.75\,\text{kPa}$$

$$e_a = 4.75\times 40/100 = 1.90\,\text{kPa}$$

Saturation water vapor at canopy temperature (e_{sc}):

$$e_{sc} = 0.61078\exp\left[\frac{17.27\times 30}{237.3+30}\right] = 4.23\,\text{kPa}$$

Aerodynamic resistance to water vapor flow is estimated from wind speed (U = 1.5 m s^{-1} at a height (z) of 2 m) using Eq. 5.11, where d_z, z_0, and z_{0H} are calculated as 65%, 13%, and 2.6% of plant height (h = 0.5 m):

$$r_{aH} = \frac{\ln\left(\dfrac{2-0.325}{0.065}\right)\ln\left(\dfrac{2-0.325}{0.013}\right)}{0.4^2\times 1.5} = 65.8\,\text{s}\,\text{m}^{-1}$$

While evaporation proceeds from the water film and droplets covering the foliage, transpiration may be considered negligible so r_c = 0 s m^{-1}. Therefore, the latent heat flux will be:

$$LE = \frac{\rho C_p}{\gamma}\frac{(e_{sc}-e_a)}{(r_{aH}+r_c)} = \frac{1220}{0.067}\frac{(4.23-1.9)}{(65.8+0)} = 645\,\text{W}\,\text{m}^{-2}$$

The latent heat of evaporation is 2.45 MJ per kg of water, so LE is equivalent to an evaporation rate of 0.9 mm h^{-1}. Therefore, the time required for evaporating the rainwater intercepted by the canopy (1 mm) will be 1.05 h.

Example A7.5
Evaluate the components of the energy balance for a bare soil covered by a transparent plastic mulch at the time of maximum temperature for a sunny day in March 21st in Librilla, Spain (38°N). Daily solar radiation and maximum temperature records were 22 MJ m^{-2} and 19 °C. The soil had an apparent density of 1.4 g cm^{-3}, a water content of 0.2 cm^3 cm^{-3}, and thermal diffusivity of 0.35 mm^2 s^{-1}. Estimate net radiation as 60% of solar radiation. Consider calm and moderate wind conditions leading to atmospheric admittances of 3000 and 8000 J K^{-1} m^{-2} s$^{-0.5}$, respectively.

Assuming that the maximum temperature takes place 3 h after solar noon, solar radiation will take a value of around 84% of that of solar noon on a sunny day. At this time and under these conditions, net radiation (R_{nx}) may be estimated from daily solar radiation (R_{sd} = 22 MJ m^{-2} day^{-1}) and daylength (N_s = 12 h on March 21st) as:

$$R_{nx} = 0.6 \times 0.84 \times \frac{\pi}{2} \frac{R_{sd}}{3600 N_s} = 0.6 \times 0.84 \times \frac{\pi}{2} \frac{22}{3600 \times 12} = 403\,\mathrm{W\,m^{-2}}$$

The plastic sheet creates a barrier that suppresses evaporation, so $LE = 0$. All the energy will be spent in H and G, the partitioning between them depending on turbulence and soil thermal properties (Eq. 6.11). The specific heat of the soil per unit of volume (C_V) is calculated from Eq. 6.3:

$$C_V = 0.85 \times \rho_b + 4.18\,\theta_v = 0.85 \times 1.4 + 4.18 \times 0.2 = 2.06\,\mathrm{J\,cm^{-3}\,K^{-1}}$$

Thermal conductivity (k) is calculated from the product of thermal diffusivity (0.35•10^{-6} m^2 s^{-1}) and C_v (2.06•10^6 J m^{-3} K^{-1}), which leads to 0.71 W m^{-1} K^{-1}. Therefore, applying Eq. 6.11:

Calm conditions (μ_{atm} = 3000 J K^{-1} m^{-2} s$^{-0.5}$):

$$\frac{G}{H} = \frac{\sqrt{kC_v}}{\mu_{\mathrm{atm}}} = \frac{\sqrt{0.71 \times 2.06 \cdot 10^6}}{3000} = 0.40$$

so G and H will be 161 and 242 W m^{-2}, respectively.

Windy conditions (μ_{atm} = 8000 J K^{-1} m^{-2} s$^{-0.5}$):

$$\frac{G}{H} = \frac{\sqrt{0.71 \times 2.06 \cdot 10^6}}{8000} = 0.15$$

so G and H will be 60 and 343 W m^{-2}, respectively.

Example A7.6

At the time of sunset on December 1st in Pisa, Italy (43.7°), the soil surface temperature was 11 °C. During the night, net radiation was −60 W m^{-2}. Discuss quantitatively whether plowing the soil has an impact on the temperature of the surface at sunrise considering the following:

(a) Non-tilled: Apparent density of 1.4 g cm^{-3}, water content of 0.2 g g^{-1}, and thermal conductivity of 0.83 W m^{-1} K^{-1}
(b) Tilled: Plowing results in a reduction of 20% in the apparent density and in a decrease of thermal conductivity, which is now 0.60 W m^{-1} K^{-1}. The water content remains unchanged.
(a) According to Eq. 7.2, the temperature decrease over the night is proportional to longwave radiation loss ($R_n = -60$ W m^{-2}) and the square root of the duration of the night, and inversely proportional to thermal admittance. The duration of the night can be deduced from the latitude (λ = 43.7 °C) and solar declination (δ), the latter being a function of the day of year (DOY = 335 for December 1st):

$$\delta = 23.45\cos\left[360\times\left(DOY-172\right)/365\right] = -22.14°$$

The duration of the night (N_n) is deduced from Eq. 3.10:

$$N_n = 24 - N_s = 24 - \frac{1}{7.5}\text{acos}\left[-\tan\lambda\tan\delta\right] = 15.05\text{h} = 54{,}183\text{s}$$

Soil thermal admittance is the square root of the product of thermal conductivity (k = 0.83 W m^{-1} K^{-1}) and the specific heat per unit volume (C_V). The latter is estimated from Eq. 6.3. Required input data include the apparent density of the soil in g cm^{-3} (ρ_b = 1.4 g cm^{-3}) and the volumetric water content (θ_v), which in turn is calculated from gravimetric moisture (θ_g = 0.2 g g^{-1}), ρ_b and the density of water (ρ_w = 1 g cm^{-3}):

$$\theta_v = \theta_g \rho_b / \rho_w = 0.2\times 1.4/1.0 = 0.28\text{cm}^3\,\text{cm}^{-3}$$

$$C_V = 0.85\times 1.4 + 4.18\times 0.28 = 2.36\text{J}\,\text{cm}^{-3}\,\text{K}^{-1} = 2.36\cdot 10^6\,\text{J}\,\text{m}^{-3}\,\text{K}^{-1}$$

Given the surface temperature at sunset (T_{s0} = 11 °C), we deduce its temperature at sunrise (T_s) as:

$$T_s = T_{s0} + \frac{2}{\sqrt{\pi}}\frac{1}{\sqrt{k\times C_V}}R_n\sqrt{t} = 11 + \frac{2}{\sqrt{\pi}}\frac{1}{\sqrt{0.83\times 2.36\cdot 10^6}}\left(-60\right)\sqrt{54{,}183} = 0.3°\text{C}$$

(continued)

Example A7.6 (continued)

(b) We have to account for the impact of plowing on soil thermal admittance. Apparent density is reduced by 20% so:

$$\rho_b = (1-0.2)\times 1.4 = 1.12\,\mathrm{g/cm^3}$$

$$\theta_v = \theta_g \rho_b / \rho_w = 0.2\times 1.12/1.0 = 0.224\,\mathrm{cm^3\,cm^{-3}}$$

These changes lead to a lower C_V:

$$C_V = 0.85\times 1.12 + 4.18\times 0.224 = 1.89\,\mathrm{J\,cm^{-3}\,K^{-1}} = 1.89\cdot 10^6\,\mathrm{J\,m^{-3}\,K^{-1}}$$

Surface temperature at the end of the night results:

$$T_s = T_{s0} + \frac{2}{\sqrt{\pi}}\frac{1}{\sqrt{k\times C_V}} R_n \sqrt{t} = 11 + \frac{2}{\sqrt{\pi}}\frac{1}{\sqrt{0.6\times 1.89\cdot 10^6}}(-60)\sqrt{54{,}183} = -3.8\,°\mathrm{C}$$

Therefore, plowing the soil leads to higher surface cooling during the night.

Example A7.7

Evaluate the daily energy balance of a 1-m-high crop on April 1 under clear sky conditions in Montoro, Spain (38°N, 160 m). Measured daily average values of temperature, wind speed, and relative humidity at 2 m were 20 °C, 1 m s^{-1}, and 60%, respectively. The average temperature gradient in the soil was 4 K m^{-1} (with the surface layer warmer than the layer immediately below) and the thermal conductivity was 0.75 W m^{-1} K^{-1}. The albedo of the crop was 0.25. Estimate:

(a) The daily components of the energy balance if the average crop temperature was 20.2 °C.
(b) The canopy resistance.
(a) We will start with the radiation balance. In the absence of in situ measurements, we can estimate solar radiation from extraterrestrial radiation (R_A) with Eq. 3.7. Input data include the latitude (λ = 38°) and the date (April 1 is day of year 91). These are used for computing intermediate variables including solar declination (δ, Eq. 3.4), the angle defining half of the day

(continued)

Example A7.7 (continued)

length (h_s, Eq. 3.8), and the factor accounting for changes in the distance between the sun and the Earth (d_r, Eq. 3.9):

$$\delta = 23.45\cos\left[360\left(91-172\right)/365\right] = 4.1°$$

$$h_s = \mathrm{acos}\left[-\tan 38 \tan 4.1\right] = 93.4°$$

$$d_r = 1 + 0.033\cos\left[360\times 91/365\right] = 1.00$$

These values lead to:

$$R_A = 37.4\times 1\left[\sin 38 \sin 4.1 93.4\frac{\pi}{180} + \cos 38 \cos 4.1 \sin 93.4\right] = 32.1\,\mathrm{MJ\,m^{-2}day^{-1}}$$

On a sunny day, the fraction of clear sky is 1 (n_s/N_s=1), so solar radiation may be estimated as 75% of extraterrestrial radiation (Eq. 3.5):

$$R_s = \left(0.25 + 0.5\times 1\right)\times 32.1 = 24\,\mathrm{MJ\,m^{-2}day^{-1}}$$

Daily losses of longwave radiation (R_b) are estimated assuming again clear sky conditions (n_s/N_s = 1) and the mean values of average temperature (T = 293 K) and vapor pressure (e_a). The latter is obtained by calculating the vapor pressure at saturation (Eq. 5.2) and by inverting Eq. 5.3:

$$e_s = 0.6108\,\mathrm{EXP}\left[17.27\times 20/\left(237.3+20\right)\right] = 2.34\,\mathrm{kPa}$$

$$e_a = 2.34\times 60/100 = 1.40\,\mathrm{kPa}$$

Equation 3.11 is used for estimating R_b:

$$R_b = \left(0.9\times 1 + 0.1\right)\left(0.34 - 0.14\sqrt{2.34}\right)4.910^{-9}\,293^4 = 6.3\,\mathrm{MJ\,m^{-2}day^{-1}}$$

Considering the albedo of the crop (α = 0.25), net radiation (R_n) will be (Eq. 3.13):

$$R_n = 24\left(1-0.25\right) - 6.3 = 11.9\,\mathrm{MJ\,m^{-2}day^{-1}}$$

(continued)

Example A7.7 (continued)

Now let us focus on the calculation of sensible heat flux (H) between the canopy and the atmosphere. Assuming that wind speed (U_z = 1 m s^{-1}) was measured above the crop at 2 m height (z = 2 m), the aerodynamic resistance (r_{aH}) is calculated from the zero plane displacement (d_z), roughness length (z_0), and roughness length for heat exchange (z_{0H}). These can be estimated from crop height (h = 1 m), leading to values of 0.65 m, 0.13 m, and 0.026 m, respectively. Von Karman's constant (k_k) is 0.4, so, applying Eq. 5.11:

$$r_{aH} = \frac{\ln\left(\frac{2-0.65}{0.13}\right)\ln\left(\frac{2-0.65}{0.026}\right)}{0.4^2 \times 1} = 57.8\,\mathrm{s\,m^{-1}}$$

The volumetric specific heat of the air (ρC_p) is calculated as a function of temperature (T = 293 K), vapor pressure (e_a = 1.4 kPa), and atmospheric pressure (P_{at}) with Eq. 5.9. The latter is estimated from the altitude of the location (AL = 160 m) as (Eq. 5.10):

$$P_{at} = 101.3\left(1-\frac{160}{44308}\right)^{5.2568} = 99.4\,\mathrm{kPa}$$

$$\rho C_p = \frac{29000\times 99.4}{8.31\times 293}\left(1.01+1.88\frac{0.622\times 1.4}{99.4-1.4}\right) = 1215\,\mathrm{kPa}$$

Then, H can be computed from Eq. 5.8, where T_c is the canopy temperature (20.2 °C) and T_a is the air temperature at the reference height (20 °C):

$$H = 1215\times\frac{20.2-20}{57.8} = 4.2\,\mathrm{W\,m^{-2}}$$

This figure corresponds to the average daily value of H, which, integrated over a 24 h period, leads to 0.36 MJ m^{-2} day^{-1}.

The sensible soil heat flux (G) is determined from thermal conductivity (k = 0.75 W m^{-1} K^{-1}) and the average temperature gradient (dT/dz = −4 K/m):

$$G = -(0.75\times -4) = 3\ \mathrm{W\,m^{-2}}$$

Integrated over a 24-h period, G is 0.26 MJ m^{-2} day^{-1}.

(continued)

Example A7.7 (continued)

Finally, LE may be deduced from the energy balance equation (Eq. 7.1), assuming that the energy consumed in photosynthesis (P) and that stored in the crop and the air (S) are negligible:

$$LE = R_n - H - G = 11.1\,\mathrm{MJ\,m^{-2}day^{-1}}$$

This is equivalent to an average flux of 128.6 W m^{-2}. Therefore, most of the available energy (~95% of R_n) is invested in the evaporation of water (i.e., LE) while only a small fraction is consumed in heating of the air and the soil (i.e., H+G only take ~5% of R_n)

(b) According to Eq. 5.12, LE is inversely proportional to canopy resistance (r_c). In this equation, γ is the psychrometric constant (0.067 kPa K^{-1}), r_{aW} is the aerodynamic resistance to the transport of water vapor (assumed equal to r_{aH}, i.e. 57.8 s m^{-1}) and e_{sc} is the saturation vapor pressure at canopy temperature (i.e., a proxy of the vapor pressure at the substomatal cavities). Applying Eq. 5.2, for a temperature of 20.2 °C:

$$e_{sc} = 0.6108\exp\left[17.27 \times 20.2/\left(237.3 + 20.2\right)\right] = 2.37\,\mathrm{kPa}$$

Now we can invert Eq. 5.12 to deduce r_c:

$$r_c = \frac{\rho C_p}{\gamma}\frac{e_{sc} - e_a}{LE} - r_{aW} = \frac{1215}{0.067}\frac{2.37 - 1.40}{128.6} - 57.8 = 78.3\,\mathrm{s\,m^{-1}}$$

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The Water Budget

8

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Abstract

The components of the water balance (infiltration, deep percolation, evaporation from the soil surface, etc.) determine the amount of water available to the crop. Water flows in the soil following the water potential gradient, which can be analyzed by the Richards equation. Infiltration rate decreases with time until a steady-state value. Layered soils have lower infiltration than homogenous soils. Deep percolation can be estimated based on soil properties and water content above Field Capacity, depending also on soil evaporation and transpiration. Runoff is calculated based on the Curve Number and the amount of precipitation. Monthly effective rainfall, i.e. not lost by runoff, can be calculated by the methods of the Food and Agriculture Organization (FAO) and the United States Department of Agriculture-Soil Conservation Service (USDA-SCS).

8.1 Introduction

The functioning of terrestrial ecosystems depends largely on the inputs and outputs of water, which determine the quantity and quality of water available for life on Earth. Water is the main limiting factor of agricultural productivity. Agriculture is

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the main consumer of water for humans, taking two thirds of the total globally. Irrigation consumes more than 80% of the developed water in most countries of the arid regions. Therefore, it is essential to understand and quantify the dynamics of the flows in and out of the agricultural system, that is, to calculate the water balance components that determine the availability of water for crops and, where appropriate, to quantify irrigation needs.

As described in Chap. 2, soils are comprised of solids, liquid, and gas, with typical fractions of 45–50% of mineral material, 0–5% of organic matter, and 50% of pore space that allows the flow of water and gases. The porosity (volume fraction of pore space) is determined by the arrangement of the soil particles, being low when soil particles are very close together (e.g., compacted soil) and higher when soils have high organic matter. Porosity is typically between 0.4 and 0.5 (Table 8.1) and decreases with soil depth because the subsoil tends to be more compacted. Soil bulk density (ρ_b) is the mass of soil per unit volume (solids + pore space) and is reported on an oven-dry basis (Table 8.2).

Table 8.1 Porosity, soil water content (θ) at Field Capacity (−33 kPa) and Permanent Wilting Point (−1500 kPa) and soil hydraulic conductivity at saturation (K_s) for different texture classes

	Porosity %		θ at −33 kPa $m^3\ m^{-3}$		θ at −1500 kPa $m^3\ m^{-3}$		K_s kg s m^{-3}
Texture class	Mean	Range	Mean	Range	Mean	Range	$\times 10^{-3}$
Sand	0.44	0.37–0.50	0.09	0.02–0.16	0.03	0.01–0.06	5.8
Loamy sand	0.44	0.37–0.51	0.12	0.06–0.19	0.06	0.02–0.09	1.7
Sandy loam	0.45	0.35–0.56	0.21	0.13–0.29	0.09	0.03–0.16	0.72
Loam	0.46	0.38–0.55	0.27	0.19–0.34	0.12	0.07–0.17	0.37
Silt loam	0.50	0.42–0.58	0.33	0.26–0.40	0.13	0.08–0.19	0.19
Sandy clay loam	0.40	0.33–0.46	0.26	0.19–0.32	0.15	0.08–0.21	0.12
Clay loam	0.46	0.41–0.52	0.32	0.25–0.39	0.20	0.11–0.28	0.064
Silty clay loam	0.47	0.42–0.52	0.37	0.30–0.43	0.21	0.14–0.28	0.042
Sandy clay	0.43	0.37–0.49	0.34	0.24–0.43	0.24	0.16–0.32	0.033
Silty clay	0.48	0.43–0.53	0.39	0.33–0.44	0.25	0.19–0.31	0.025
Clay	0.47	0.43–0.52	0.40	0.33–0.45	0.27	0.21–0.34	0.017

Adapted from Rawls et al. 1982. Trans ASAE 25:1316-1320

Table 8.2 Campbell's model parameters (Eq. 8.3) for different texture classes

	Percent		Bulk density	Ψ_e	b	θ_{SAT}
Texture class	Silt	Clay	t/m^3	kPa	–	$m^3\ m^{-3}$
Sand	5	3	1.68	−0.7	1.9	0.37
Loamy sand	25	10	1.64	−0.9	2.1	0.38
Sandy loam	12	7	1.56	−1.5	3.1	0.41
Loam	40	18	1.43	−1.1	4.6	0.43
Silt loam	65	15	1.41	−2.1	4.7	0.43
Sandy clay loam	13	27	1.4	−2.8	4.0	0.41
Clay loam	34	34	1.31	−2.6	5.2	0.45
Silty clay loam	58	33	1.27	−3.3	6.6	0.46
Sandy clay	7	40	1.33	−2.9	6.0	0.44
Silty clay	45	45	1.23	−3.4	7.9	0.51
Clay	20	60	1.21	−3.7	7.6	0.5

Adapted from Bittelli et al. 2015. Soil Physics with Python. Transport in the Soil–Plant–Atmosphere System. Oxford Univ Press

8.2 The Status of Water in the Soil: Water Content and Water Potential

The water content of the soil can be expressed in terms of volume (θ_v = volume of water/volume of soil) or mass (gravimetric, θ_g = mass of water/mass of dry soil). Both measurements are related through the soil bulk density so that $\theta_v = \rho_b\, \theta_g$. The amount of water (expressed in mm) in a soil depth Z (mm), i.e., the total soil water for that depth (TSW, mm), will be:

$$TSW = \left(1 - F_{VC}\right) Z \cdot \theta_v \tag{8.1}$$

where F_{VC} is the volume fraction of coarse fragments (soil particles exceeding 2 mm in diameter) which can be estimated as a function of the mass fraction of coarse fragments (F_{MC}) as:

$$F_{VC} = \frac{F_{MC}\, \rho_b}{2.65 - F_{MC}\left(2.65 - \rho_b\right)} \tag{8.2}$$

where ρ_b has units of t m^{-3} and is calculated excluding coarse fragments. Note that 2.65 t m^{-3} is the average density of soil solids.

Example 8.1
A soil of 1 m depth has 30% of coarse fragments (mass basis) and bulk density 1.4 t m^{-3}. Calculate the total soil water if the water content is 0.2 m^3 m^{-3}.

$$F_{VC} = \frac{F_{MC}\, \rho_b}{2.65 - F_{MC}\left(2.65 - \rho_b\right)} = \frac{0.3 \cdot 1.4}{2.65 - 0.3\left(2.65 - 1.4\right)} = 0.18\, \text{m}^3\text{m}^{-3}$$

$TSW = (1 - F_{VC})\, Z \cdot \theta = (1 - 0.18)\; 1000 \cdot 0.20 = 164$ mm

Water is held in the matrix of soil particles by adsorption and moves by capillarity in the pores. Three values of soil water content characterize the soil water retention capacity (Table 8.1):

– Permanent wilting point (PWP, also called lower limit) (θ_{PWP}): The soil water content below which plant roots are unable to extract water, corresponding to −1.5 MPa.
– Field capacity (FC, also called drained upper limit) (θ_{FC}): The soil water content at which soil hydraulic conductivity is negligible, so drainage stops. It corresponds to water potential between −0.01 and −0.03 MPa depending on texture.
– Saturation (θ_{SAT}): The maximum water content observed in the soil. It is on average 85% of the porosity (η). As the average density of the soil solid fraction is 2.65 t m^{-3}, we can calculate the porosity as a function of bulk density as $\eta = 1 - \rho_b/2.65$.

The state of water in the soil can be characterized as a function of its potential (Ψ), i.e. the potential energy per unit mass or volume (units 1 J/kg = 1 kPa ≈ 0.1 m water column). The soil water potential is the sum of four components:

– Pressure potential (Ψ_p) which is the pressure exerted by free water above. In an unsaturated soil, $\Psi_p = 0$.
– Gravitational potential (Ψ_g) is the potential energy of water due to its position in a gravitational field. It is calculated as $g\ h$, where g is the acceleration of gravity (9.81 m/s^2) and h is the height above the arbitrary reference plane.
– Matric potential (Ψ_m) is caused by the attraction of the soil matrix and the water molecules. The relationship between matric potential and soil water content, $\Psi_m = f(\theta_v)$, is called the soil-water characteristic curve (Fig. 8.1). The matric potential is zero in saturated soil and gets more negative as the soil dries. Campbell has proposed the following equation for computing the soil-water characteristic curve:

$$\Psi_m = \Psi_e \left(\frac{\theta_v}{\theta_{SAT}} \right)^{-b} \quad (8.3)$$

where Ψ_e is called the air entry water potential, b is an empirical parameter, and θ_{SAT} is the saturation water content. The values of Ψ_e, θ_{SAT}, and b for different soil textures are presented in Table 8.2.

Values of water content at wilting point and field capacity may be deduced from the characteristic curves. However, factors other than texture affect the limits of water content in the soil. Table 8.1 compiles the means and intervals of variation.

– Osmotic potential (Ψ_o) is due to salts in the soil solution. This potential is zero for pure water and becomes more negative as the concentration of salts increases. An approximate relationship between Ψ_o (kPa) and the salt concentration (C_s, g m^{-3}) is:

$$\Psi_o = -0.05625\, C_s \quad (8.4)$$

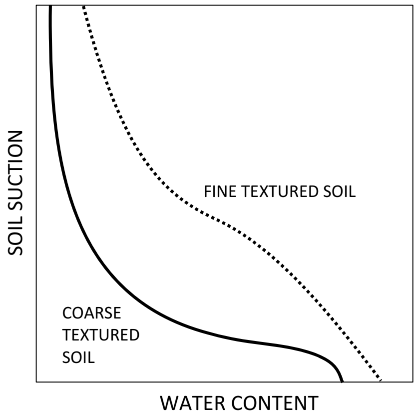

Fig. 8.1 Soil-water characteristic curves for a fine and a coarse texture soil

Example 8.2

The soil characteristic curve of a sandy loam soil is

$$\Psi_m = -1.5\left(\frac{\theta_v}{0.41}\right)^{-3.1}$$

We will calculate water potential for this soil at 1 m depth if the water content is 0.2 $cm^3\ cm^{-3}$ and the salt concentration in the soil solution is 64 g/m^3. We fix the reference level on the soil surface and positive upwards. Therefore:

$$\Psi = \Psi_m + \Psi_g + \Psi_o = -1.5\left(\frac{0.2}{0.41}\right)^{-3.1} - 9.81\times 1 - 0.05625\times 64$$
$$= -13.9 - 9.8 - 3.6 = -27.3\,\text{kPa}$$

Which is equivalent to −0.027 MPa or −0.27 bar.

Example 8.3

A water table is located at a depth of 1 m in a sandy loam soil. What is the water content at the soil surface under hydraulic equilibrium if the osmotic potential does not change with depth?

Hydraulic equilibrium implies that the water potential will be equal at the water table and at the surface; as the osmotic potential is also equal:

$$\Psi_{\text{m-wt}} + \Psi_{\text{g-wt}} = \Psi_{\text{m-sf}} + \Psi_{\text{g-sf}}$$

The matric potential at the water table is zero (saturation) and the reference level is the soil surface ($\Psi_{g-sf}=0$), so:

$$\Psi_{m-sf} = \Psi_{g-wt} = -9.81\times 1 = -9.81\,\text{kPa}$$

Equation 8.3 can be rearranged to calculate the soil water content from Ψ_m:

$$\theta = \theta_{\text{SAT}}\left(\frac{\Psi_e}{\Psi_m}\right)^{1/b} = 0.41\left(\frac{-1.5}{-9.81}\right)^{1/3.1} = 0.22\,\text{cm}^3\text{cm}^{-3}$$

8.3 Water Flow in the Soil

In the simplest case, we consider one-dimensional (vertical) water flow in the soil that obeys Darcy's law:

$$J_w = -K(\Psi_m)\frac{d\Psi}{dz} \tag{8.5}$$

where $K(\Psi_m)$ is the hydraulic conductivity, a function of matric potential and J_w is the water flow (kg/m^2/s). At saturation (zero matric potential), the hydraulic conductivity reaches its maximum value, the saturated hydraulic conductivity (K_s). The components of the water potential to be considered are the matric and gravitational potentials. Then, the equation above is equivalent to:

$$J_w = -K(\Psi_m)\frac{d\Psi_m}{dz} - K(\Psi_m)\frac{d\Psi_g}{dz} = -K(\Psi_m)\left(\frac{d\Psi_m}{dz} + g\right) \tag{8.6}$$

The hydraulic conductivity may be calculated using a model proposed by Campbell with the same parameters used in Eq. 8.3 (Table 8.2):

$$K(\theta) = K_s\left(\frac{\theta}{\theta_{SAT}}\right)^{2b+3} \tag{8.7}$$

or

$$K(\Psi_m) = K_s\left(\frac{\Psi_e}{\Psi_m}\right)^{2+3/b} \tag{8.8}$$

8.4 The Water Budget

Figure 8.2 shows a schematic diagram of the water balance of a field. We may write the mass conservation equation for water inputs and outputs from that field to calculate the increment in total soil water content in the crop root zone (*TSWC*):

$$\Delta TSWC = R + I - E_s - E_p - SR - DP + WTC \tag{8.9}$$

where P is the precipitation, I is the applied irrigation, E_s is the evaporation from the soil surface, E_p is the transpiration, *SR* is the surface runoff, i.e. water not infiltrated, *DP* is the deep percolation, and *WTC* is the upward water flow from the water table. For Irrigation Scheduling it is better to express the amount of soil water as a deficit (Soil Water Deficit, *SWD*), which is the amount of water required to bring the soil to field capacity.

The water balance may be computed for different periods (hour, day, decade, months). We will focus first on methods to calculate daily values.

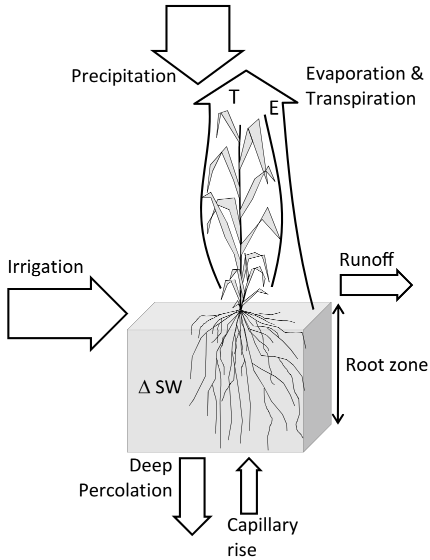

Fig. 8.2 Diagram of the water balance of a field

8.5 Infiltration

The flow rate of water into the soil surface (infiltration rate) decreases with time, until a relatively constant value that depends on the soil (Fig. 8.3), being higher for sandy than for clay soils. The initial infiltration rate is inversely proportional to the initial water content. This is because the water potential gradient between the water and the soil is greater if the latter is drier. The water not infiltrated stays on the surface and moves to the lower parts running off the field (see Sect. 8.7).

Infiltration is usually lower in layered than in homogenous soils. This is due to two mechanisms:

(a) When a fine texture unsaturated layer is on top of an unsaturated coarser (e.g., sandy) layer, the hydraulic conductivity of the lower layer is much smaller than that of the top layer, which accumulates water. After some time, as the soil gets wetter, the effect will disappear.
(b) When a coarse saturated layer is on top of a fine-textured layer, the latter will limit infiltration (low saturated hydraulic conductivity) so water will accumulate longer in the top layer. This implies that more water will be available for root uptake despite the low water-holding capacity of the coarse soil.

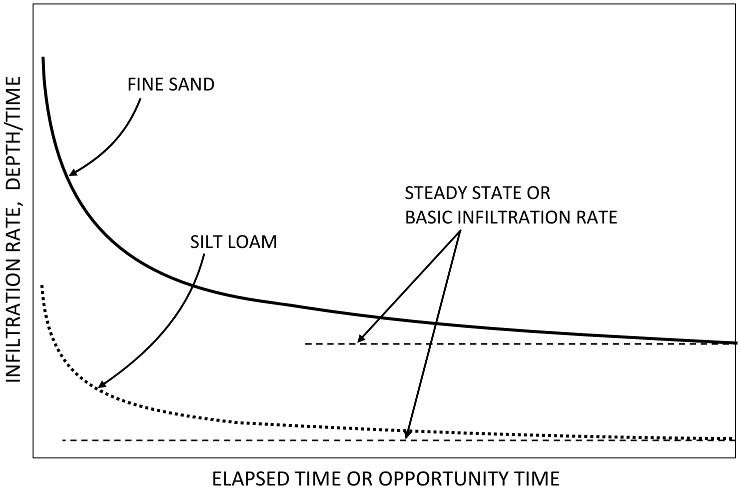

Fig. 8.3 Infiltration rate for two soils differing in saturated hydraulic conductivity

8.6 Deep Percolation

An amount of water P_I (mm) has infiltrated a soil of depth *Z*. The amount of water that can be stored in the short term (*SWCC*) is:

$$SWCC = \left(\theta_{SAT} - \theta\right) Z \tag{8.10}$$

where θ is the average water content in the soil. If P_I is higher than *SWCC*, the excess is lost by deep percolation on the same day. If the water content, after adding infiltrated water, does not exceed Field Capacity, there is no percolation. Otherwise, percolation is:

$$DP = SWCON\left(\theta - \theta_{FC}\right) Z \tag{8.11}$$

Where *SWCON* is a dimensionless parameter that is the fraction of water above Field Capacity lost by percolation in one day.

Some simple models assume *SWCON* = 1, that is, all water that exceeds *FC* is instantly lost. Such simplification may be valid in very permeable soils, fallow situations, or early crop stages. However, *SWCON* is lower than 1, so plant roots can extract some of the water that exceeds *FC*, reducing percolation. When there is no crop or it has just been planted, deep percolation estimates are less sensitive to *SWCON*. Ritchie has suggested *SWCON* for different soil types:

Clay soil (very slow to moderately slow drainage): 0.01 to 0.25
Medium-textured soils (moderate to moderately rapid drainage): 0.40 to 0.65
Sandy soils (fast to very rapid drainage): 0.75 to 0.85

Example 8.4
We will calculate deep percolation for a maize crop growing on a 1−m deep loam soil with the following parameters:

$$\theta_{PWP} = 0.10\,\text{cm}^3\,\text{cm}^{-3}, \theta_{FC} = 0.25\,\text{cm}^3\,\text{cm}^{-3}, \theta_{SAT} = 0.35\,\text{cm}^3\,\text{cm}^{-3}, SWCON = 0.4.$$

The soil starts with a soil water content $\theta = 0.30$ cm^3 cm^{-3}. A rainfall of 45 mm has fallen and 5 mm has not infiltrated.

Total water infiltrated will be:

$$P_I = 45 - 5 = 40\,\text{mm}$$

Short-term storage is given by:

$$SWCC = Z\left(\theta_{SAT} - \theta\right) = 1000\,\left(0.35 - 0.30\right) = 50\,\text{mm}$$

which is greater than total infiltration. Therefore, 40 mm will be stored in the short term. Soil water content increases to:

$$\theta = \theta + 40/1000 = 0.30 + 0.04 = 0.34\,\text{cm}^3\,\text{cm}^{-3}$$

which is higher than θ_{FC}. Therefore, some deep percolation will occur. The soil is a medium texture soil ($SWCON = 0.4$):

$$DP = SWCON \cdot Z \cdot \left(\theta - \theta_{FC}\right) = 0.4 \cdot 1000\,\left(0.34 - 0.25\right) = 36\,\text{mm}$$

In the previous example, we applied Eq. 8.11 to a single day. However, we can extend this analysis to the days after the rainfall event to calculate the total percolation. We consider a soil of depth Z (mm) with an initial water content θ_i that loses water by evaporation from the soil and crop transpiration at a rate equal to ET (mm/day) (Chap. 9). After rainfall, an amount P_I (mm) has infiltrated, so water content now is $\theta_i + P_I/Z$, which is greater than θ_{FC} (otherwise, there would be no percolation). We start with the differential equation describing the variation of water content:

$$\frac{d\theta}{dt} = SWCON\left(\theta - \theta_{FC}\right) - \frac{ET}{Z} \tag{8.12}$$

After integrating:

$$\theta = \theta_{FC} + \frac{\left[SWCON\left(\theta_i + \frac{P_I}{Z} - \theta_{FC}\right) + \frac{\mathrm{ET}}{Z}\right]e^{-SWCON\,t} - \mathrm{ET}/Z}{SWCON} \tag{8.13}$$

Equation 8.13 may be used to calculate the soil water content at time *t* (days after rainfall) as a function of *SWCON* and *ET*. This equation may also be used to calculate the time it takes to reach Field Capacity:

$$t_{FC} = \frac{\ln\left(1 + \frac{SWCON\left(\theta_i + \frac{P_I}{Z} - \theta_{FC}\right)}{ET/Z}\right)}{SWCON} \tag{8.14}$$

During that time, a total of $t_{FC} \cdot ET$ will be lost by evaporation from the soil and the plants, so we may deduce the total percolation from rainfall until time t_{FC}, when the soil water content returns to Field Capacity:

$$\sum_{1}^{t_{FC}} DP = Z\left(\theta_i + \frac{P_I}{Z} - \theta_{FC}\right) - t_{FC}\,ET \tag{8.15}$$

This equation shows that evaporation losses partly offset percolation losses (Example 8.5).

Example 8.5

50 mm infiltrates a sandy clay loam soil of 1 m depth with a water content of 0.23 m^3/m^3. We will calculate percolation if: (a) $ET = 1$ mm/day, (b) $ET = 8$ mm/day. These values are typical of soil covered by vegetation in winter and summer, respectively, in Southern Spain.

Soil data: $\theta_{FC} = 0.25$, $SWCON = 0.6$

(a) $ET = 1$ mm/day

$$t_{FC} = \frac{\ln\left(1 + \frac{0.6\left(0.23 + \frac{50}{1000} - 0.25\right)}{1/1000}\right)}{0.6} = 4.91\,\text{days}$$

$$\sum_{1}^{t_{FC}} DP = Z\left(\theta_i + \frac{P_I}{Z} - \theta_{FC}\right) - t_{FC}\,ET = 1000\left(0.23 + \frac{50}{1000} - 0.25\right) - 4.91 \cdot 1 = 25.1\,\text{mm}$$

(continued)

Example 8.5 (continued)

(b) $ET = 8$ mm/day

$$t_{FC} = \frac{\ln\left(1 + \frac{0.6\left(0.23 + \frac{50}{1000} - 0.25\right)}{8/1000}\right)}{0.6} = 1.96\,\text{days}$$

$$\sum_{1}^{t_{FC}} DP = 1000\left(0.23 + \frac{50}{1000} - 0.25\right) - 1.96 \cdot 8 = 14.3\,\text{mm}$$

8.7 Surface Runoff

The main factors that determine surface runoff are rainfall intensity, soil type, vegetation type, topography, and surface roughness. In the method of the Soil Conservation Service (US-SCS) all these factors are combined into a single factor, the "runoff curve number" (*CN*) that is proportional to runoff potential.

To calculate the *CN*, soils are classified into four hydrologic groups from low to high runoff potential:

A. Low runoff potential: These are soils with a high infiltration rate when wet. It is generally the case of sandy or gravelly soils, deep and well drained.
B. Soils with moderate infiltration rate when wet, average depth and medium texture.
C. Soils with low infiltration rates when wetted. These soils are of fine texture or have a horizon that hinders drainage.
D. High runoff potential: It includes soils with very low infiltration rates when wet, such as expansive clay soils, soils with high water table, soils with a clay layer near the surface and shallow soils over impervious materials.

In addition to soil characteristics, in the calculation of *CN*, the hydrological condition of the field is considered, which can be good or bad depending on the slope and cultural practices. Table 8.3 shows the *CN* values based on hydrologic conditions and soil groups, for different types of crops and conservation practices. Data in Table 8.3 correspond to *CN2*, i.e. the soil is at Field Capacity when precipitation occurs. For low (*CN1*) or high (*CN3*) water content, we use the following equations:

$$CN_1 = CN_2 - 20\frac{100 - CN_2}{100 - CN_2 + e^{2.533 - 0.0636(100 - CN_2)}} \tag{8.16}$$

$$CN_3 = CN_2\, e^{0.00673(100 - CN_2)} \tag{8.17}$$

Table 8.3 Runoff Curve Number (*CN*2) for different soils and cover types when the soil is at Field Capacity at the time of rainfall

Cover type	Treatment	Hydrologic condition	Soil hydrological group			
			A	B	C	D
Fallow	Bare Soil	–	77	86	91	94
	Crop residues CR	Poor	76	85	90	93
		Good	74	83	88	90
Row crops	Straight row (SR)	Poor	72	81	88	91
		Good	67	78	85	89
	SR & CR	Poor	71	80	87	90
		Good	64	75	82	85
	Contoured (C)	Poor	70	79	84	88
		Good	65	75	82	86
	C & CR	Poor	69	78	83	87
		Good	64	74	81	85
	Contoured & Terraced (C&T)	Poor	66	74	80	82
		Good	62	71	78	81
	C&T + CR	Poor	65	73	79	81
		Good	61	70	77	80
Small grain	SR	Poor	65	76	84	88
		Good	63	75	83	87
	SR + CR	Poor	64	75	83	86
		Good	60	72	80	84
	C	Poor	63	74	82	85
		Good	61	73	81	84
	C&CR	Poor	62	73	81	84
		Good	60	72	80	83
	C&T	Poor	61	72	79	82
		Good	59	70	78	81
	C&T + CR	Poor	60	71	78	81
		Good	58	69	77	80
Close-seeded or broadcast legumes or rotation meadow	SR	Poor	66	77	85	89
		Good	58	72	81	85
	C	Poor	64	75	83	85
		Good	55	69	78	83
	C&T	Poor	63	73	80	83
		Good	51	67	76	80
Pasture, grassland, or range-continuous grazing		Poor	68	79	86	89
		Fair	49	69	79	84
		Good	39	61	74	80
Meadow-continuous grass, protected, mown for hay			30	58	71	78
Brush-weed-grass mixture		Poor	48	67	77	83
		Fair	35	56	70	77
		Good	30	48	65	73
Woods-grass combination (orchard)		Poor	57	73	82	86
		Fair	43	65	76	82
		Good	32	58	72	79
Woods		Poor	45	66	77	83
		Fair	36	60	73	79
		Good	30	55	70	77

The values of *CN1* or *CN3* cannot exceed 100. The curve number can be calculated as a function of soil water content in the upper soil layer:

(a) If soil water content is higher than Field Capacity:

$$CN = CN2 + (CN3 - CN2)\frac{(\theta - \theta_{FC})}{(\theta_{SAT} - \theta_{FC})} \quad (8.18)$$

(b) If soil water content is below Field Capacity:

$$CN = CN1 + (CN2 - CN1)\frac{(\theta - \theta_{PWP})}{(\theta_{FC} - \theta_{PWP})} \quad (8.19)$$

Once *CN* is known, we calculate the maximum water depth (*SMX*, mm) that may be infiltrated or stored on the soil surface:

$$SMX = 254\left(\frac{100}{CN} - 1\right) \quad (8.20)$$

If daily rainfall (*P*) is lower than 20% of *SMX*, runoff is nil. Otherwise, runoff (*SR*, mm) is calculated as:

$$SR = \frac{(P - 0.2\,SMX)^2}{P + 0.8\,SMX} \quad (8.21)$$

Example 8.6

We have sunflower growing on a deep medium-textured soil with almost zero slope. A rain event of 40 mm occurs when the soil is at Field Capacity.

(a) The soil can be included in the B type, and the hydrologic condition is good due to the absence of slope. In Table 8.3, we choose *CN2* = 78.
(b) As the soil is at *FC*, we assign *CN* = *CN2*= 78
(c) We calculate *SMX*:

$$SMX = 254\left(\frac{100}{90} - 1\right) = 71.6\,\text{mm}$$

(d) We compare 20% of SMX (14.3 mm) with rainfall (40 mm). As *P* > 0.2 *SMX*, the runoff will be:

$$SR = \frac{(40 - 0.2 \cdot 71.6)^2}{40 + 0.8 \cdot 71.6} = 6.8\,\text{mm}$$

8.8 Effective Rainfall

Effective rainfall (P_e) is the fraction of total precipitation not lost by runoff or percolation and thus stored in the crop root zone. It is a broad concept, sometimes used to characterize the seasonal or monthly water balance. Several methods have been proposed for calculating monthly effective rainfall. They should not be used for shorter time intervals. The methods provide rough estimates as they ignore key factors like soil properties or the rainfall distribution within the month.

8.8.1 FAO Method

This method was the result of a study conducted by FAO in arid and sub-humid areas. The equation was developed to estimate the monthly effective rainfall (P_e) exceeded in 80% of the years and is used for irrigation system design. Effective rainfall is estimated as:

$$P_e = 0.6\,P - 10 \qquad \text{if } P < 70\,\text{mm} \tag{8.22a}$$

$$P_e = 0.8\,P - 24 \qquad \text{if } P > 70\,\text{mm} \tag{8.22b}$$

8.8.2 USDA-Soil Conservation Service method

In this method, in addition to rainfall, crop evapotranspiration (*ET*) and soil water deficit before irrigation are taken into account:

$$P_e = f\left(SWD\right)\left(1.25\,P^{0.824} - 2.93\right)10^{0.001\,ET} \tag{8.23}$$

$$f\left(SWD\right) = 0.53 + 0.0115\,SWD - 8.94\,10^{-5}\,SWD^2 + 2.32\,10^{-7}\,SWD^3 \tag{8.24}$$

where *SWD* (mm) is the soil water deficit just before irrigation and *ET* is given in mm/month.

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9 The Components of Evapotranspiration

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Abstract

Evapotranspiration is the sum of evaporation from the soil and the plant surfaces, and transpiration. The evaporation from the soil in most cases follows a two-stage process depending on whether the soil surface is wet after rain or irrigation or has already dried up. When the soil surface is wet, the evaporation rate is potentially very high; that is why the rainfall frequency is the main driver of soil evaporation, especially at low ground cover. The core model to quantify evaporation is the combination equation, later applied to crop canopies and for computing plant transpiration known as the Penman–Monteith equation. This equation has two resistance variables (the aerodynamic and canopy resistance) which are hard to quantify as they change constantly with the physical environment and the plant's physiological state. The Penman–Monteith equation is the established method to analyze the evaporation processes in plants and stands and has been thoroughly verified. The transpiration of trees is heavily dependent on canopy conductance and scales up well with the ground cover or the fraction of intercepted radiation.

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9.1 Introduction

Evaporation from vegetated surfaces (or evapotranspiration, as it combines evaporation from soils and transpiration from plants) is the main component of water loss from terrestrial ecosystems so its quantification is of great importance in hydrology, agronomy, and related sciences. Moreover, in agronomy, evaporation is usually directly proportional to crop productivity, as discussed in Chap. 14.

Evapotranspiration (*ET*) is the sum of direct evaporation from the soil surface (E_s), plant transpiration (E_p), and direct evaporation from plant surfaces (E_{ps}):

$$ET = E_s + E_p + E_{ps} \tag{9.1}$$

Transpiration is the water vapor flow through the stomata of plants, fed by evaporation in the substomatal cavities. If the canopy surface is dry, $E_{ps} = 0$, so:

$$ET = E_s + E_p \tag{9.2}$$

Maximum transpiration (and *ET*) occurs when soil water is not limiting root water uptake, which usually happens for soil water content above one-third of available soil water (Fig. 9.1).

9.2 Measurement of Evapotranspiration

Crop *ET* can be measured directly by determining the mass of water lost from a vegetated surface or estimated indirectly. Direct *ET* measurement is done in weighing *lysimeters* which are large containers open at the top to enclose a volume of soil whose mass can be measured accurately and where plants are grown. Lysimeters are placed in the middle of large fields to ensure that the microclimate experienced by the plants inside them is the same as that of the surrounding plants. They are large and deep enough to ensure unrestricted root growth. For example, at the Agricultural Research Center of Cordoba (Spain), two weighing lysimeters were installed in 1987 with an area of 6 m^2 each and a depth of 1.5 m. The measurement systems were accurate enough to register water losses equivalent to the ET of short sub-hourly periods (5–10 min).

Estimates of *ET* and fluxes of other scalars (e.g., canopy photosynthesis) may be obtained using micrometeorological methods (Box 9.1).

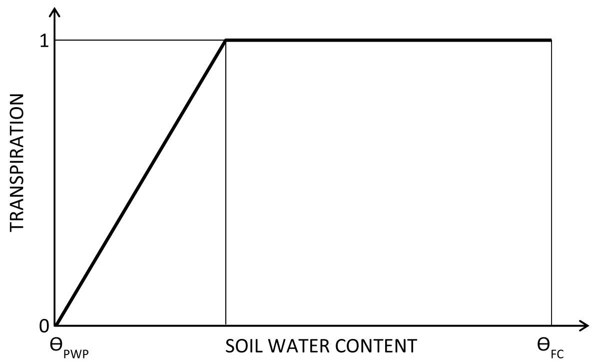

Fig. 9.1 Effect of soil water content on transpiration or evapotranspiration

The simplest method for estimating *ET* is the water balance, which requires estimating the water balance components so that *ET* is obtained by difference. From Eq. 8.9 in Chap. 8:

$$ET = P + I - SR - DP + WTC - \Delta TSWC \tag{9.3}$$

Example 9.1
Soil water content measurements were taken of a 1-m deep soil under a soybean crop on two dates (August 11 and August 19). The average soil water content was 0.22 (August 11) and 0.175 $cm^3\ cm^{-3}$ (August 19). In that period there has been a rain episode of 20 mm. Assuming no runoff, no deep percolation, and that the water table is too deep to supply water to the root zone through capillary rise, we can calculate the *ET* for the period as the difference between rainfall and the increase in total soil water content:

$$ET = P - \Delta TSWC$$

The soil water content in the first date will be:

$$TSWC\left(11\text{Aug}\right) = 0.22 \times 1000 = 220 \text{ mm}$$

Analogously we calculate the water content on 19 August (175 mm).
The increase will be: $\Delta TSWC = 175\text{–}220 = -45$ mm
And so ET will be:

$$ET = 20 + 45 = 65 \text{ mm}$$

Box 9.1: Micrometeorological Methods
Measurements of meteorological variables close to the canopy allow the estimation of the energy balance components. For instance, by measuring net radiation, soil heat flux, and the gradients of temperature and vapor pressure above the canopy it is possible to estimate latent heat flux, using the Bowen Ratio method.

Instead of measuring the gradients, we can measure canopy temperature with an infrared thermometer, to calculate sensible heat flux and thus deduce latent heat flux.

A more sophisticated approach is the eddy covariance method. It is based on high-frequency measurements of scalars (temperature, absolute humidity, CO_2 concentration) and vertical wind velocity. The covariance of any scalar and vertical wind speed (*w*) provides a measure of the flux of the scalar. For instance, the covariance of temperature and w is directly proportional to sensible heat flux, while that of water vapor concentration and *w* leads to latent heat flux. Note that this technique may be applied to measure the flux of any gaseous molecule (e.g., ammonia), provided that we have the proper instrument for measuring its concentration.

9.3 Evaporation from the Soil Surface

Philip described the evaporation from a bare soil surface (E_s) after wetting, as a three-stage process. In the first stage (energy limited) the soil surface is wet and the hydraulic conductivity is high, so the evaporation rate is only limited by the amount of energy available at the surface. In this case, the evaporation is approximately equal to the evaporation from a short grass field, defined in Chap. 10 as reference evapotranspiration ET_0. This stage continues until a certain amount of water has evaporated (U_e) which depends on soil type, ranging from 5–6 mm (well-drained soils) to 12–14 mm (heavy clay soils).

If the soil is partly covered by a crop canopy or by crop residues, the energy reaching the soil surface is reduced and so will be E_s in the first stage, E_{s1}:

$$E_{s1} = \left(1 - f_{PI}\right) ET_0 \tag{9.4}$$

where f_{PI} is the fraction of radiation intercepted that does not reach the soil surface.

When the second (soil-limited) stage begins, the soil hydraulic conductivity has been reduced to values that limit the water flow to the soil surface from the deeper soil layers. During this stage, E_s decreases as a function of the square root of time since the start of the second stage (t):

$$E_s = c_e\left(\sqrt{t} - \sqrt{t-1}\right) \tag{9.5}$$

where c_e is a constant that depends on the soil type, although its value is usually close to 3.5 mm day$^{-0.5}$.

The third stage described by Philip corresponds to extremely dry soil in which water is transported to the soil surface as water vapor and the evaporation is extremely low. For practical purposes in agronomy, we can calculate E_s considering only the first two stages.

Therefore, soil evaporation depends primarily on the availability of energy at its surface and the water content of the upper soil layers (down to about 30 cm). Thus, when the soil is thoroughly wet, E_s is similar to the evaporation from a full cover crop and can be assumed equal to ET_0. By contrast, when the soil surface is dry, E_s is very low (Fig. 9.2).

Example 9.2

A bare soil ($f_{PI} = 0$) is thoroughly wetted by a rainfall event. The soil parameter for evaporation during the first stage (energy limited) is $U_e = 9$ mm and ET_0 is 4.5 mm/day.

In this case, the first stage (E_s equal to ET_0) will last 2 days, the time required to evaporate 9 mm:

$$U_e / ET_0 = 9 / 4.5 = 2 \text{ days}$$

Therefore, $E_s(1) = E_s(2) = 4.5$ mm/day

(continued)

Example 9.2 (continued)

The second stage of E_s starts on the third day so taking c_e as 3.5 mm/day$^{0.5}$:

$$E_s(3) = 3.5\,(1^{0.5} - (1-1)^{0.5}) = 3.5 \text{ mm/day}$$

$E_s(4) = 3.5\ (2^{0.5} - (2\text{–}1)^{0.5}) = 1.45$ mm/day, and so on.

If the same situation occurred in an olive orchard intercepting 40% of radiation ($f_{PI} = 0.4$), then evaporation in stage 1 would be:

$$E_s(1) = ET_0\,(1 - f_{PI}) = 4.5 \cdot 0.6 = 2.7 \text{ mm/day}$$

In this case, the first stage will last 3.3 days (it may be rounded to 3). On the fourth day, the second stage will start so:

$$E_s(4) = 3.5\,(1^{0.5} - (1-1)^{0.5}) = 3.5 \text{ mm/day}$$

$E_s(5) = 3.5\ (2^{0.5} - (2\text{–}1)^{0.5}) = 1.45$ mm/day, and so on.

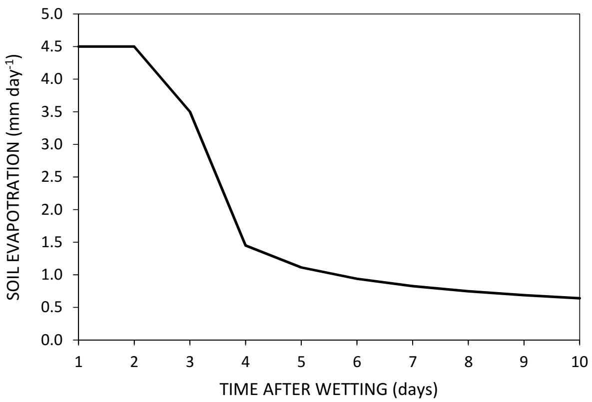

Fig. 9.2 Soil evaporation rate after soil wetting. Reference ET is 4.5 mm/day. The parameter U_e is 9 mm

According to the two-stage soil evaporation model, the average E_s for a given period (month, year) will be proportional to the frequency of wetting. If wetting events have an average duration of *WD*, and the average interval between two consecutive events is *WI*, we calculate the average daily E_s as:

$$E_{\text{sm}} = \frac{(WD-0.5)(1-f_{\text{PI}})ET_0 + U_e + c_e\sqrt{WI-(WD-0.5)-\dfrac{U_e}{(1-f_{PI})ET_0}-t'}}{WI} \tag{9.6}$$

where $t' = (c_e/[(1–f_{PI})\ ET_0])^2$ if $c_e>(1–f_{PI})\ ET_0$. Otherwise $t' = 0$. Please note that the square root function in Eq. 9.6 is only valid when positive. A negative value means that the soil stays in first-stage evaporation so the average evaporation rate is equal to $(1–f_{PI})\ ET_0$.

Equation 9.6 is obtained by assuming first-stage evaporation during WD–0.5 days and the two equations (9.4 and 9.5) for $WI – WD + 0.5$ days, assuming that on day WD the rainfall stops in the middle of the day.

Example 9.3

A farmer has sown a summer crop during June in southern Italy ($ET_0 = 6$ mm/day). To ensure crop emergence, irrigations are applied every 5 days ($WI = 5$ day, $WD = 1$ day). The soil has a parameter for first stage $U_e = 9$ mm and $c_e = 3.5$ mm day$^{-0.5}$. Calculate the average evaporation for the period.

Applying Eq. 9.6:

$$E_{\mathrm{sm}} = \frac{0.5 \cdot 5 + 9 + 3.5\sqrt{5 - 0.5 - 9/6}}{5} = 3.51\,\mathrm{mm/day}$$

Example 9.4

The average number of rainy days in Cordoba (Spain) during March ($ET_0 = 3$ mm/day) is 9.3. In principle, this would imply that on average a rainfall event would occur every 3.3 days. However, rainy days tend to cluster, to occur in consecutive days. According to Villalobos and Fereres, the average interval between two consecutive rainy spells may be estimated as:

$$WI = \frac{1}{0.75 f_w \left(1 - f_w\right)} \tag{9.7}$$

where f_w is the mean frequency of rainy days. In the case of Cordoba $f_w = 9.3/31 = 0.3$, thus $WI = 6.3$ days.

Each period of 6.3 days would be composed of 1.9 rainy days (30% of 6.3 days) and 4.4 dry days. Now taking $WI = 6.3$ days and $WD = 1.9$ days, we will calculate the average evaporation during March for a bare soil with $U_e = 6$ mm and $c_e = 3.5$ mm$^{-0.5}$:

$$E_{\mathrm{sm}} = \frac{\left(1.9 - 0.5\right) \times 3 + 6 + 3.5\sqrt{6.3 - \left(1.9 - 0.5\right) - \frac{6}{3} - \left(\frac{3.5}{3}\right)^2}}{6.3} = 2.3\ \mathrm{mm/day}$$

9.4 Analysis of Evapotranspiration with the Penman–Monteith Equation

The first formulation of a combination equation to calculate evaporation was due to Penman in 1948, who combined the energy balance equation with those of latent heat and sensible heat fluxes. Similar solutions were proposed by Ferguson in Australia and Budyko in Russia. The most widespread formulation of the combination equation is due to Monteith who started from the following equations:

The energy balance (Chap. 7):

$$R_n - G = LE + H \tag{9.8}$$

Latent heat flux (Chap. 5):

$$LE = \frac{\rho C_p}{\gamma} \frac{\left(e_{sc} - e_a\right)}{\left(r_c + r_a\right)} \tag{9.9}$$

Sensible heat flux (Chap. 5):

$$H = \rho C_p \frac{\left(T_c - T_a\right)}{r_a} \tag{9.10}$$

In this method, the slope of the saturation vapor pressure function versus temperature (Δ, kPa K^{-1}) is approximated as:

$$\Delta = \frac{e_{sc} - e_s}{T_c - T_a} \tag{9.11}$$

where e_{sc} is the saturation vapor pressure at canopy temperature (T_c) and e_s is the saturation vapor pressure at air temperature (T_a). Rearranging Eq. 9.11:

$$e_{sc} = e_s + \Delta\left(T_c - T_a\right) \tag{9.12}$$

Now using Eq. 9.12 and adding and subtracting e_s:

$$e_{sc} - e_a = e_{sc} - e_a + e_s - e_s = \Delta\left(T_c - T_a\right) + e_s - e_a = \Delta\left(T_c - T_a\right) + VPD \tag{9.13}$$

So Eq. 9.9 can be written as:

$$LE = \frac{\rho C_p}{\gamma} \frac{\Delta\left(T_c - T_a\right) + VPD}{\left(r_c + r_a\right)} \tag{9.14}$$

From Eqs. 9.10 and 9.8, we can write the term $\Delta(T_c - T_a)$ as:

$$\Delta\left(T_c - T_a\right) = \frac{\Delta r_a H}{\rho C_p} = \frac{\Delta r_a\left(R_n - G - LE\right)}{\rho Cp} \tag{9.15}$$

Which placed in Eq. 9.14 allows solving for LE, leading to the Penman–Monteith equation:

$$LE = \frac{\Delta\left(R_n - G\right) + \frac{\rho C_p}{r_a} VPD}{\Delta + \gamma\left(1 + \frac{r_c}{r_a}\right)} \tag{9.16}$$

The Penman–Monteith equation indicates that crop evaporation depends on meteorological (radiation, temperature, humidity, wind speed) and crop factors (r_c). In the case of r_a apart from canopy characteristics (height, leaf area) there is a dependence on meteorological conditions (wind speed).

This equation has the drawback of requiring information on canopy resistance (r_c, see Chap. 5) which depends on different environmental factors such as temperature, radiation, and Vapor Pressure Deficit (*VPD*). Canopy resistance is proportional to *VPD* in many species. Thus, on the one hand, *LE* increases with *VPD*, but if r_c increases as well, the response of *LE* to *VPD* will be asymptotic.

The Penman–Monteith equation is useful from a conceptual standpoint. For example, when the *VPD* tends to zero (extremely humid conditions) and the canopy resistance is small compared with the aerodynamic resistance (e.g., flat, smooth surfaces such as a short grass crop) evaporation tends to:

$$LE = \frac{\Delta\left(R_n - G\right)}{\Delta + \gamma} \tag{9.17}$$

This value has been termed "equilibrium evaporation." The same equation applies to a canopy with infinite aerodynamic resistance. In these cases, evaporation depends only on radiation and temperature (as Δ depends on temperature). These conditions are found in short, smooth crop canopies with high humidity and large aerodynamic resistance (low wind) or crops growing in greenhouses.

The opposite situation occurs with high aerodynamic roughness canopies under windy conditions (low r_a) and high canopy resistance (e.g., forests with variable tree heights and isolated trees with small leaves such as olives). In this case, evaporation (called "imposed evaporation") depends only on *VPD* and canopy resistance:

$$LE = \frac{\rho C_p}{\gamma} \frac{1}{r_c} VPD \tag{9.18}$$

These two extremes of equilibrium and imposed evaporation correspond to uncoupled and coupled canopies with the atmosphere. In a perfectly coupled canopy, the absence of aerodynamic resistance makes transpiration highly responsive to changes in *VPD*. On the contrary, the uncoupled canopy (e.g., grass in the absence of wind) is somehow isolated from changes in atmospheric conditions above it. If stomata close, reduced transpiration leads to higher canopy temperature, which tends to increase transpiration (see Eq. 5.12 in Chap. 5). In the field, crop canopies are not perfectly coupled or uncoupled but somewhere in between. Those better coupled to the atmosphere (for example, tree crops) can exert more control of transpiration via stomata closure than those uncoupled such as smooth field crops.

Box 9.2: Limitations of the Penman–Monteith Equation

Several authors (e.g., Paw U and Gao. 1988. Agric For Meteorol, 43:121–145) have questioned the validity of the PM equation when canopy temperature departs greatly from air temperature. In that case, the linear approximation to the slope of vapor pressure versus temperature may lead to large errors. The equation may be reformulated using a polynomial for saturated vapor pressure. Using that "corrected" equation, the limit of LE when aerodynamic resistance tends to infinity is the available energy (R_n-G) and not the value obtained with Eq. 9.17. However, the limit of *LE* when *VPD* is zero is still the equilibrium evaporation (Eq. 9.17).

The other problem of the Penman–Monteith model lies in considering net radiation as an independent variable, while it will depend on canopy temperature and thus, on *LE*.

9.5 Transpiration

The calculation of actual transpiration is difficult as it depends on meteorological (e.g., radiation) and plant factors, primarily through the response of stomata to the aerial environment but also including root system responses. For well-watered conditions, we may assume that the transpiration coefficient, the ratio transpiration/ET_0, is proportional to the fraction of intercepted radiation. Then, transpiration (E_p, mm day^{-1}) can be calculated as:

$$E_p = f_{PI} \, K_{tf} \, ET_0 \tag{9.19}$$

where f_{PI} is the fraction of radiation intercepted, K_{tf} is the transpiration coefficient for full interception, which is close to 1 for most herbaceous and evergreen tree crops and between 1.2 and 1.8 for deciduous tree crops (Table 9.1).

For isolated trees, Eq. 9.19 becomes:

$$E_{p\mathrm{tree}} = REA \, K_{tf} \, \mathrm{ET}_0 \tag{9.20}$$

Table 9.1 Transpiration coefficient and empirical parameters to calculate bulk canopy conductance (Eq. 9.21) of some cultivated tree species

Species	a (μE mol^{-1})	b (μE mol^{-1} kPa^{-1})	K_{tf}
Orange	1002	1666	0.8
Walnut	1287	673	1.4
Apple	442	911	1.8
Olive	1211	1447	1.1
Apricot	452	2050	
Peach	333	633	1.8
Pistachio	359	624	1.9
Almond			1.25

where $E_{p\,\mathrm{tree}}$ is the tree transpiration (L day^{-1} tree^{-1}) and REA (m^2) is the radiation interception equivalent area (the ratio between tree intercepted radiation and incoming radiation; see Chap. 3).

Example 9.5
In Example 3.5, we calculated the radiation interception equivalent area of a small olive tree with radius 0.5 m in Cordoba, Spain on 21 March as $REA = 0.69$ m^2.

If ET_0 is 3 mm day^{-1}:

$$E_{p\mathrm{tree}} = REA K_{tf}\, ET_0 = 0.69 \cdot 1 \cdot 3 = 2.07 \ \ \mathrm{L\,day^{-1}}$$

Villalobos et al. (2013) proposed a more detailed model for calculating the transpiration of orchard canopies. The model considers a daily "bulk" canopy conductance (G_c), i.e. the inverse of the canopy resistance for the whole stand, a parameter that is related to VPD and to the radiation intercepted by the canopies as:

$$G_c = \alpha \frac{QR_s}{a + bVPD} \tag{9.21}$$

where Q is the fraction of radiation intercepted by the canopy (see Chap. 3), R_s is the daily solar radiation (MJ m^{-2} s^{-1}), VPD is the vapor pressure deficit (kPa), α is constant, and a and b are empirical coefficients that vary with the tree species (see Table 9.1). As $r_c = 1/G_c$, we can use the Penman–Monteith equation (Eq. 9.16) to calculate the transpiration of the stand. As orchard canopies are generally well coupled to the atmosphere, similar results may be obtained using the "imposed" evaporation equation (Eq. 9.18), which is much more practical as it does not require knowledge of the aerodynamic resistance, r_a. The transpiration (in mm day^{-1}) can be calculated as:

$$E_p = 37.08\ 10^3 \frac{QR_s}{a + bVPD} \frac{VPD}{P_{at}} \tag{9.22}$$

where P_{at} is the atmospheric pressure (kPa). The coefficient 37.08 10^3 is used to convert the units to mm day^{-1}. This model has been developed and tested in semi-arid climates, where transpiration is primarily regulated by the evaporative demand of the atmosphere rather than by solar radiation only.

Example 9.6

An intensive olive orchard at an altitude of 100 m intercepts 52% of the incident daily radiation. Let us calculate its transpiration on a sunny day with a daily solar radiation of 27.6 MJ m^2 day^{-1} and an average *VPD* of 2.8 kPa. Assume an atmospheric pressure of 101 kPa.

Using Eq. 9.22 with the coefficients of Table 9.1 for olive ($a = 1211$ μE mol^{-1} and $b = 1447$ μE mol^{-1}kPa^{-1}),

$$E_p = 37.08\ 10^3 \frac{0.52 \cdot 27.6 \cdot 2.8}{(1211 + 1447 \cdot 2.8) \cdot 101} = 2.80\,\text{mm day}^{-1}$$

9.6 Evaporation from Wetted Canopies

When the plant is wet just after rainfall, the water film and droplets covering the foliage will eventually evaporate directly into the atmosphere. Note that this evaporation flux is neither transpiration nor evaporation from the soil, but the water involved is still coming from the rain or irrigation: it should then be evaluated and considered as part of ET (see Eq. 9.1) to assess correctly the components of the water budget.

Although the direct evaporation flux from wetted canopies is often overlooked, it may be appreciable when frequent rains wet dense canopies with high *LAI*, as they can intercept significant amounts of water. The maximum capacity of rainfall interception by agricultural species with full ground cover is around 0.25 mm per unit of *LAI*, i.e. a wheat canopy with $LAI = 4$ can intercept 1 mm of rain. High direct evaporation occurs also with high-frequency irrigation using center pivots, as a significant part of the application is intercepted by the canopy. In all cases, direct evaporation is the main process to be evaluated to assess the canopy wetness duration after rainfall. This duration is strongly related to the risk of infection by many fungal diseases; furthermore, during that interval, the transpiration rate is nil (see Fig. 9.3), so

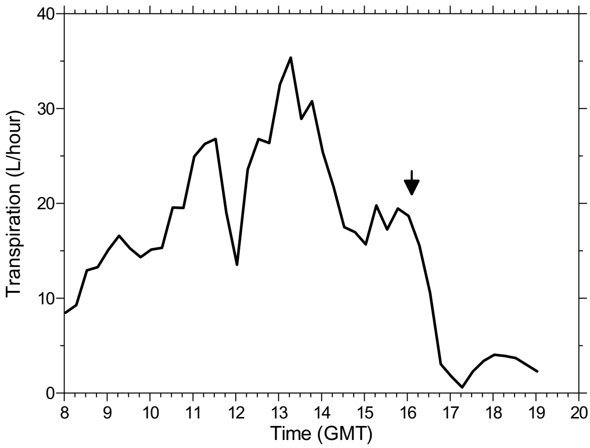

Fig. 9.3 Time course of transpiration of a walnut tree in Cordoba (Spain) on June 5, 2009. Rain started at 14:20 (vertical arrow) and lasted one hour

the root uptake of water and nutrients is reduced. Wet canopy evaporation may be calculated with the Penman–Monteith equation assuming zero canopy resistance.

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Calculation of Evapotranspiration and Crop Water Requirements

10

Francisco J. Villalobos, Luca Testi, and Elias Fereres

Abstract

Reference *ET* (ET_0) is defined as the *ET* of short grass with full soil cover, and an unlimited supply of water and nutrients. In the absence of water deficit, the *ET* of any crop may be calculated as the product $K_c \times ET_0$, where K_c is the crop coefficient, which depends on crop related factors (leaf area, roughness) and ET_0, the reference *ET* (grass), which is a function of climatic variables (radiation, temperature, humidity, and wind speed). The main equation for calculating ET_0 is the Penman–Monteith-FAO, although the Hargreaves equation can be used when only air temperature data are available. K_c is calculated by the method proposed by FAO that uses linear functions between the initial, maximum, and harvest dates of the cycle. The initial K_c depends on the frequency of soil wetting and ET_0. The maximum values of K_c of annual crops and deciduous fruit trees are typically between 1.0 and 1.3 (median 1.2). The crop irrigation water requirement is the difference between *ET* and the sum of effective rainfall and soil water depletion. The latter may be an important contributor to meeting the *ET* demand and thus reduce the capacity (and investment) of irrigation networks.

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10.1 Introduction

The evapotranspiration (*ET*) in the absence of water stress may be calculated as:

$$ET = K_c \, ET_0 \tag{10.1}$$

where K_c is the crop coefficient, which depends on factors related to the crop (leaf area, roughness, and crop management) and ET_0 is the reference *ET*, the *ET* of a well-irrigated short grass canopy. The ET_0 is ideally only a function of climatic variables (radiation, temperature, humidity, and wind speed). This equation holds unless water stress reduces *ET*, which generally occurs after 65–80% of the extractable soil water is depleted. If depletion proceeds, the K_c decreases linearly to 0 when soil water reaches the Permanent Wilting Point (Fig. 9.1).

The use of Eq. 10.1 requires first calculating ET_0 as a function of meteorological data and then applying a K_c that changes as the crop grows. Several methods have been proposed for estimating ET_0 (e.g., Penman-FAO) or the K_c (e.g., FAO) that will be discussed below.

10.2 Reference *ET*

Reference *ET* (ET_0) is defined as the *ET* of short (8–15 cm height) grass with full soil cover and a good supply of water and nutrients. The concept of ET_0 replaced the term "potential *ET*" which lacked a precise definition.

In many regions, automatic weather station networks provide daily information via the Internet that allows applying formulas based on the Penman–Monteith equation. In other areas, the lack of agrometeorological data limits using the most precise methods. If only maximum and minimum temperature data are available, the equation of Hargreaves (see Sect. 10.2.1) provides a good approximation. In some cases, evaporation pans are available and they provide another estimate of ET_0, as shown in Appendix B.

When time series of daily weather data and ET_0 are not available, they can be obtained using stochastic weather generators such as *ClimaSG* (https://www.uco.es/fitotecnia/climasg.html).

The annual time course of ET_0 follows a pattern similar to that of solar radiation. For example, Fig. 10.1 shows the daily ET_0 calculated by the Penman–Monteith equation in Santaella (southern Spain, semi-arid Mediterranean climate), typical of mid-latitudes. The mean values range from 1 mm/day in winter to 7 mm/day in summer. The average annual total ET_0 is 1278 mm.

10.2.1 Method of Hargreaves

In 1985, Hargreaves and Samani proposed a simple equation for estimating ET_0 (in mm/day):

$$ET_0 = 5.5210^{-3} \, K_{RS} \, R_A \left(T_{\text{avg}} + 17.8\right)\sqrt{T_{\max} - T_{\min}} \tag{10.2}$$

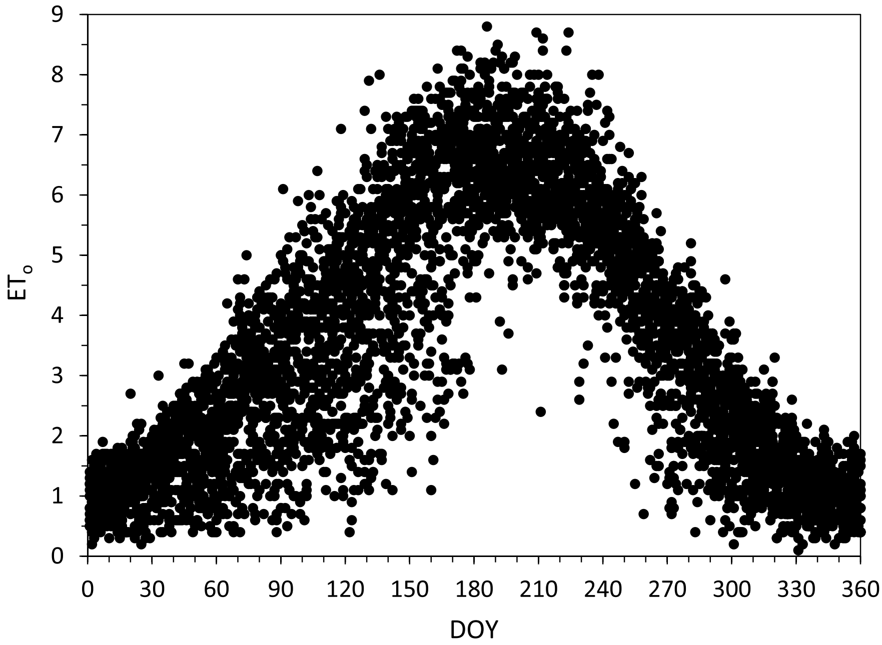

Fig. 10.1 Annual time course of reference *ET* calculated using the method of Penman–Monteith-FAO for Santaella (Spain) from 2000 to 2013

where R_A is the extraterrestrial radiation (MJ m^{-2} day^{-1}), and T_{avg}, $T_{max,}$ and T_{min} are the average, maximum, and minimum air temperatures (°C), respectively, while K_{RS} is another coefficient already defined in Chap. 3 on solar radiation (Eq. 3.6). K_{RS} vary between 0.16 and 0.19 for interior and coastal locations, respectively. This equation has shown good performance for different areas despite being based only on measured air temperature. This is because it includes a term associated with the potential radiation of the location, by considering the extraterrestrial radiation and a variable related to the degree of cloudiness (the amplitude of air temperature). Thus, on very cloudy days, there is little heating during the day (low solar radiation) and little cooling during the night (clouds reduce longwave radiation loss). Therefore, the maximum and minimum temperatures will not differ much. By contrast, on clear days the greater warming during the day and the increased cooling at night lead to a greater daily temperature oscillation. The Hargreaves method may be less reliable when applied in areas with little daily temperature oscillation or where the temperature amplitude is influenced by factors not related to solar radiation, e.g. the presence of massive water bodies (coastal regions).

10.2.2 Penman–Monteith-FAO method

This equation has become the standard for ET_0 calculation as proposed by FAO. Applying the Penman–Monteith equation (Eq. 9.16) to a hypothetical grass canopy of height 0.12 m and canopy resistance 69 s m^{-1}, we can deduce the ET_0 (mm day^{-1}) for 24-h periods as:

$$ET_0 = \frac{\Delta R_n + 0.5\,VPD\,U_2}{2.45\left[\Delta + 0.067\left(1 + 0.33\,U_2\right)\right]} \tag{10.3}$$

where Δ (kPa K^{-1}) is the slope of the saturation vapor pressure function versus temperature, R_n is the net radiation (MJ m^{-2} day^{-1}), VPD is the vapor pressure deficit (kPa), and U_2 is the wind speed at 2-m height (m s^{-1}).

The slope Δ (kPa K^{-1}) can be calculated as:

$$\Delta = \frac{4098\,e_s}{\left[237.3 + T\right]^2} \tag{10.4}$$

where T is the air temperature (°C) and e_s is the saturation vapor pressure (kPa) that is a function of temperature (Eq. 5.2).

10.3 Crop Coefficients

The crop coefficient reflects specific features of the crop as they affect ET, such as leaf area, height and fraction of ground cover. By definition:

$$K_c = \frac{ET}{ET_0} \tag{10.5}$$

In irrigated crops, K_c depends primarily on the fraction of ground cover, and, if the latter is low, it depends on the water content of the soil surface as it determines soil evaporation (see Sect. 9.3). Thus, when the crop has not emerged yet, the K_c of bare dry soil may be as low as 0.1, but if the soil surface is wet, the K_c increases to around 1. With full ground cover, the K_c becomes almost independent of the water content of the soil surface and usually exceeds 1 (1.05–1.30), with a typical value of 1.20.

In some cases, the latent heat flux exceeds the net radiation, that is, sensible heat is used to evaporate water. This phenomenon typically occurs due to the movement of hot, dry air from dry areas surrounding a wet area where water is available for evaporation (oasis effect). We may distinguish the clothesline effect when advection occurs at the field level and is characterized by sensible heat input decreasing inwards from the edge of the plot. At a smaller scale (micro-advection), sensible heat is transported from dry soil to the surrounding plants. If an isolated irrigated field is surrounded by dry land (fallow, stubble, dry crops), the clothesline effect provides additional energy for ET so that the crop coefficient may be much greater than the values indicated previously. This enhancement will be greater for small plots with tall plants, but there is no reliable model to quantify the K_c in these situations. Some authors suggest that the extreme value of K_c for isolated irrigated plots may be as high as 2.5, which should be considered a hypothetical limit reached only under infrequent extreme conditions and for a limited time.

The K_c is not constant during the season but changes with the ground cover, the plant height, soil surface wetting, and plant aging. The most widespread method for estimating the K_c at any time of the growing season is the one proposed by FAO (Doorenbos & Pruitt, 1977). This method represents the K_c curve as a set of straight lines. To define the curve it is necessary to know in advance the length of phases A, B, C, and D, and the value of K_c at three points (K_{c1}, K_{c2}, and K_{c3}). The initial phase (A) ends when the crop reaches 20% of ground cover, while the rapid growth phase (B) ends when ground cover is 70–80%, which corresponds to values of Leaf Area Index around 2.5–3.0. Figure 10.2 shows an example of a curve of K_c for annual crops in which the phase durations are 40, 30, 30, and 30 days, and the crop coefficients that define the curve are 0.3, 1.2, and 0.5. Table 10.1 shows K_{c2} (mid) and K_{c3} (final) for several crops, and Appendix C presents a more complete list.

Although the methodology proposed by FAO allows fitting the crop coefficient to specific climatic conditions, in Table 10.1, we show the intervals of K_c that we believe may hold for temperate areas. Moreover, Table 10.1 also shows indicative values of the phase durations for different species. These durations should be taken merely as examples since the actual duration depends on many factors (cultivar, date of sowing or bud burst in trees, climatic conditions of the year, etc.). The main factor affecting the duration of the crop stages is temperature, which may change from year to year or if the sowing date is changed. For real-time ET calculation, the K_c curve should always be obtained using on-season information on the phases (beginning and duration) obtained from field data.

The K_c in the initial phase (K_{c1}) is a function of the frequency of rain and irrigation and ET_0 during that period because most of the ET of a crop during this phase is direct evaporation from the soil surface. Bare soil evaporation is approximately

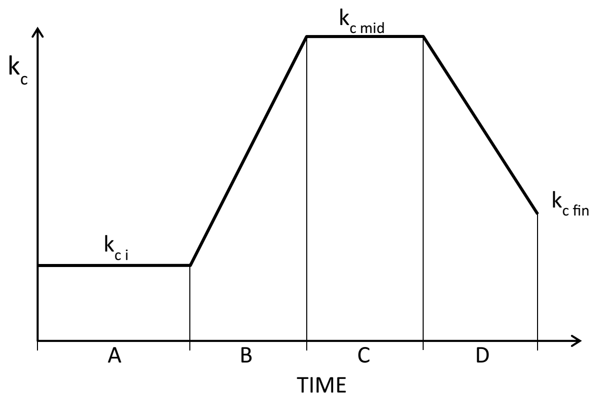

Fig. 10.2 Crop coefficient curve for an annual crop according to the FAO method. The duration of the four phases is 40, 30, 30, and 30 days, respectively

Table 10.1 Duration of phases of the growth cycle (FAO method) and crop coefficients in phase C (mid) and at harvest (end) for different crop species

Crop species	Date of start of crop cycle (N hemisphere)	Stage duration (days)				K_c *mid*	K_c *end*
		A	B	C	D		
Alfalfa (hay)	Mar–Oct[a]	5	10–20	10	5–10	0.9–1.15[b]	0.90
Barley	Nov–Mar	20–40	25– 30	40–65	20–40	1.15	0.2–0.4
Bean (Phaseolus) (dry seed)	May–Jun	15–25	25–30	30–40	20	1.15	0.30
Citrus (70% CC)*	Jan	60	90	120	95	0.65	0.75
Coffee						0.95	0.95
Cotton	Mar–May; Sept	30–45	50–90	45–60	45–55	1.15–1.25	0.4–0.7
Grapes (table or raisins)	Mar–May	20	40–50	75–120	20–60	0.85	0.45
Grapes (wine)	April	30	60	40	80	0.70	0.45
Lettuce	Nov–April	20–35	30–50	15–45	10	1.00–1.05	0.95
Maize (grain)	Mar–Jun	20–30	35–50	40–60	30–50	1.20	0.35–0.6
Millet	Apr–Jun	15–20	25–30	40–55	25–35	1.00	0.30
Olives (60% CC)*	Mar	30	90	60	95	0.70	0.70
Palm trees						1.00	1.00
Peas (dry harv.)	Mar–May	15–35	25–30	30–35	30	1.15	0.30
Pome fruits, cherries (60–70% CC)*	Mar	20–30	50–70	90–130	30–60	1.10	0.75
Potato	Nov–Jan; Apr–May	25–45	30–35	40–70	20–30	1.15–1.25	0.7–0.8
Rapeseed	Nov–Dec	25–40	35–40	60–70	30–35	1.10	0.35
Rice	May (Medit.); May–Dec (tropics)	30	30	60–80	30–40	1.20	0.9–0.6
Sorghum (grain)	Apr–Jun	20	35	40–45	30	1.00–1.10	0.55
Soybean	May–Jun; Dec (tropics)	15–20	15–35	40–75	15–30	1.15	0.50
Stone fruits (60–70% CC)*	Mar	21–30	51–70	91–130	31–60	1.10	0.65
Sugar beet	Nov–June	25–50	30–75	50–100	10–65	1.20	0.70
Sugar cane (ratoon)		25–35	70–105	135–210	50–70	1.25	0.75
Sugar cane (virgin)		35–75	60–105	190–330	120–210	1.25	0.75
Sunflower	Feb–May	25–45	35–40	45–60	25	1.20	0.35–0.5
Tea						1.00	1.00
Tomato	Jan–May	30–35	40–45	40–70	25–30	1.15–1.25[c]	0.7–0.9
Wheat (Winter)	Oct–Dec	20–30	60–140	40–70	30	1.15	0.25–0.4

Adapted from Doorenbos and Pruitt (1977) and Allen et al. (1998). For some crops, the final K_c shows a wide interval, as its value depends on crop use (fresh or dry). This Table should be used with caution as the actual duration of phases may change for different regions, cultivars, and weather conditions of each year. * When cover crops or weeds are present, add 0.2 to the crop coefficient. If canopy cover (CC) is lower than the value indicated in the table (CC'), then $K_c = 0.15 + CC\ (K_c'-0.15)/CC'$ where K_c' is the value shown

[a]For the first cut cycle use durations twice the values shown

[b]Lower value is the seasonal average; higher value is at full cover-before cutting

[c]When cultivated on stalks, the $K_{c\ mid}$ should be increased by 0.05–0.1

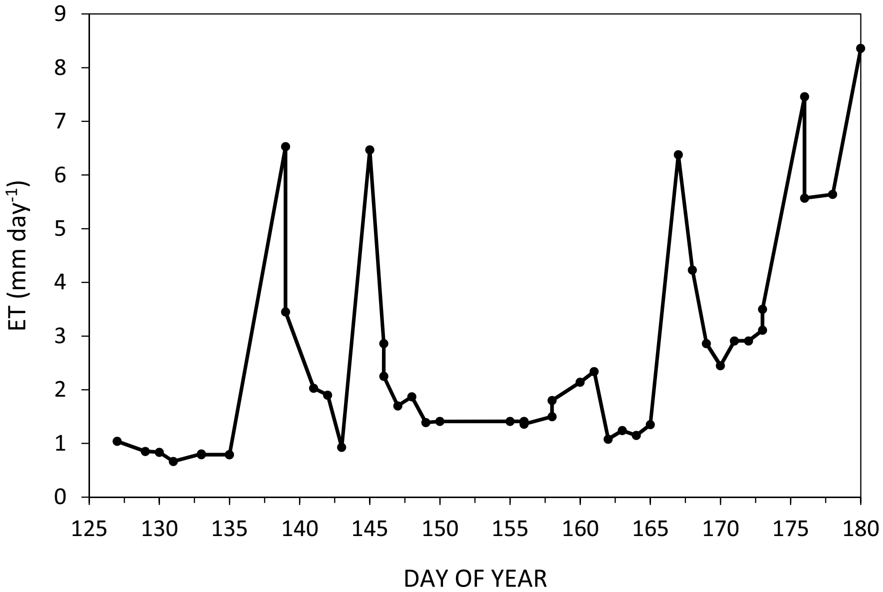

Fig. 10.3 Evapotranspiration of cotton in Cordoba (Spain) for phases A and B. Inter-row tillage was performed on DOY 156 causing an increase in soil evaporation

equal to the ET_0 while the soil surface is wet (energy-limited or first-stage evaporation, see Sect. 9.3). As the soil dries, the soil hydraulic conductivity decreases (soil limited or second stage). The importance of E_s in determining the initial K_c is manifested in significant variations of ET in the early stages of the crop cycle associated with rainfall or irrigation (Fig. 10.3). Doorenbos and Pruitt (1977) proposed a method of calculating the K_c in the initial development stage (until the onset of rapid crop growth, K_{c1}) that was summarized in the following equations by Allen et al. (1998):

For $WI < 4$ days:

$$K_{c1} = \left(1.286 - 0.27 \ln WI\right) \exp\left[\left(-0.01 - 0.042 \ln WI\right) ET_{01}\right] \qquad (10.6a)$$

For $WI > 4$ days:

$$K_{c1} = \frac{2}{\left(WI\right)^{0.49}} \exp\left[\left(-0.02 - 0.04 \ln WI\right) ET_{01}\right] \qquad (10.6b)$$

where WI is the interval between irrigations or rainfall events during the initial stage and ET_{01} is the average ET_0 during that period (mm/day). If we consider the effect of rainfall, major errors may arise if we assume that rainy days are evenly distributed over the period (Villalobos and Fereres, 1989. Trans ASAE, 32(1):181–188), thus a correction should be applied to calculate the interval between rainfall events (see Example 9.4). It is important to calculate the initial K_c accurately because any error will translate into errors in K_c during the rapid growth period (phase B) as it is interpolated between the values of K_{c1} and K_{c2}.

If real-time information on the ground cover fraction (f_{GC}) is available, we can use it to calculate K_c in arid and semi-arid areas as:

$$K_c = K_{c1} + f_{\mathrm{GC}} \frac{K_{c2} - K_{c1}}{f_{GC2}} \quad (10.7)$$

where f_{GC2} is the ground cover fraction associated to K_{c2} ($f_{GC2} = 1$ for full cover crops)

The method described above is valid for well-watered plants and would thus be valid for irrigated crops or rainfed crops when soil water does not limit *ET*. Transpiration is reduced as soil water is depleted below a threshold (water stress), so the K_c is reduced. A simple model for estimating the K_c as a function of soil water would be:

$$K_c = K_c^* \frac{3(\theta - \theta_{PWP})}{(\theta_{\mathrm{FC}} - \theta_{PWP})} \quad (10.8)$$

Where K_c^* is the crop coefficient with no water stress, θ is the average soil water content, and θ_{FC} and θ_{PWP} are the soil water content at field capacity and wilting point, respectively. This equation is valid for θ lower than $\theta_{PWP} + (\theta_{FC} – \theta_{PWP})/3$. If θ is higher, then the K_c is not reduced, which implies that most crops can use around 2/3 of extractable water without reducing *ET*.

10.4 Crop Coefficients of Perennial Species

Forage crops and pastures have a variable K_c depending on management (cutting frequency, maximum *LAI*). For instance, alfalfa has an average seasonal K_c close to 1, oscillating between 0.6 after cutting and then increasing to 1.2 before the next cut.

For fruit trees, evaporation from the soil may play an important role throughout the cycle depending on the fraction of the soil exposed to solar radiation. If the tree canopy is small, the K_c will be higher during periods with frequent rainfall. The contribution of tree transpiration is proportional to ground cover and nil during the winter season in deciduous fruit trees, contrary to evergreen fruit trees (olive, citrus) that keep their leaf area the whole year. In these evergreen species, under mild Mediterranean climates, the K_c may be maximum in winter (high soil evaporation due to high frequency of rain) and minimum during summer (low soil evaporation, high stomatal resistance in response to high *VPD*) (Fig. 10.4).

10.5 Correction of Crop Coefficients

The FAO method for calculating *ET* was originally developed by William Pruitt in California by considering *actual* grass *ET* as the reference crop. It turns out that according to theory, the ratio of crop *ET* and grass *ET* should increase as the aerodynamic component of the combination *ET* formula increases, i.e. as wind speed and *VPD* increase. Therefore, the FAO manual 24 included a correction for crop coefficients taking into account crop height, wind, and relative humidity.

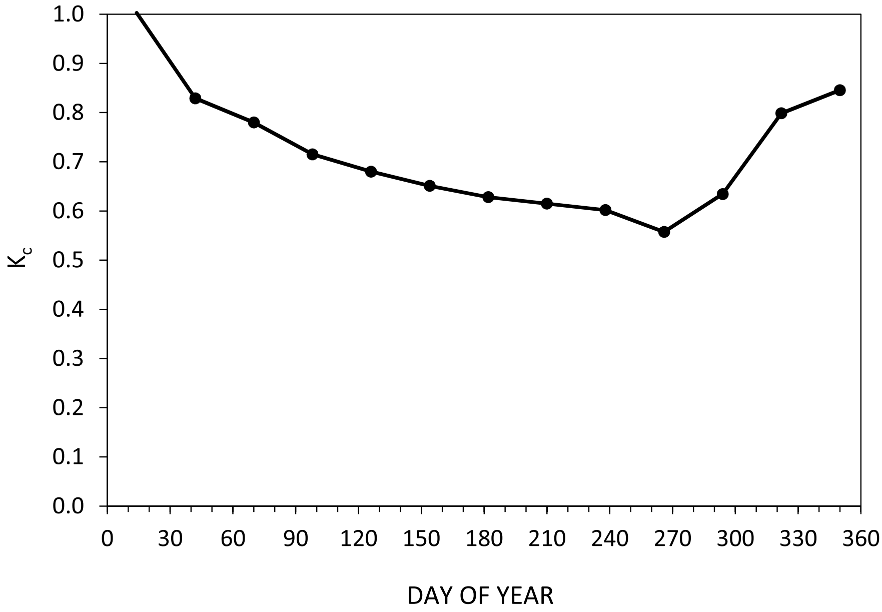

Fig. 10.4 Average crop coefficient for an olive orchard with 40% ground cover in Cordoba (Spain) in 2001 and 2002. The data have been grouped in 4-week periods

The revision of the FAO methodology by Allen et al. (1998) changed the reference crop from a real grass crop to a hypothetical grass with constant height and surface resistance. Nevertheless, they kept the same correction of crop coefficients. This is an important flaw. Most plants control water loss by partial stomatal closure when evaporative demand increases. Therefore, with a reference grass with constant stomatal aperture, crops should tend to *decrease* the K_c as evaporative demand increases. This is exactly the opposite of the proposed correction included in FAO 56. We show evidence of the decrease of K_c as ET_0 increases for different crops in Table 10.2. Therefore, we recommend sticking to the coefficients proposed in Table 10.1 and Appendix C and making only corrections based on local measurements if they are required.

10.6 Evapotranspiration in Greenhouses

The *ET* inside greenhouses is usually lower than in the open field because the shelter cover reduces the incoming radiation, the driving force of *ET*, and turbulence. Specific methods have been developed to evaluate the *ET* of screened or sheltered crops. In sophisticated greenhouses, such as those used for high-value crops or ornamental horticulture, with climatic control (heating/cooling, supplemental light, etc.) sensor data are available to run complex transpiration models in short time steps (e.g., 10 min). Furthermore, the sensors may provide indirect estimates

Table 10.2 Slope of linear regressions of K_c versus reference ET (Penman–Monteith-FAO) for different crops and locations

	Location	Year	Slope K_c vs. ET_0
Apple	Lerida	2008	-0.155
Orange	Valencia	2010	-0.0159
Orange	Mairena	2008	-0.0089
Peach	Cordoba	2008	-0.042
Walnut	Cordoba	2009	-0.023
Pistachio	Madera, CA	2006	-0.0989

of greenhouse *ET*. For instance, measurements of airflow into the greenhouse (Q_{in}, m^3 s^{-1}) along with sensors of temperature and air vapor pressure in air going in (T_{in}, e_{in}) and out (T_{out}, e_{out}) allow calculating *ET* of a greenhouse (mm/hour) of surface area A_g (m^2) as:

$$ET = \frac{Q_{in}}{A_g}\frac{3600}{0.4615}\left(\frac{e_{out}}{T_{out}} - \frac{e_{in}}{T_{in}}\right) \tag{10.9}$$

where temperatures are given in *K* and vapor pressures in kPa.

A different case is that of unheated greenhouses with passive ventilation, typically with plastic covers, such as those on the Mediterranean coast of Almeria (Spain) and other mild climate areas. The conditions inside the greenhouse are characterized by reduced turbulence, higher humidity, and higher temperature than the outside. This combination in theory leads to equilibrium *ET* (see Eq. 9.17), i.e. *ET* is governed by radiation, which has been confirmed empirically leading to an equation for reference evapotranspiration (ET_0, mm day^{-1}) of the form:

$$ET_0 = \frac{1}{2.45} 0.7 \frac{\Delta}{\Delta + \gamma} R_{si} \tag{10.10}$$

where R_{si} (MJ m^{-2} day^{-1}) is the solar radiation inside the greenhouse, which can also be estimated from the solar radiation measured in the open if the transmissivity of the cover (τ_{gc}) is known ($R_{si} = \tau_{gc} R_s$). For instance, the transmissivity of polyethylene film of 0.2 mm is around 0.7.

Once the reference *ET* is known inside the greenhouse, the calculation of *ET* requires a crop coefficient, which is usually somewhat higher (10–20%) than that of crops grown outside. For instance, measurements of K_c values of greenhouse tomatoes have reached 1.4 while those in open fields seldom exceed 1.2.

10.7 Calculation of Maximum *ET* for Designing Irrigation Systems

The crop *ET* can vary from year to year depending on weather conditions. To design irrigation systems, it would be desirable to have a historical series of *ET* (and precipitation) to determine the water requirements at different probability levels.

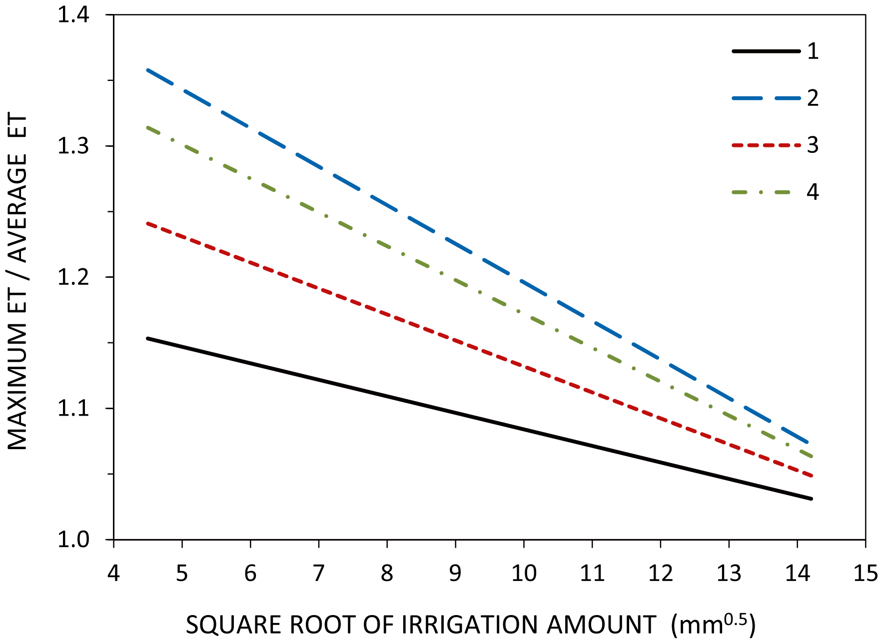

Fig. 10.5 Ratio of 75% probability *ET* and average *ET* as a function of the square root of mean irrigation applied in each irrigation event. Four climate types are considered. 1: Arid and semi-arid with clear skies during summer. 2: Continental climates in mid-latitudes and sub-humid climates with variable cloudiness. 3: Mid-latitude continental climates with *ET* up to 5 mm/day. 4: Mid-latitude continental climates with *ET* up to 10 mm/day

Often we only have the average values of crop *ET*, which will be exceeded in some years. Doorenbos and Pruitt (1977) proposed an adjustment method for calculating the *ET* which corresponds to a probability level of 75% (ET_{75}, which will be exceeded only 25% of the years) as a function of the average *ET* (ET_{avg}) and the mean irrigation applied (I_a). The method is shown in Fig. 10.5, where four different climate types are considered. Each line can be calculated as:

$$\frac{ET_{75}}{ET_{avg}} = C - 0.06(C-1)\sqrt{I_a} \tag{10.11}$$

where the mean irrigation applied is given in mm and the coefficient *C* is 1.21, 1.49, 1.33, and 1.43, for types 1, 2, 3, and 4, respectively.

Note that, ideally, irrigation systems should be designed to supply the peak or maximum *ET* level corresponding to the period of the highest *ET* of the crop mix of the farm rotation or of the irrigated area. The decision to determine the size of the irrigation network is economic. Flow rates below the maximum requirements of the extreme year and the highest demanding crop of the rotation will require less capital investment but will increase the risks of crop water deficits. If the system is dimensioned for annual crops of low requirements (for example, winter cereals), its conversion to summer crops or perennials is not possible without leaving some of the land unirrigated.

Example 10.1
We will calculate the *ET* of maize during August (K_c = 1.2) in Evora, Portugal (ET_0 = 7.0 mm/day) and Paris, France (ET_0 = 4.0 mm/day) for 75% probability assuming that irrigation doses of 60 mm are applied.

We calculate the average *ET* for both locations:

Evora. $ET = 1.2 \times 7.0 = 8.4$ mm day^{-1}
Paris. $ET = 1.2 \times 4.0 = 4.8$ mm day^{-1}

Evora has a semi-arid climate so it corresponds to type 1 (Fig. 10.5). Paris has a sub-humid climate during summer (type 2). Applying Eq. 10.11 for Evora (C = 1.21):

$$\frac{ET_{75}}{ET_{\text{avg}}} = 1.21 - 0.06\left(1.21 - 1\right)\sqrt{60} = 1.11$$

For Paris C = 1.49 so:

$$\frac{ET_{75}}{ET_{\text{avg}}} = 1.49 - 0.06\left(1.49 - 1\right)\sqrt{60} = 1.26$$

Therefore, the values of ET_{75} for the two locations will be:

Evora: $ET_{75} = 1.10 \times 8.4 = 9.2$ mm/day

Paris : $ET_{75} = 1.26 \times 4.8 = 6.0$ mm/day

10.8 Calculation of Crop Water Requirements

Crop irrigation water requirement is the amount of water to be supplied to maintain a maximum level of *ET*. It can be calculated invoking the water balance (Chap. 8) as the difference between the *ET* (the potential value, without restrictions of any kind) and water supplied by rainfall or extracted from the soil during a given period:

$$I_{\text{req}} = ET - P_e - \left(-\Delta TSWC\right) = ET - P_e + \Delta TSWC \tag{10.12}$$

Note that the soil water extraction is expressed as an increase in the total soil water content (*TSWC*) with a negative sign. In this equation, P_e is the effective precipitation, i.e. precipitation not lost by runoff or deep percolation (see Chap. 8).

We can distinguish between net and gross water requirements. In the first case, we refer to the amount of water required assuming no losses during irrigation and perfect uniformity in the spatial distribution of irrigation water. These assumptions are never met and we are forced to apply more water than the net requirement (Chap. 23). The total amount to apply including excess water is the gross irrigation water requirement (I_{req}/application efficiency).

The term related to soil water storage is frequently omitted in the calculations which may lead to large overestimations of I_{req}. The soil water stored at sowing depends on the recharge during the fallow period since the harvest of the previous crop. This can be calculated by adding effective precipitation and discounting soil evaporation (Eq. 9.6) during fallow. This value should not exceed the soil water storage capacity (Chap. 8). Stored soil water is seen in irrigated agriculture as an insurance against irrigation system failures and extremely high *ET* periods, thus keeping a moderately high level of soil water during the irrigation season reduces risks. However, by the end of the season, soil water should be nearly depleted, thus it is possible to use a large fraction of stored soil water (e.g., 80–90%) that should be discounted from the requirements of the final period (see Chap. 20 on irrigation scheduling).

The calculation of I_{req} may be performed for different time intervals (weeks, months) and different spatial scales (field, farm, irrigation scheme). The first step is always computing the I_{req} of each field and then obtaining the weighted average using the fractions of the area as weights.

For instance, the average farm I_{req} is:

$$I_{req\,\mathrm{farm}} = \sum_{1}^{n} I_{req\,i} \cdot s_i$$

where n is the number of crops, and $I_{\mathrm{req}\,i}$ and s_i are irrigation water requirement and the fraction of farm area of crop i, respectively.

Appendices

Appendix A: Class A Evaporation Pan

A relatively simple way to obtain ET_0 is to measure the evaporation from a free water surface in a standardized device and then apply some empirical relationships to convert the direct evaporation of water to that of grass. This method became quite popular because it does not require weather stations, thus it is affordable for farmers even in undeveloped countries. However, the corrections to apply depend also on the micrometeorology of the place where the device is installed.

The most popular model of these devices is the standard *National Weather Service Class A* type evaporation pan that has a diameter of 1.21 m and a height of 0.254 m. It is normally installed on a wooden platform set on the ground. The pan is filled with water to within 6 cm of the top and exposed to represent an open body of water. The evaporation rate is measured as the difference in water level between consecutive measurements.

Then, the reference *ET* may be calculated as:

$$ET_0 = K_p E_{\text{pan}} \tag{A10.1.1}$$

where E_{pan} is the measured pan evaporation (mm/day) and K_p is the pan coefficient that is in the range of 0.35–0.85 with an average value of 0.75. The actual value will depend on the surroundings of the pan, relative humidity, and wind speed. According to FAO manual 24, if the pan is surrounded by crops, the pan coefficient is:

$$K_p = 0.108 - 0.0286U + 0.0422\ln(X) + 0.1434\ln(RH) - 0.000631\left[\ln(X)\right]^2 \ln(RH) \tag{A10.1.2}$$

Where U is the wind speed (m/s) at 2-m height, X is the distance (m) covered with crops around the pan, and RH is the mean relative humidity.

If the pan is located on a dry location (bare soil, stubble), the pan coefficient is:

$$K_p = 0.61 + RH\left(0.00341 - 0.000162U\right) + U\left[0.00327\ln(X) - 9.5910^{-6}X\right] + \left[4.459 + \ln(U)\right]\left[-0.0106\ln(X) + 0.00063\left[\ln(X)\right]^2 - 0.00289U\right] \tag{A10.1.3}$$

A simpler formula may be applied to both cases:

$$K_p = 0.85\exp\left(-0.15\frac{2.45 \cdot Epan}{R_n}\right) \tag{A10.1.4}$$

where R_n is the calculated net radiation (MJ m^{-2} day^{-1}).

Appendix B: Calculating Crop Coefficients Following the Model of Ritchie's

As a crop grows, intercepted radiation increases and so does the energy available for transpiration. At the same time, the energy available for evaporation at the soil surface decreases. In 1972, Professor Joe T. Ritchie proposed a model for calculating crop *ET* by computing transpiration and evaporation from the soil surface separately. Using this model, the K_c may be calculated as a function of ground cover and soil wetting frequency.

Model results are summarized in Eq. A10.2.1 where K_c is a function of ET_0, the interval between rain events or irrigations (*WI*) and the fraction of ground covered by the crop (f_{GC}). The lower values of K_c occur when *WI* is large and ET_0 is high, if f_{GC} is very small. In contrast, when f_{GC} is high, K_c varies little with ET_0 and *WI*.

$$K_c = 0.14 + 1.08 f_{gc} + \frac{13.3 - 5.2 f_{gc}}{WI\, ET_0} \tag{A10.2.1}$$

Example A10.1
A garlic crop in March has a ground cover of 0.3. The last rain occurred seven days ago. Since then, the average ET_0 has been 3.5 mm/day. Let us calculate the *ET* during that period.

$$K_c = 0.14 + 1.08 \times 0.3 + \frac{13.3 - 5.2 \cdot 0.3}{7 \cdot 3.5} = 0.14 + 0.32 + 0.48 = 0.94$$

Appendix C

Crop coefficients in phase C (mid) and at harvest (end) for different species. Adapted from Doorenbos and Pruitt (1977) and Allen et al. (1998). For some crops, the final K_c shows a wide interval, as its value depends on crop use (fresh or dry). * When cover crop or weeds are present, add 0.2 to the K_c. If canopy cover (*CC*) is lower than the value indicated in the table (*CC′*), then K_c = 0.15 + *CC* (K_c'–0.15)/*CC′*, where K_c' is the value shown. Indicative values of maximum crop height and maximum root depth are also shown. The factor F_{AD} is used for calculating Allowable Depletion (see Chap. 20).

Crop species	*Kc mid*	*Kc end*	Max. crop height (m)	Max. root depth (m)	F_{AD}
Cereals					
Barley	1.15	0.2–0.4	1	1.0–1.5	0.09
Maize (grain)	1.2	0.35–0.60	2	1.0–1.7	0.09
Maize, sweet	1.15	1.0–1.05	1.5	0.8–1.2	0.10
Millet	1	0.3	1.5	1.0–2.0	0.09
Oats	1.15	0.2–0.4	1	1.0–1.5	0.09
Rice	1.2	0.90–0.60	1	0.5–1.0	0.16
Rye	1.15	0.2–0.4	1	0.9–2.3	0.08
Sorghum (grain)	1.00–1.10	0.55	1.0–2.0	1.0–2.0	0.09
Sorghum (sweet)	1.1–1.2	1.05	2.0–4.0	1.0–2.0	0.10
Wheat (spring)	1.15	0.25–0.4	1	1.0–1.5	0.09
Wheat (winter)	1.15	0.25–0.4	1	1.5–1.8	0.09
Forages					
Alfalfa hay	0.9–1.15[a]	0.9	0.7	1.0–2.0	0.09
Bermuda hay	1	0.85	0.35	1.0–1.5	0.09
Bermuda (spring crop for seed)	0.9	0.65	0.4	1.0–1.5	0.08
Clover hay, berseem	0.9	0.85	0.6	0.6–0.9	0.10
Rye grass hay	1.05	1	0.3	0.6–1.0	0.08
Sudan grass hay (annual)	0.9	0.85	1.2	1.0–1.5	0.09
Pasture (rotated grazing)	0.85–1.05	0.85	0.15–0.30	0.5–1.5	0.08
Pasture (extensive grazing)	0.75	0.75	0.1	0.5–1.5	0.08

(continued)

Crop species	*Kc mid*	*Kc end*	Max. crop height (m)	Max. root depth (m)	F_{AD}
Turf grass (cool season)	0.95	0.95	0.1	0.5–1.0	0.12
Turf grass (warm season)	0.85	0.85	0.1	0.5–1.0	0.10
Fruit trees, vines, and shrubs					
Almonds (70% CC)*	1.1–1.2	0.65	5	1.0–2.0	0.12
Apple (60–70% CC) *	1.1	0.75	4	1.0–2.0	0.10
Apricot (60–70% CC)*	1.1	0.65	3	1.0–2.0	0.10
Avocado (70% CC)*	0.85	0.75	3	0.5–1.0	0.06
Banana (year 1)	1.1	1	3	0.5–0.9	0.13
Banana (year 2)	1.2	1.1	4	0.5–0.9	0.13
Berries (bushes)	1.05	0.5	1.5	0.6–1.2	0.10
Cacao	1.05	1.05	3	0.7–1.0	0.14
Citrus (70% CC)*	0.65	0.75	3.0–4.0	1.0–1.5	0.10
Cherry (60–70% CC)*	1.1	0.75	4	1.0–2.0	0.10
Coffee	0.95	0.95	2.0–3.0	0.9–1.5	0.12
Conifers	0.9–1	0.9–1	10	1.0–1.5	0.06
Grapevine (table or raisin)	0.85	0.45	2	1.0–2.0	0.13
Grapevine (wine)	0.7	0.45	1.5–2	1.0–2.0	0.11
Kiwi	1.05	1.05	3	0.7–1.3	0.13
Olives (60% CC)*	0.7	0.7	5–7	1.2–1.7	0.07
Palm (date)	0.95	0.95	8	1.5–2.5	0.10
Palm tree	1	1	8	0.7–1.1	0.07
Peach (60–70% CC)*	1.1	0.65	3	1.0–2.0	0.10
Pear (60–70% CC)*	1.1	0.75	4	1.0–2.0	0.10
Pineapple	0.3	0.3	0.6–1.2	0.3–0.6	0.10
Pistachio (60–70% CC)*	1.1	0.45	3–6	1.0–1.5	0.12
Plum (60–70% CC)*	1.1	0.65	3	1.0–2.0	0.10
Rubber trees	1	1	10	1.0–1.5	0.12
Tea (non-shaded)	1	1	1.5	0.9–1.5	0.12
Tea (shaded)	1.15	1.15	2	0.9–1.5	0.11
Walnut (70% CC) *	1.1	0.65	4–5	1.7–2.4	0.10
Horticultural crops					
Artichokes	1	0.95	0.7	0.6–0.9	0.11
Asparagus	1	0.3	0.2–0.8	1.2–1.8	0.11
Bean (green)	1.1	0.95	1.5	0.5–0.7	0.11
Beet (table)	1.1	0.95	0.2	0.6–1.0	0.10
Broccoli	1.05	0.95	0.3	0.4–0.6	0.11
Brussel sprouts	1.05	0.95	0.4	0.4–0.6	0.11
Cabbage	1–1.1	0.9–1	0.4	0.5–0.8	0.11
Carrots	1.05	0.95	0.3	0.5–1.0	0.13
Cauliflower	1.05	0.95	0.4	0.4–0.7	0.11
Celery	1.05	1	0.6	0.3–0.5	0.16
Cucumber	1	0.75–0.9	0.3	0.7–1.2	0.10
Eggplant	1.05	0.9	0.8	0.7–1.2	0.11
Faba bean (fresh)	1.1	0.9	0.8	0.5–0.7	0.11
Lettuce	1–1.05	0.95	0.3	0.3–0.5	0.14
Melon	1.05–1.1	0.7–0.75	0.4	0.8–1.5	0.12
Melon (cantaloupe)	0.85	0.6	0.3	0.9–1.5	0.11
Mint	1.15	1.1	0.6–0.8	0.4–0.8	0.12
Peas (fresh)	1.2	1	0.7	0.6–1.0	0.13
Pepper	1.05–1.15	0.70–0.90	0.7	0.5–1.0	0.14
Pumpkin, winter squash	1	0.8	0.4	1.0–1.5	0.13
Radish	0.9	0.85	0.3	0.3–0.5	0.14

(continued)

Crop species	*Kc mid*	*Kc end*	Max. crop height (m)	Max. root depth (m)	F_{AD}
Spinach	1	0.95	0.3	0.3–0.5	0.16
Squash, zucchini	0.95–1.0	0.75–0.9	0.3	0.6–1.0	0.10
Strawberries	0.85	0.75	0.2	0.2–0.3	0.16
Tomato	1.15–1.25[b]	0.70-0.90	0.6	0.7–1.5	0.12
Watermelon	1	0.75	0.4	0.8–1.5	0.12
Legumes					
Beans (Phaseolus)	1.1–1.25	0.3–0.9	0.4	0.6–0.9	0.11
Beans (lima)	1.1	0.5	0.5	0.8–1.2	0.11
Chick pea	1	0.35	0.4	0.6–1.0	0.10
Faba bean (broad bean)	1.15–1.25	0.3–1.1	0.8	0.5–0.7	0.11
Green gram and cowpeas	1.05	0.3–0.6	0.4	0.6–1.0	0.11
Groundnut (peanut)	1.15	0.6	0.4	0.5–1.0	0.10
Lentil	1.1–1.2	0.3–0.5	0.5	0.6–0.8	0.10
Peas	1.15	0.3–1.1	0.5	0.6–1.0	0.12
Soybeans	1.15–1.25	0.5	0.5–1.0	0.6–1.3	0.10
Roots, tubers, and bulbs					
Cassava (year 1)	0.8	0.3	1	0.5–0.8	0.13
Cassava (year 2)	1.1	0.5	1.5	0.7–1.0	0.12
Garlic	1–1.2	0.7–1.05	0.5	0.3–0.5	0.14
Onions	1–1.1	0.75–1	0.3–0.5	0.5–0.8	0.14
Parsnip	1.05	0.95	0.4	0.5–1.0	0.12
Potato	1.15–1.25	0.70–0.80	0.6	0.4–0.6	0.13
Sugar beet	1.2	0.7	0.5	0.7–1.2	0.09
Sweet potato	1.15	0.65	0.4	1.0–1.5	0.10
Turnip (and rutabaga)	1.1	0.95	0.6	0.5–1.0	0.10
Sugar, oil, and fiber crops					
Cotton	1.15–1.25	0.4–0.7	1.2–1.5	1.0–1.7	0.07
Castor bean	1.15	0.55	0.3	1.0–2.0	0.10
Flax	1.1	0.25	1.2	1.0–1.5	0.10
Hops	1.05	0.85	5	1.2	0.10
Rapeseed, canola	1.1	0.35	0.6	1.0–1.5	0.08
Safflower	1.1	0.25	0.8	1.0–2.0	0.08
Sesame	1.1	0.25	1	1.0–1.5	0.08
Sisal	0.4–0.7	0.4–0.7	1.5	0.5–1.0	0.04
Sugar cane	1.25	0.75	3	1.2–2.0	0.07
Sunflower	1.2	0.35–0.5	2	0.8–1.5	0.11
Tobacco	1.15	0.8	1.5–2.0	0.8	0.10

[a]Lower value is the seasonal average; higher value is at full cover-before cutting
[b]When cultivated on stalks, the $K_{c\ mid}$ should be increased by 0.05–0.1

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Part II

Crop Productivity

Crop Development and Growth

11

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Abstract

Growth of crops, plants, or plant parts is defined as the irreversible increase in size, whereas development is the continuous change in plant form and function with characteristic transition phases. Growth is primarily associated with the capture and allocation of resources, whereas development is mostly related to non-resource environmental cues such as temperature, photoperiod, and light quality. We separate development and growth conceptually, but both types of processes are closely linked. Thermal time and variations of thermal time corrected to account for photoperiod and vernalization are useful to model crop phenological development. Crop development, in particular the time of flowering, is one of the most important traits for crop adaptation. Breeders, agronomists, and growers understand the importance of matching the pattern of phenological development to their particular environments and use a combination of genetic and agronomic tools to manipulate development. Crop growth depends on (i) the capacity of the canopy to capture CO_2 and radiation and the capacity of the root system to capture water and nutrients from the soil, (ii) the efficiency of the crop to transform resources (water, nutrients, radiation, carbon dioxide) into dry matter, and (iii) the partitioning of dry matter among plant parts. Stresses such as water deficits or soil compaction reduce growth by reducing the amount of resources captured by the crop, by reducing the efficiency in the use of resources, or both.

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11.1 Introduction

Growth of crops, plants, or plant parts is defined as the increase in size or mass, whereas *development* is the qualitative change in plant form and function with characteristic transition phases. The expansion of a leaf or the accumulation of crop biomass is typically a growth process, whereas the transition from a vegetative meristem, producing leaves, to a reproductive meristem producing flowers is a characteristic developmental process. We distinguish morphological development (e.g., appearance of successive structures in the plant) from phenological or phasic development, which deals with the duration of the different phases of the crop cycle.

The distinction between growth and development is important for two reasons. First, growth is primarily associated with the capture and allocation of resources, whereas development is mostly related to non-resource environmental cues such as temperature, photoperiod, and light quality. Second, the physiological processes involved are different, as discussed in this chapter. Whereas we separate growth and development conceptually, organs, plants, and crops grow and develop simultaneously, and for many agronomically important traits, the limits between growth and development are blurred. For example, a wheat grain grows, i.e. it expands in volume, and gains mass and also develops, e.g. leaf and root primordia are differentiated in the embryo. Developmental biology (Box 11.1) and crop growth analysis are thus distinct perspectives underpinning the investigation of development and growth. In this chapter, we outline agronomically important aspects of these processes.

Box 11.1: Developmental Biology

The fundamental question of developmental biology is this: how do different cellular phenotypes emerge from cells that share a common set of genes? A typical flowering plant has 30 different cell types, whereas a typical vertebrate has about 120 cell types. All this diversity has to be explained in terms of differential gene expression, as the 30 or so cell types in a plant share the same genome—genetically, the cells of the wheat root endodermis and the mesophyll cells in the flag leaf of the same plant are essentially identical. Likewise, your neurons and liver cells are genetically identical, but their shape and physiology are different. For readers interested in this question, we recommend the book by Mary Jane West-Eberhard: Developmental plasticity and evolution (Oxford University Press, 2003).

Some examples demonstrate the practical implications of understanding the process of cell differentiation. Stem cells, which are undifferentiated cells with the potential to generate any cell type, present animal and human health with potential opportunities for new therapies. Short time between generations is one of the cornerstones of successful plant breeding programs. Making use of advanced knowledge of cell differentiation and tissue culture, breeders can currently grow up to six generations of chickpeas in a single year. Likewise, tissue culture exploiting the principles of cell differentiation is a rapid, effective, and cheap method to generate virus-free seedlings of high value in horticulture.

11.2 Phenological Development

Scales have been devised to characterize phenological development in annual and perennial crops. They are based on the concept of phenostage; major phenostages in annual crops include

1 Sowing
2 Germination
3 Emergence
4 Juvenile phase/initiation of leaves
5 Floral initiation (formation of primordia of reproductive structures)
6 Flowering
7 Physiological maturity
8 Harvest maturity

The case of perennial species is more complex. Trees stay in the juvenile phase, thus not flowering, for several years after seed germination. However, most trees of agricultural interest are not propagated by seeds but vegetatively from cuttings that are rooted in nurseries. In this case, the cutting may not be juvenile, which reduces the time until flowering. In some tree species, the growth of the main stem beyond a certain length accelerates the end of the juvenile period. Once the juvenile phase is over, the tree will follow annual cycles that resemble those of an annual plant, following two possible strategies:

(a) Deciduous species: Most fruit trees and vines belong to this category. All the leaves fall in autumn-winter in response to cold temperatures and/or short photoperiod. Buds stay dormant during winter and usually require low temperatures for an extended period (chilling requirement) until they respond to warm temperatures and bud break occurs. After that, vegetative and reproductive growth will occur with a degree of overlap that depends on the species. For instance, flowering may occur before leaf growth starts (stone fruits, e.g. peach) or later (pome fruits, e.g. apple), while harvest may occur in early to midsummer (several months before leaf fall, e.g. cherry) or in late summer or start of autumn (e.g., apple).
(b) Evergreen species: They include *Citrus spp*., olive, and tropical fruit trees (e.g., mango). Leaves stay in the tree for long periods (2–3 years). In some cases (e.g., olive), the tree stays dormant (no vegetative growth) during winter and resumes growth in the spring.

The period between two phenostages constitutes a phenophase; we can be interested, for example, in the phase sowing-emergence or emergence-flowering. Some of these phases are well defined biologically, for example, the phase between floral initiation and flowering. Other phases are not defined biologically but with agronomic criteria; for example, the phase from physiological maturity, when grain reaches its maximum dry matter, to harvest maturity, when grains reach a moisture content suitable for mechanical harvest. Harvest maturity of wine grapes is defined by oenological criteria, including sugar concentration and acidity, and complementary traits such as color and aromas. Sugar/acid ratio is an important trait for the decision of harvest in most fruit crops.

The duration of the cycle of different crops is shown in Appendix (Table 11.1).

All phenophases are responsive to temperature, which is the main environmental influence on development (Box 11.2). The phase sowing-emergence is also influenced by the content of water and oxygen in the soil. In sorghum and pulses such as faba bean and chickpea, soil water content also modulates the transition to reproduction. In wheat, mild water deficits accelerate flowering while severe deficits delay it. In some species, photoperiod also affects the duration of some phenophases. Some species and phases are also responsive to low temperatures in a process called vernalization. Here we outline the effects of mean temperature, low temperature (vernalization), and photoperiod on phenological development.

Box 11.2: Phenology and Global Warming

Phenological shifts are the most conspicuous biological signal of global warming. Using a systematic phenological network data set of more than 125,000 observational series of 542 plant and 19 animal species in 21 European countries between 1971 and 2000, it was found that 78% of all leafing, flowering, and fruiting records advanced (30% significantly) and 3% were significantly delayed.

The consequences of warming for agriculture are numerous and varied. At high latitudes, warming is extending the window for cropping, with overall positive implications for crop production. In China and the USA, milder winters are allowing for earlier crop sowing, which combined with new varieties and practices is improving crop production. Climate projections and modelling indicate that Finland's crop productivity by 2050 will be close to the productivity in Denmark in the 2000s. In 2000, the EU has accepted Denmark as a wine-producing country, and the Association of Danish Winegrowers now counts more than 1400 members. In temperate environments like the Pampas, warming over the last few decades has shortened the season of wheat crops, allowing for early sowing and higher yield of soybean in wheat/soybean double cropping. In temperate and subtropical environments, warming is shortening the season of crops, leading to yield reduction in the absence of adaptive practices. Increasing the frequency and incidence of heat waves may reduce both the yield and quality of crops. Thus, the outcomes of warming are complex and varied, particularly when warming interacts with changes in rainfall, but a good deal of crop responses to warming is related to phenological changes.

Another interesting consequence of warming is the decoupling of processes, from ecosystems to molecules. In the last five decades, the productivity of Northern Sea fisheries has declined. The main reason is that warming has "decoupled" the phenology of the components of the trophic web. This means that for example, predators and prey that were phenologically

(continued)

Box 11.2 (continued)
synchronized before are now out of phase, with direct consequences for the structure and function of the whole ecosystem. In red grapevine varieties, warming is decoupling sugars and anthocyanins. This means that fruit reaches sugar maturity with less pigmentation; growers have therefore two choices. They can wait longer to harvest, hence allowing color to develop; this leads to undesirably high sugar and alcohol concentrations. Alternatively, they can harvest at the right sugar level and deal with the lack of color in the winery. The process of decoupling is therefore an agronomically important aspect of warming, which is related to developmental and growth processes.

11.2.1 Effects of Daily Mean Temperature

Figure 11.1 shows the relationship between the daily rate of phenological development (R, day^{-1}) and daily mean temperature (T, °C). The daily rate of development is the inverse of the duration of the phenophase (D, day); for example, if it takes 10 days to complete the phase sowing-emergence, the daily rate of development is 0.1 day^{-1}. The rate of development increases linearly with temperature between the base (T_b) and the optimum temperature (T_o) and decreases between the optimum and maximum temperature (T_m) for development. These three parameters T_b, T_o, and T_m constitute the "cardinal" temperatures for development, which vary with the plant species (and in some cases between varieties) and phenological phase.

The daily rate of development is zero (i.e., the plant does not develop) if the mean temperature is below T_b or above T_m. The concept of "thermal time" (also called *degree days* or heat units) is useful to predict the duration of a phase for different temperatures. Thermal time (TT, °Cd) is defined as the sum of daily mean temperature (T_i, °C), above the base temperature, from the beginning to the end of the phase; for example for the phase sowing-emergence:

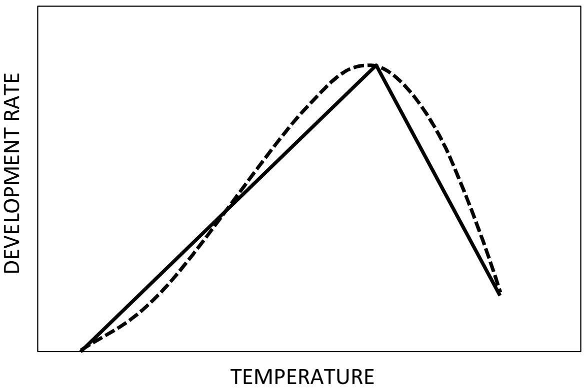

Fig. 11.1 Responses of development rate to temperature. The dashed line represents the actual response and the solid line is a linear approximation

$$TT = \sum_{\text{sowing}}^{\text{emergence}} \left(T_i - T_b\right) \tag{11.1}$$

As the response is linear, we can use the average temperature during the period (T_{avg}):

$$TT = \sum_{\text{sowing}}^{\text{emergence}} \left(T_i - T_b\right) = D\left(T_{avg} - T_b\right) \tag{11.2}$$

So the daily rate of development when the daily mean temperature is between T_b and T_o is

$$R = 1/D = \left(T_{avg} - T_b\right)/TT \tag{11.3}$$

The duration of a phase can thus be calculated if we know the daily mean temperature, the base temperature, and the thermal time required to complete the phase:

$$D = TT/\left(T_{avg} - T_b\right) \tag{11.4}$$

Table 16.1 in Chap. 16 shows T_b and TT for the phase sowing-emergence for several crops. With an adequate supply of water and oxygen, the thermal time required to complete the phase is approximately constant. Thus, we can predict that wheat will take approximately 11 days to emerge at a mean temperature of 10°C [D = 110/(10–0)] and 7 days if the mean temperature is 15°C [D = 110/(15–0)].

Base temperatures have physiological and ecological meaning, as they reflect differences between species and stages and contribute to the coupling of organisms in trophic webs. For example, the base temperature for the sowing-emergence phase is much lower for winter crops than for spring-sown crops (Table 16.1). Base temperatures normally decline from early to late stages in summer crops, e.g., for sunflower and soybean, and increase from early to late stages in winter crops such as wheat. The thermal time model applies not only to plants but also to other organisms including insects, which are—like plants—unable to regulate body temperature. The base temperature for the emergence of bollworms after overwintering in the soil is very close to the base temperature for the sowing-emergence phase of cotton; this coincidence of base temperatures ensures that a new generation of bollworms emerges in synchrony with a suitable food source.

The thermal time model (Eq. 11.2) is a simplification of a more complex response of development to temperature, as it rests on the assumption of a linear relationship between the rate of development and temperature. However, above the optimum temperature, the rate of development declines with increasing temperature, until a maximum temperature (T_m) is reached (Fig. 11.1). For some phenostages, particularly those related to reproduction, development is also responsive to vernalization and photoperiod. In these cases, the thermal time required to complete the phase is not constant but is influenced by low temperatures and day length.

11.2.2 Vernalization and Photoperiod

Annual crops have specific windows of development when grain number, the main yield component, is most affected by environmental stresses such as frost, heat, and water stress (Fig. 11.2). These windows vary but are more or less centered on flowering in most crops. For this reason, mechanisms have evolved that reduce the probability of coincidence of extreme stress and the most sensitive developmental stages. These mechanisms are based on two environmental cues: vernalization and photoperiod. Flowering time is indeed one of the most important traits for crop adaptation to particular environments in agricultural systems. Consider, for example, wheat in a Mediterranean region. If it flowers too early, a significant frost risk would reduce seed production in some seasons. If it flowers too late, frost risk is reduced at the expense of increased risk of heat and water stress. Early wheat varieties introduced to Australia reached flowering at 125 days after sowing, hence exposing the sensitive reproductive window to a high frequency of heat and water stress. Recognizing this problem, breeders selected for shorter-season varieties, which were better adapted to their environments. When compared under the same conditions, the time from sowing to anthesis was 119 days for cultivars released earlier than 1950 and 108 days for cultivars introduced later. Rain-fed sunflower in southern Spain grows on stored soil water that is depleted during the growing season. In these environments, hybrids with very long cycles may deplete soil water reserves during a long vegetative stage thus suffering a more severe water deficit during grain filling than short-cycle hybrids. To manipulate the timing of key phenological events, plant breeders make use of fundamental genetic understanding including the manipulation of vernalization and photoperiod genes in selecting varieties adapted to

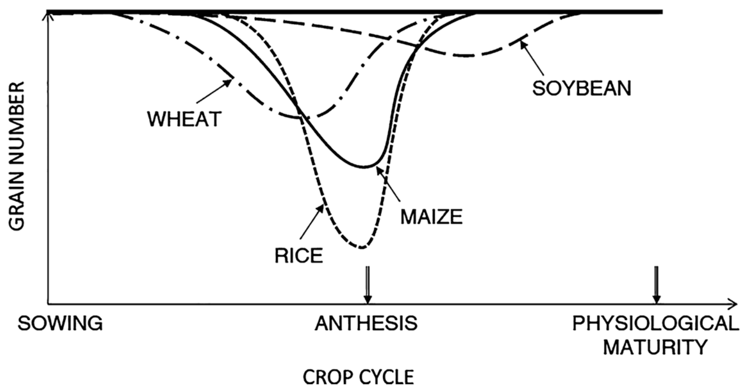

Fig. 11.2 Critical period for grain number determination, the main yield component of annual crops. Grain number is presented in an arbitrary scale where the *vertical line* represents 100%, of the grain number in unstressed controls. Deviations from this line represent reductions due to stress in different periods of the crop cycle. (Source: Calviño and Monzon (2014) in Sadras and Calderini and Hsiao TC 1982. In: Drought resistance of crops with emphasis on rice. IRRI, Los Baños, Manila, Philippines, p 39–52)

particular environments. To manipulate the timing of key phenological events, growers combine two practices: cultivar selection and sowing date.

Vernalization is a response to low temperatures necessary for some plants to become competent for the transition to the reproductive phase (Box 11.3). The plant apex may sense vernalizing temperatures since seed imbibition, throughout the vegetative phase. Vernalization requirements are characteristic of temperate crops such as wheat, barley, *Brassica spp.*, and field pea. In many of these species, "winter" types require vernalization, whereas "spring" types have little or no vernalization requirements. For instance, for winter wheat, temperatures between 0 and 8°C are the most effective, although vernalization happens with temperatures up to 15°C. Vernalization may be reversed by high temperatures (usually >20°C), in a process known as "devernalization." In some species, vernalization combines with photoperiod to modulate the time of flowering.

Vernalization is also important in horticultural crops. In biennial plants such as sugar beet and carrot, vernalization modulates the development of flower buds in the second year of growth. In proteranthous perennials (i.e., those that flower before leafing) vernalization modulates flowering time. In horticulture, the vernalization requirement is also known as "chilling hours," which is the time below a species-specific base temperature. Understanding vernalization requirements is important to determine the geographical limits and risks of growing particular crops. Apple trees, for example, have a high vernalization requirement, hence they cannot be grown successfully in warm-winter environments where these requirements are not met. Almond trees have a relatively low vernalization requirement, and this implies the risk of early flowering with subsequent yield losses due to frost. Breeders have selected horticultural perennials with a broad range of vernalization requirements to extend their cropping areas and reduce risks of crop failure. Agronomists have developed technologies to partially compensate for insufficient chilling. For example, farmers in warm locations with a high risk of suboptimal chilling in South-Eastern Australia, spray winter oil in pistachio orchards to support commercially viable yield (Fig. 11.3).

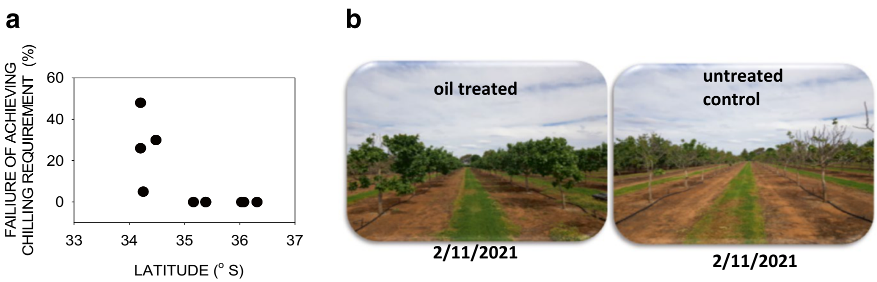

Fig. 11.3 (**a**) The risk of failure to reach the required chilling units for pistachio reproduction and yield in a latitudinal gradient in South-Eastern Australia. (**b**) Winter oil spraying favors uniform bud burst and flowering. Oil treatment was 5.1% petroleum oil at 1200 L/ha in late August 2021. (Data and picture courtesy of Dr. M. Mahadevan)

Virtually in all plant species, photoperiod-sensitive genotypes can be found, or rather, genotypes sensitive to the duration of the night. Gardner and Allard classified annual species into two categories: long-day plants and short-day plants. The short-day plants accelerate their development (shorten the time to flowering) when the days are short, while long-day plants develop faster if the days are long.

Small grains (wheat, barley, oats, and rye) are long-day species, while maize, rice, sorghum, and soybeans are short-day species. However, within each species, there is often great variability in sensitivity to photoperiod. In general, photoperiod response is quantitative, i.e. development rate increases or decreases with the photoperiod but never becomes zero, which would be a qualitative response. By manipulating photoperiod genes in soybean, varieties have been developed that can be grown between high latitudes in the northern hemisphere to the tropics; a classification system of maturity types, with 00 the shortest (90 days) and VIII the longest season (190 days) shows the wide range of phenological patterns in soybean.

11.2.3 Soil Water Content

Figure 11.4 presents two contrasting examples of the influence of soil moisture on plant phenological development. In a collection of seven sorghum lines, the effect of drought on time to panicle initiation ranged from insignificant in fast-developing lines to 19 days delay in their slow-developing counterparts (Fig. 11.4a). In a collection of 20 chickpea lines grown in eight environments, water deficit accelerated flowering (Fig. 11.4b). The effect depended on genotype, with a larger response to soil water in slow-developing types. The mechanisms of these responses are largely unknown and attempts to include soil moisture in models of crop phenology are incipient.

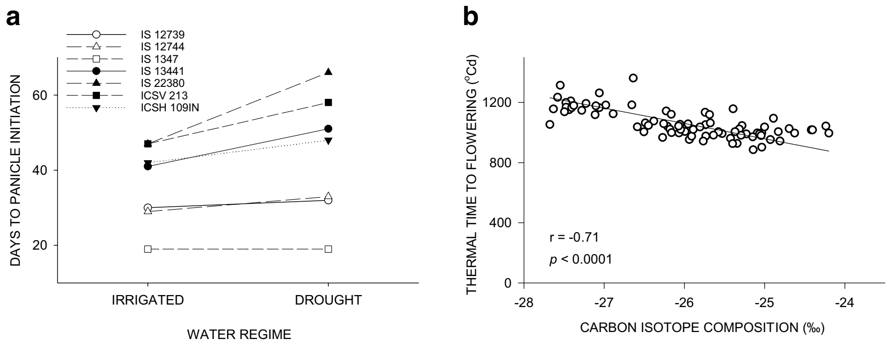

Fig. 11.4 Effect of water stress on crop phenology. (**a**) Time from sowing to panicle initiation in seven lines of weekly-irrigated sorghum in comparison to droughted crops grown with stored soil water. (**b**) Thermal time from sowing to flowering as a function of carbon isotope composition for 20 chickpea lines in eight environments. A more negative carbon isotope composition indicates a higher intensity of water stress. (Source: (**a**) Craufurd et al. 1993. Exp Agr 29:61–76. (**b**) Li et al. 2022. J Exp Bot 73:4981–4995)

Box 11.3: Lysenko and Vernalization
Trofim Lysenko (1898–1978) was a Ukrainian agronomist very influential in the Soviet Union first and later in China. He coined the term "vernalization" as the conversion of winter to spring crop types by applying cold to seeds before sowing. His success within the ranks of the soviet elite led him to be the main controller of agricultural science in the Soviet Union for almost 40 years. He contributed to the destruction of genetics as a discipline in the USSR (including the death of many good scientists) and to the propagation of pseudoscientific ideas about heredity, negating the existence of genes. His ideas were close to Lamarckism as they would fit Marxism theory better.

11.3 Morphological Development

The architecture of the plant is under genetic control and is modulated by environmental factors including temperature, photoperiod, and light quality. Agronomically, the architecture of the crop is important because it influences traits such as lodging, harvestability, competition with weeds, responses to herbivory, and distribution of light and chemicals in the canopy profile. The node where the first pod is set is an important trait of grain legumes, as genotypes with pods too close to the ground cannot be harvested effectively. The introduction of semi-dwarf genes in rice and wheat has led to significant improvements in crop production, and part of the success of these semi-dwarf crops is related to their improved architecture, which allows for higher nutrient inputs with reduced lodging risk. Shorter phenotypes with more erect canopies are less competitive and therefore more reliant on effective weed control; Chap. 12 further develops the relations between competitive ability and crop yield.

Plants have numerous meristems (buds) that can follow one of three fates: they can remain dormant, they can activate to produce vegetative structures, or they can become reproductive structures. Different species combine different meristem allocation strategies, which involve trade-offs. For example, the adaptation of grasses to browsing and their exploitation in agriculture is directly related to their underground, dormant meristems that allow re-growth after grazing. Plants with profuse branching or tillering are more able to fill gaps originating, for example, from failures in sowing or damage by pests or diseases. As an example of trade-off, strong apical dominance, whereby most lateral buds are dormant, favors growth in height, competition for light, and capacity to recover after herbivory, at the expense of limited capacity for growth and reproduction, and constraints to expand into neighboring gaps.

Interactions between neighboring plants influence the morphology of individual plants and the final architecture of the crop. Some of these interactions are mediated by the ability of plants to sense changes in the quantity, quality, and direction of light, which in turn triggers developmental responses called photomorphogenesis. The main groups of photoreceptors involved in plant photomorphogenesis are the red (*R*)/far-red (*FR*) light-absorbing phytochromes and the blue/*UV-A* light-absorbing cryptochromes and phototropins. As the green tissue of plants differentially reflects and absorbs light of different wavelengths, plants can detect the presence of neighbors by detecting changes in the spectral composition of light, and in particular, reductions in the *R/FR* ratio. Typically, a shade-avoidant plant responds to neighbors by extending internodes, increasing stem:leaf ratio, reducing activation of lateral buds, producing more erect shoots, and in some cases advancing the time of flowering. In some weeds, germination can be triggered by changes in the *R/FR* ratio associated with soil cultivation. Light signals interacting with the central circadian oscillator enable plants to monitor photoperiod and adjust the timing of the transition from vegetative to reproductive development (Sect. 11.2.2). It has recently been discovered that the light receptor phytochrome *B* (*phyB*) is also a temperature sensor involved in morphological and developmental responses to temperature called thermomorphogenesis. Common sensors and common metabolic pathways are incipient elements for the integration of plant responses to temperature and light.

The successive appearance of plant leaves is an important component of morphological development. In general, the thermal time between the appearance of two consecutive leaves, known as phyllochron, is constant. For example, wheat has a phyllochron around 100°C d with a base temperature of 0°C. In sunflowers, the phyllochron is around 20°C d with a base temperature of 4°C.

11.4 Growth

Box 11.4 outlines the methods used to quantify crop growth. Crop growth depends on the capacity of the canopy to capture CO_2 and radiation, the capacity of the root system to capture water and nutrients from the soil, and the efficiency of the crop to transform resources (water, nutrients, radiation, carbon dioxide) into biomass (Fig. 11.5). Some environmental factors, such as ambient temperature or soil salinity modulate the rate of capture of resources and the efficiency in the transformation of resources in plant biomass. Other chapters deal in detail with the capture and efficiency in the use of radiation (Chap. 13), water (Chap. 14), and nutrients (Chaps. 26, 27, and 28).

The capture and efficiency in the use of resources changes with the stage of phenological development. The growth of a typical annual crop is characterized by a sigmoid curve (Fig. 11.6) with three phases. First, in a lag phase, plants grow slowly, as they mostly depend on seed reserves, whereas small root and canopy systems

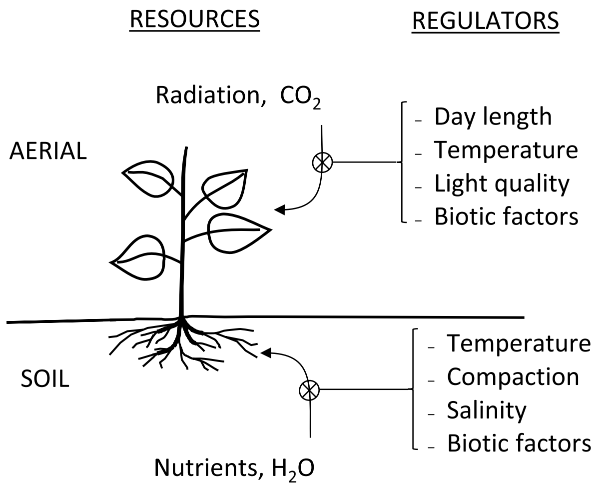

Fig. 11.5 Crop growth depends on the ability of crops to capture above-ground and soil resources and on the capacity of crops to transform these resources into biomass. Environmental factors (regulators) modulate the rate of capture and the efficiency in the transformation of resources. (Adapted from Sadras and McDonald. 2012. Water use efficiency of grain crops in Australia: principles, benchmarks and management. Grains Research and Development Corporation, Canberra)

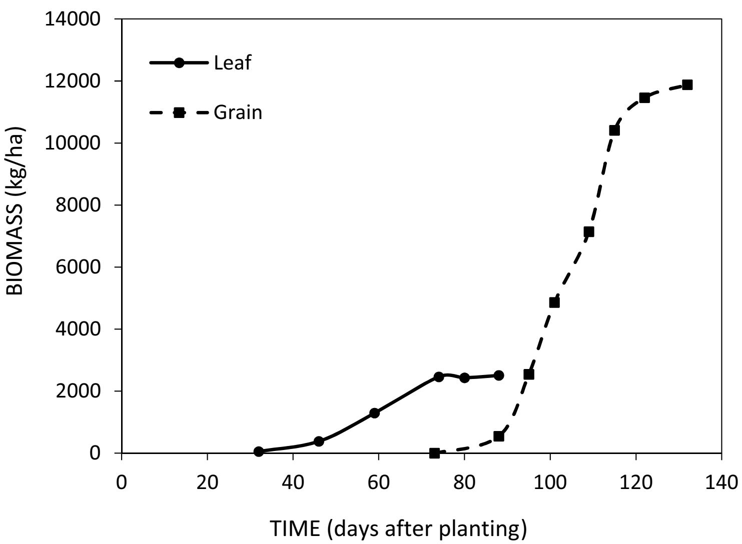

Fig. 11.6 Time course of biomass of leaves and grain of a maize crop in Florida. (Data were taken from DSSAT 4.6, experiment UFGA8201MZ)

constrain their capacity to capture resources. Many practices (e.g., sowing date, fertilizer) seek to reduce the duration of this lag phase, also known as "period lost to growth." Second, the growth increases rapidly to reach a linear phase when a sufficiently large canopy and root system allow for a high capacity to capture resources. Third, crop growth slows down as both canopy and root systems age, entering a senescence phase in parallel to the accumulation of carbon and nitrogen in reproductive organs. The senescence of leaves and roots is genetically driven by a process known as monocarpic senescence, whereas stresses such as shortage of water or nutrients may accelerate the process.

Figure 11.7 illustrates the relationship between crop growth and the capture of resources in crops with favorable and stressful conditions. As the season progresses, and roots and canopies expand, the crop captures more soil and above-ground resources. A straight line represents increasing growth with increasing resource capture. Stresses such as deficit of nutrients or soil compaction reduce growth through two processes: reducing the amount of resources captured by the crop (horizontal arrow in Fig. 11.7) reducing the efficiency in the use of resources. The vertical arrow in Fig. 11.7 indicates the reduction in growth for the same amount of resource captured; this means lower efficiency.

In general, shortage of resources (water or nutrient deficits) and soil constraints (compaction, salinity) reduce crop growth by reducing first the capture of resources, while the efficiency in the use of resources is affected later, as the constraints become more severe.

Ambient temperature influences growth directly, by changing the rate of processes such as cell division, leaf expansion, and crop photosynthesis, and indirectly by affecting phenological development and the duration of key phenophases, as

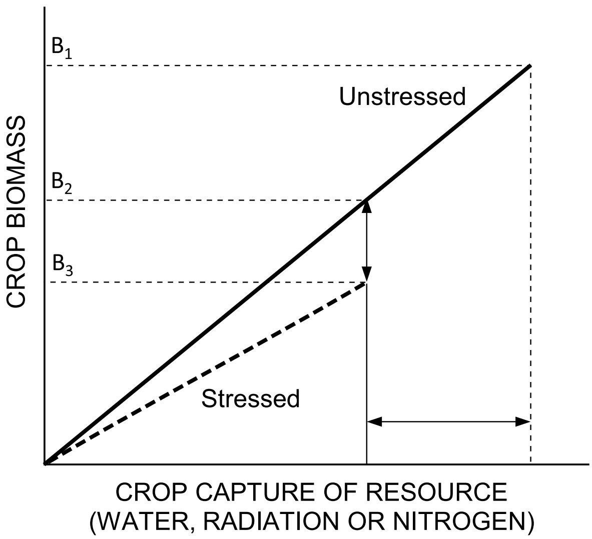

Fig. 11.7 Crop biomass increases with increasing capture of resources, primarily water, radiation, and nitrogen. Maximum crop biomass is shown as B_1. Stress reduces crop growth by reducing the capture of resources (horizontal arrow) resulting in B_2, reducing production per unit resource (vertical arrow), or both, which leads to B_3

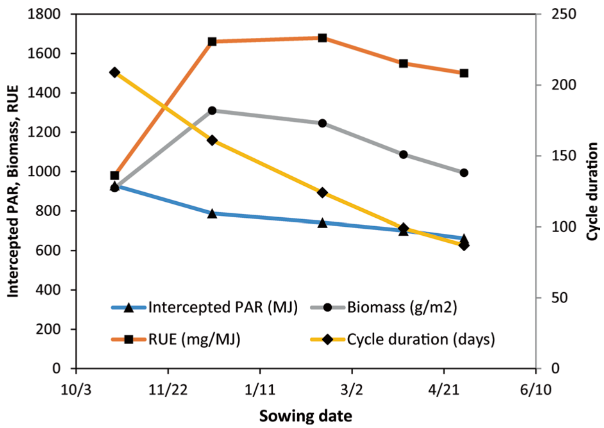

Fig. 11.8 Effect of sowing date on crop duration (time sowing maturity), intercepted Photosynthetically Active Radiation (*PAR*), Radiation Use Efficiency (*RUE)*, and biomass production of *Vicia faba*. (Adapted from Confalone et al. 2010. Field Crops Res 115:140–148)

discussed before. Within agronomically sensible ranges, the main effect of temperature on crop production is related to the modulation of phenological development. In temperate environments, late sowing shifts the crop cycle to warmer conditions, development proceeds faster, the period available to capture resources and growth is reduced, and biomass at maturity is normally lower. Figure 11.8 illustrates the interplay between development and growth in faba bean crops sown between October (autumn) and early May (spring) in Lugo, Spain. As the sowing is delayed, both temperature and photoperiod increase. This shortens the phenophases of the crop, resulting in a reduction of the crop cycle from 209 to 87 days. With shorter cycle duration, the peak leaf area is reduced, the amount of radiation captured by the crop is reduced, and the final production of biomass is also reduced. Hence, the effects of temperature and photoperiod on development (cycle length) have a dominant role in seasonal growth. Of interest, the first sowing date does not conform to this pattern. For the earliest sowing, the crop has the longest cycle duration and the highest capture of radiation as expected; therefore, it should also have the highest biomass. However, it has the lowest biomass. The explanation is that the extremely low temperature in the earliest sowing reduced the photosynthetic efficiency of the crop. In this case, the physiological response (photosynthesis) was stronger than the developmental response.

Box 11.4: Quantification of Crop Growth

Depending on the objectives of measurements, we could be interested in describing growth in terms of crop height, leaf surface area, fruit volume, or grain mass. As crop growth depends on the capture of resources, and this is in turn related to the size of the canopy and root system, we often use the leaf area index (*LAI*, m^2 leaf/m^2 ground) to measure the size of the canopy and the rooting depth and density characterized as Root Length Density (L_v, m root/m^3 soil) to quantify the size of the root system. *LAI* is the ratio of leaf area (assuming single-sided leaves) and ground area and L_v is the length of roots per unit of soil volume. For many agronomic applications, shoot mass is measured by taking crop samples (e.g., 1 m^2 of crop cut to ground level), which are dried to constant weight to express the dry matter in g/m^2 or kg/ha; this measure of dry matter is also called biomass. Periodic sampling of biomass combined with periodic measurements of radiation interception, nutrient uptake, and evapotranspiration allows for calculating the efficiency in the use of radiation, nutrients, and water as illustrated in Fig. 11.7.

Indirect methods are also used for quantifying biomass or *LAI*. For trees, empirical relationships between biomass and trunk diameter have been widely used. Transmittance of *PAR* or reflectance of radiation in different wavelengths (e.g., red and far red) (see Chap. 3) may be related to *LAI* and is the base of most indirect methods for non-destructive measurement of *LAI*.

Appendix

Table 11.1 Durations of phases of the growth cycle (FAO method; Chap. 10) for different crop species and climatic areas

			Duration of crop stage				
Crop species	Climate	Sowing date	A	B	C	D	Total
Horticultural crops							
Artichoke (year 1)	M	April	40	40	250	30	360
Artichoke (year 2)	M	May	20	25	250	30	325
Asparagus	M-warm winter	Feb	50	30	100	50	230
Asparagus	M	Feb	90	30	200	45	365
Beets (table)	M	Apr/May	15	25	20	10	70
Broccoli	A	Sept	35	45	40	15	135
Brussel sprouts	M	Feb/April	20–25	30–35	20–25	10	80–95
Cabbage	A,M	Sept	40	60	50	15	165
Cabbage	M	Feb/April	20–25	30–35	20–25	10	80–95
Melon (cantaloupe)	M-warm winter	Jan	30	45	35	10	120
Melon (cantaloupe)	M	Aug	10	60	25	25	120

(continued)

Table 11.1 (continued)

Crop species	Climate	Sowing date	Duration of crop stage				
			A	B	C	D	Total
Carrots	A	Oct/Jan	20	30	40	20	110
Carrots	M	Feb/Mar	30	40	60	20	150
Carrots	A	Oct	30	50	90	30	200
Cauliflower	A	Sept	35	50	40	15	140
Celery	SA	Oct/Jan	25–30	40–55	95–105	20	180–210
Celery	M	April	25	40	45	15	125
Cucumber	A	May-August	20	30	40	15	105
Cucumber	A-warm winter	Nov/ Feb	25	35	50	20	130
Eggplant	A	October	30	40	40	20	130
Eggplant	M	May/June	30	45	40	25	40
Lettuce	M	April	20	30	15	10	75
Lettuce	M	Nov/Jan	30	40	25	10	105
Lettuce	A	Oct/Nov	25	35	30	10	100
Lettuce	M	Feb	35	50	45	10	140
Melon	M	March/May	25–30	30–35	40–50	20–30	120–140
Melon	A	Aug	15	40	65	15	135
Melon	A	Dec/Jan	30	45	65	20	160
Onion (dry harvest)	M	April	15	25	70	40	150
Onion (dry harvest)	A	Oct/ Jan	20	35	110	45	210
Onion (green harvest)	M	April/May	25	30	10	5	70
Onion (green harvest)	A	October	20	45	20	10	95
Pepper	T & M	April/June	30	35	40	20	125
Pepper	A	October	30	40	110	30	210
Pumpkin, winter squash	M	Mar, Aug	20	30	30	20	100
Pumpkin, winter squash	T	June	25	35	35	25	120
Radish	M, T	Mar/Apr	5	10	15	5	35
Radish	A	Winter	10	10	15	5	40
Spinach	M	Apr; Sep/Oct	20	20	20	5	65
Spinach	A	November	20	30	40	10	100
Squash, zucchini	M, A	Apr; Dec.	25	35	25	15	100
Squash, zucchini	M,T	May/June	20	30	25	15	90
Tomato	A	January	25–30	40	40–70	30	135–155
Tomato	M	Apr/May	35	40	50	30	155
Tomato	A	Oct/Nov	35	45	70	30	180
Water melon	M	April	20	30	30	30	110
Water melon	A	May/Aug	10	20	20	30	80
Roots, tubers, and bulbs							
Cassava (year 1)	T	rainy season	20	40	90	60	210
Cassava (year 2)	T		150	40	110	60	360
Potato	SA	Jan/Nov	25	30	40	30	125
Potato	C	April/May	25–30	30–35	45–50	30	130–145
Potato	C	Apr/May	45	30	70	20	165
Potato	A	Dec	30	35	50	25	140

(continued)

Table 11.1 (continued)

Crop species	Climate	Sowing date	Duration of crop stage				
			A	B	C	D	Total
Sweet potato	M	April	20	30	60	40	150
Sweet potato	T	Rainy seas.	15	30	50	30	125
Sugar beet	M	March/April	25–30	35–45	50–80	20–50	160–180
Sugar beet	M	Oct/Nov	45	75	80	30	230
Sugar beet	A	Sept/Nov	25–35	60–65	70–100	40–65	205–255
Sugar beet	C	April	50	40	50	40	180
Legumes							
Beans (Phaseolus) (green)	M	Feb/Mar	20	30	30	10	90
Beans (Phaseolus) (green)	M, A	Aug/Sep	15	25	25	10	75
Beans (Phaseolus) (dry seed)	C	May/June	20–25	25–30	30–40	20	100–110
Beans (Phaseolus) (dry seed)	M	June	15	25	35	20	95
Faba bean, broad bean (green)	C, M	Mar/May	15–20	25–30	35	15	90–100
Faba bean, broad bean (green)	C,M	Oct	90	45	40	0	175
Faba bean, broad bean (dry seed)	C,M	Nov	90	45	40	60	235
Green gram, cowpeas	M	March	20	30	30	20	110
Groundnut (peanut)	T	Dry season	25	35	45	25	130
Groundnut (peanut)	C, high latitude	Spring	35	35	35	35	140
Groundnut (peanut)	M	May/June	35	45	35	25	140
Lentil	C	April	20	30	60	40	150
Lentil	A	Oct/Nov	25	35	70	40	170
Peas	C	May	15	25	35	15	90
Peas	C,M	Nov, Mar–Apr	20–35	25–30	30–35	15–20	100–110
Soybeans	T	Dec	15	15	40	15	85
Soybeans	C, high latitude	May	20	25–35	60–75	25–30	140–150
Sugar, oil, and fiber crops							
Castor beans	SA	March	25	40	65	50	180
Castor beans	T	Nov.	20	40	50	25	135
Cotton	M,A	Mar-May (M), Sept. (A)	30	50	50–65	45–55	180–195
Cotton	A	Mar	45	90	45	45	225
Flax	C	April	25	35	50	40	150
Flax	A	October	30	40	100	50	220
Hops	C	April	25	40	80	10	155
Safflower	M, A, SA	March/April	20–25	35	45–55	25–40	125–145

(continued)

Table 11.1 (continued)

Crop species	Climate	Sowing date	Duration of crop stage				
			A	B	C	D	Total
Safflower	A	Oct/Nov	35	55	60	40	190
Sesame	C	June	20	30	40	20	100
Sugarcane, virgin	T, low latitude		35	60	190	120	405
Sugarcane, virgin	T		50	70	220	140	480
Sugarcane, virgin	Pacific		75	105	330	210	720
Sugarcane, ratoon	T, low latitude		25	70	135	50	280
Sugarcane, ratoon	T		30	50	180	60	320
Sugarcane, ratoon	Pacific		35	105	210	70	420
Sunflower	M	April/May	25	35	45	25	130
Sunflower	M-warm winter	Feb	45	40	60	25	170
Cereals and pseudocereals							
Barley, oats, wheat (spring types)	Central India	November	15	25	50	30	120
Barley, oats, wheat (spring types)	Mid latitude	March/Apr	20–40	25–30	40–60	20–30	130–135
Barley, oats, wheat (spring types)	East Africa	July	15	30	65	40	150
Barley, oats, wheat (spring types)	C	Nov	40	60	60	40	200
Barley, oats, wheat (spring types)	M	Dec	20	50	60	30	160
Winter wheat	M-warm winter	December	20	60	70	30	180
Winter wheat	M	November	30	140	40	30	240
Winter wheat	C	October	160	75	75	25	335
Grains (small)	M	March-April	20	30	60	40	150
Grains (small)	A	Oct/Nov	25	35	65	40	165
Maize (grain)	A	Dec/Jan	25	40	45	30	140
Maize (grain)	T	June	20	35	40	30	125
Maize (grain)	C (dry, cool)	October	20	35	40	30	125
Maize (grain)	M,C	March-April	30	40	50	30–50	150–170
Maize (sweet)	T	March	20	20	30	10	80
Maize (sweet)	M	May/June	20	25	25	10	80
Maize (sweet)	A	Oct/Dec	20	30	40	10	100
Maize (sweet)	C	April	30	30	30	103	110
Maize (sweet)	M-warm winter	Jan	20	40	70	10	140
Millet	A	June	15	25	40	25	105
Millet	C	April	20	30	55	35	140

(continued)

Table 11.1 (continued)

Crop species	Climate	Sowing date	Duration of crop stage				
			A	B	C	D	Total
Sorghum (grain)	C,M	May/June	20	35	40	30	130
Sorghum (grain)	A	Mar/April	20	35	45	30	140
Rice	T,M	Dec; May	30	30	60	30	150
Rice	T	May	30	30	80	40	180
Forages							
Alfalfa *	frost free period		10	30	-	-	variable
Alfalfa *	M	Mar	5	10	10	5	30
Alfalfa *	C	Jun	5	20	10	10	45
Bermuda (for seed)	A	March	10	25	35	35	105
Bermuda (for hay)	A	–	10	15	75	35	135
Grass pasture	Frost free period		10	20	-	-	Variable
Sudan grass (first cutting cycle)	A	Apr	25	25	15	10	75
Sudan grass (other cutting cycles)	A	June	3	15	12	7	37
Fruit trees, vines, and shrubs							
Banana (year 1)	M	Mar	120	90	120	60	390
Banana (year 2)	M	Feb	120	60	180	5	365
Citrus	M	Jan	60	90	120	95	365
Deciduous orchard	C high latitude	March	20	70	90	30	210
Deciduous orchard	M, C low latitude	March	20–30	50–70	120–130	30	240–270
Grape	Low Latitude	April	20	40	120	60	240
Grape	M, C mid latitude	Mar/April	20–30	50–60	40–75	60–80	205–210
Grape	High latitude	May	20	50	90	20	180
Olive	M	March	30	90	60	95	365
Pineapple	T		60	120	600	10	790
Pistachios	M	Feb	20	60	30	40	150
Walnut	C high latitude	April	20	10	130	30	190

Adapted from Doorenbos and Pruitt (1977) and Allen et al. (1998). This Table should be used with caution as the actual duration of phases may change for different regions, cultivars, and weather conditions of each year. * for the first cut cycle, use durations twice the values shown. Cimates: M (Mediterranean), A (arid), SA (semi-arid), C (continental), T (tropical)

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Plant Population Density and Competition

12

Francisco J. Villalobos, Victor O. Sadras, and Elias Fereres

Abstract

Crops respond to plant population density modifying the characteristics of individual plants by changing the number and size of their organs. The yield response to density can be described mathematically by the "Law of Reciprocal Yield." Mortality of individuals occurs when density is very high. The effect is more pronounced when environmental conditions are suitable (e.g., high fertility). Yield–density curves can be asymptotic or parabolic, although the latter may reflect the existence of an additional limiting factor (e.g., water or nutrients). In general, the spatial variability in plant population density leads to yield losses that are higher when the yield–density response is a parabolic curve.

12.1 Introduction

Plant population dynamics studies the temporal variation in the number of individuals and their attributes. These aspects are important to understand the productivity of crops, especially to evaluate the effect of plant population density on yield. Population dynamics also helps us understand intra-specific competition, e.g., between neighboring wheat plants in a crop (Box 12.1), and inter-specific competition, e.g. between weed and crop plants. These processes are critical for the establishment and productivity of annual crops and for pasture longevity.

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12.2 Density and Competition

A crop is a plant population with individuals of the same genotype and similar age. The availability of resources changes in time and space and may limit crop growth and cause competition between neighboring plants. Unlike animals, higher plants show great plasticity in their growth and in their form, in response to the stress imposed by competition. Thus, the structure of individual plants is set to respond to competition stress by varying the rate of formation, growth, or mortality of their organs (leaves, branches, stems, fruits, roots, etc.). The response may involve changes in the size of the individuals, their shape or the number of individuals.

The growth rate of a plant population is proportional to density in the early stages of development. This proportionality is later reduced as the competition for resources among plants increases which leads to a phase when crop growth rate is independent of the density. The higher the initial density, the sooner the competition for resources begins. Variations in initial density are thus largely offset by variations in the growth rates of individual plants. This has been verified for many species and has been called the "law of constant final yield." This is true above a minimum plant population so there is enough opportunity to exploit all the resources. In other words, in its early stages of growth from seed, before competition, the crop biomass depends on the number of plants present. Later, the supply of resources starts to control the growth rate of individuals, until finally it becomes the limiting factor of productivity, regardless of the density. The population behaves as an integrated system in which the behavior of the individual plant is subordinated to the population's behavior.

Any factor that reduces the growth rate of plants results in a delayed onset of competition and a reduction in its intensity. The relationship between yield per plant and density is often expressed by the following equation, called "reciprocal yield law":

$$W = \frac{1}{b_1 + b_2 D_p} \tag{12.1}$$

where W is the dry mass per plant (g), D_p is the plant population density (plants m^{-2}), and b_1 and b_2 are empirical coefficients. Crop biomass (B, g m^{-2}) is the product of mass per plant and plant population density, and yield (Y) is the product of biomass and Harvest Index (Chap. 13) so:

$$Y = \frac{HI \cdot D_p}{b_1 + b_2 D_p} \tag{12.2}$$

The coefficient b_2 represents the inverse of the crop biomass (B) when the density is very high. If D_p tends to very large values in Eq. 12.2, $B \approx b_2^{-1}$

The coefficient b_1 represents the inverse of W when competition is absent, i.e. for very low density. If D_p is zero in Eq. 12.1, $W = b_1^{-1}$

Example 12.1
The maximum yield of sunflower for isolated plants of a particular cultivar is 500 g, and the maximum yield is 500 g m^{-2} when the density is very high. What is the expected yield if the planting density is 5 plants m^{-2}?

$$B \approx 1/b_2 \text{ when } D_p \text{ is high} --> b_2 = 1/B = 1/500 = 0.002 \text{ m}^2/\text{g}$$

$$1/W = b_1 \text{ when } D_p \text{ is very small} --> b_1 = 1/W = 1/500 = 0.002 \text{ plants/g}$$

$$\text{Yield} = \frac{5}{0.002 + 0.002 \times 5} = 417 \text{gm}^{-2}$$

12.3 Variability Between Plants and Hierarchy

The frequency distribution of weight per plant in a population under density stress is skewed, i.e. asymmetrical. The bias increases with both time and population density, as illustrated in Fig. 12.1 for sunflower. In a population in competition, we thus find a large number of small individuals (low biomass per plant) and fewer large individuals. The place of an individual in the hierarchy of the population is determined primarily in the early stages of development. It has been shown experimentally that the amount of biomass produced by an individual in a population under

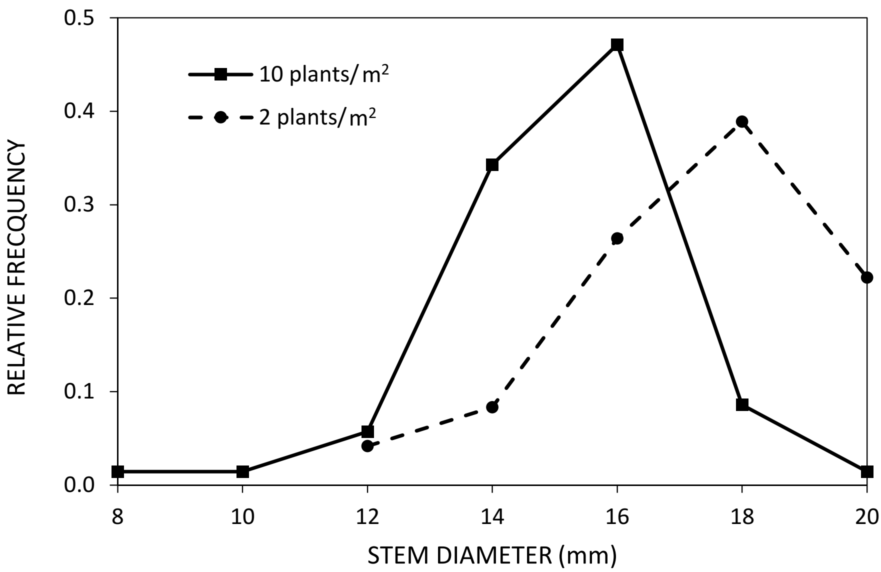


Fig. 12.1 Frequency distributions of stem diameter of sunflower plants at plant population densities of 10 or 2 plants m^{-2}. Cordoba (Spain), 1994

competition is very closely related to the relative order of its appearance (emergence) in the population. The advantage of an early appearance must be related to the increased use of resources and the corresponding deprivation of resources for plants that appear later. This implies that a likely source of variability of plant mass in the field is variability in time to emergence, which in turn depends on the variation of soil properties (water content, thermal properties, and compaction) and the sowing depth and method.

In addition to the heterogeneity of seedling emergence, herbivory, diseases, and other sources of damage (e.g., hail) are agronomically important sources of crop heterogeneity. For example, insects feeding on the growing meristem of cotton slow down plant growth, as it takes time for activation of axillary buds that would re-initiate growth. This hiatus in the growth of the damaged plant may favor the growth of undamaged neighbor plants.

Insects, diseases, or other agents that kill seedlings cause "gaps" in the crop. In the absence of compensatory capacity (when plant loss occurs very late or when it originates large gaps) yield would be reduced in proportion to the reduction of the plant stand. The relationship between yield and stand loss, however, demonstrates a compensatory mechanism which relates to the "relaxation" of competition and depends on the spatial distribution of plant loss and the time when it occurs (Fig. 12.2). In conclusion, crop heterogeneity often but not always reduces yield; the impact of heterogeneity depends on the size of the hierarchy or gap, their spatial

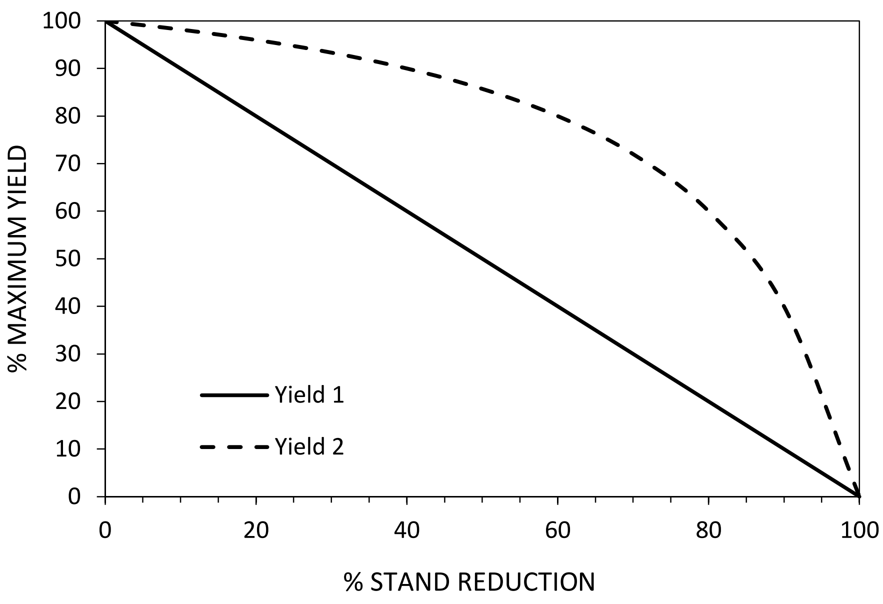


Fig. 12.2 Effects of plant stand loss on yield. The continuous line corresponds to stand loss occurring very late or when plant loss occurs in large patches so no compensatory growth is possible. The dashed line represents very early and random plant loss so maximum compensatory growth occurs

distribution, the ability of plants for compensatory growth (e.g., tillering wheat >uniculm sunflower), availability of resources, and the time available for compensatory growth.

12.4 Plant Population Density and Mortality

High plant population density tends to increase the risk of death of the individuals in the population although there are some examples of the opposite effect. The risk of mortality that increases with the density has regulatory properties, acting as negative feedback on the size of the population. Various studies on "self-elimination" (density stress-induced mortality) have shown that it occurs at high but not at low density, starts sooner with higher density, and depends on environmental conditions.

In the years 1920–1930, Suskatschew studied the dynamics of self-elimination in populations of spruce near Saint Petersburg (Russia), finding that final plant density was higher in poor and shallow soils. In deeper soils, he found lower densities of larger trees. This author then experimented with an annual plant (*Matricaria inodora*) using two levels of fertility and two densities, checking that mortality was higher with the highest density and that the risk of death increased with higher fertility. This corroborated his observations in spruce forests. Fertilization increased the growth rate of individuals thereby increasing the density stress and thus the mortality rate.

12.5 Mechanisms of Plant–Plant Competition

The density of plants in a crop determines the occurrence of numerous processes of interference between individual plants. As plant density is varied, the environment of each plant is altered in terms of light intensity and quality and availability of resources (water, nutrients).

As plant density is higher, intercepted radiation and the availability of water and nutrients are reduced for each individual, which limits their ability to grow. Light quality is changed fundamentally in the relationship between red (670 nm) and far red radiation (760 nm) (ratio *R:FR*). On average, sunlight has a ratio *R:FR* of 1.15. As red is absorbed by pigments, light transmitted or reflected by vegetation has a lower *R:FR*. For example, *R:FR* below crops may range from 0.1 to 0.5. As the density increases the ratio *R:FR* is reduced, and this reduction is detected by phytochromes, inducing morphological changes in many species (increased height growth, reduction in the formation of side branches or stems).

The main responses to increased plant population density are:

– Reduced yield per plant from the combination of the responses outlined below.
– Reduced expansive growth and mass per plant. Plant leaf area and thus radiation interception per plant are reduced.

– Change in the distribution of dry matter among vegetative plant organs: increased allocation to stem and reduced allocation to leaves (Fig. 12.3). In general, height increases while stem diameter decreases, which leads to a notable increase in its slenderness ratio and therefore a higher risk of lodging in adverse situations (for instance, strong winds).
– Change in the partition between reproductive and vegetative organs, which results in higher or lower Harvest Index depending on the species (see Chap. 13): In sunflowers, for very low density, biomass per plant may be very large while seed growth is limited by the number of seeds and potential seed growth rate, implying a fall in the *HI*. In other cases (e.g., maize), very high densities increase the percentage of sterile plants (Box 12.1).
– Reduction of the number of seeds per plant and/or mass of single seeds.
– Depressed branching in dicots (e.g., soybean) and tillering in cereals.
– Accelerated leaf senescence: In plants under high density, leaf senescence starts sooner and the rate of senescence is higher, which seems to occur in response to both shade and changes in light quality.
– Altered distribution of plants and plant parts. For instance, leaf orientation in maize plants responds to *FR*-simulating neighbors. Isolated maize plants were grown in the field with a selective mirror originating low *R:FR*, placed 15 cm toward the north. As a result, 70% of the leaves pointed E or W, while only 20% pointed N or S (Maddonni et al. 2002. Plant Physiol. 130:1181–1189). Whole plants of sunflower can also change orientation in response to high density (Fig. 12.4).
– Changed crop quality: In some cases, quality may improve with high density (e.g., percentage of oil in sunflower seed) and in other cases, it may decline (e.g., sunflower seed size for direct consumption). In general, the size of harvestable organs (grains, tubers, bulbs, etc.) is reduced as density increases.

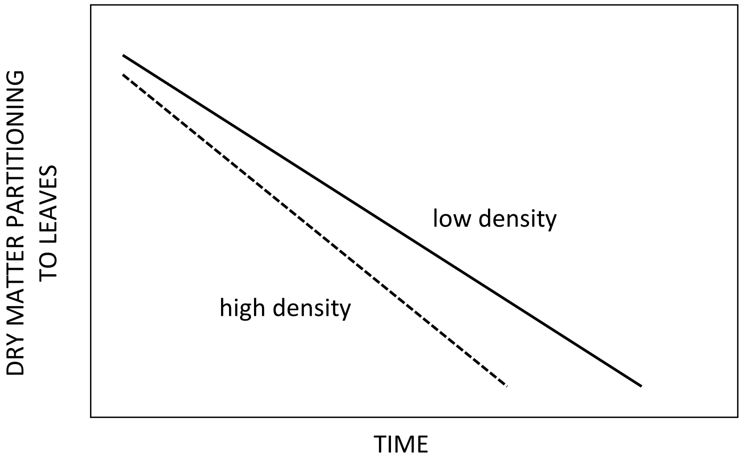


Fig. 12.3 Time course of dry matter partitioning for leaves in sunflower for low and high planting densities

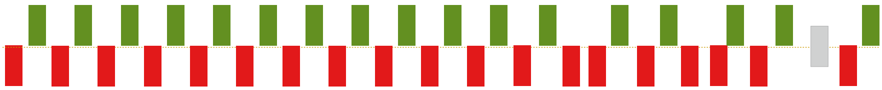


Fig. 12.4 Sunflower plants bend away from neighbors at 14 plants m^{-2} but not at 5 plants m^{-2}. Green and red rectangles indicate plants at 14 plants m^{-2} departing from vertical, and the direction of bending. The crop with naturally bending plants outyielded its counterpart where plants were forced to remain vertical at 14 plants/m^2. (Adapted from López Pereira et al. 2017. Proc Nat Acad Sci 114:7975–7980)

12.6 Yield and Plant Population Density

Throughout the twentieth century, great attention was paid to the relationships between plant density and crop yield. These relationships are important to determine the optimum density in practice, and for the selection of phenotypes adapted to high density stands (Box 12.1).

Box 12.1: Crop Yield Associates with Low Competitive Ability

The definition of crop yield evolves. For most of the history of agriculture, yield has been measured as the ratio of seed harvested to seed sown; for example, the average low grain yield in Europe in the 1770s was between four and seven seeds per seed. This definition of yield favored competitive, tall plants with profuse branching. With increasing competition for the available land, the definition of yield shifted from seeds per seed to the contemporary measure of mass of seed per unit land area. The selective pressure thus shifted to favor a "communal," less competitive phenotype first outlined by Colin Donald (Fig. 12.5).

Decades of selection for yield and agronomic adaptation in Australian wheat have shifted key traits from a low-yielding, more competitive phenotype (Fig. 12.5 left) to a high-yielding, less competitive phenotype (Fig. 12.5 right). The less competitive is shorter and intercepts less radiation per plant, which is compensated by a higher radiation use efficiency. The latter is not explained by photosynthesis or respiration at the leaf level but relates to an erectophile canopy that favors more radiation and higher nitrogen concentration in leaves at the bottom of the canopy (better distribution of radiation throughout the canopy). The less competitive phenotype has a smaller root system with a compensatory higher N uptake per unit root length.

Maize is particularly sensitive to plant–plant competition that could lead to barrenness. Selection for yield over decades has favored phenotypes with lower competitive ability, allowing for higher plant population density (Fig. 12.6). A negative correlation between crop yield (kg/ha) and plant competitive ability has been demonstrated experimentally in species of contrasting physiology and morphology, including cereals, pulses, and oilseed crops. This is the main reason why selection for yield of isolated plants rarely translates to crop yield per unit area.

(continued)

Box 12.1 (continued)

Fig. 12.5 Typical architecture of older, more competitive (left) and newer, less competitive (right) wheat Australian cultivars. (Source: Cossani and Sadras. 2021. Evolutionary Applications, 14:2064–2078)

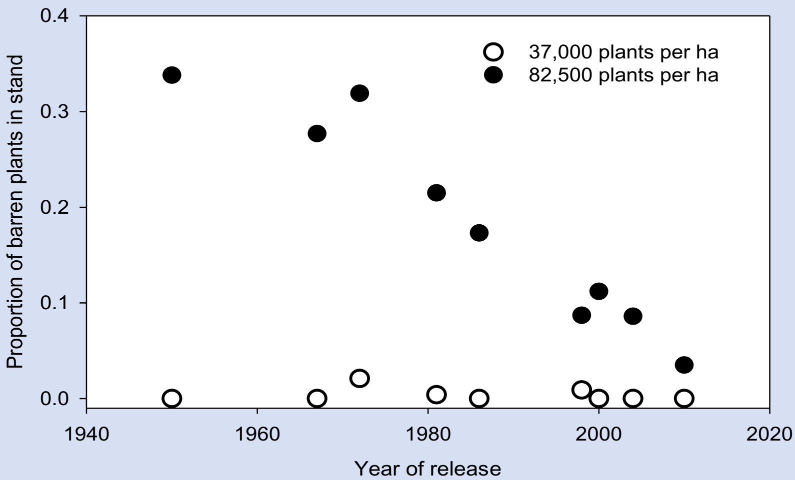
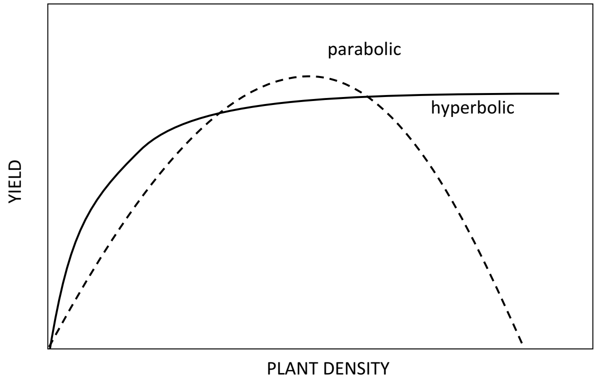


Fig 12.6 Proportion of barren plants (i.e., plants with no ears) in Chinese maize cultivars at high plant population density as a function of year of release. (Adapted from Ma et al. 2020. Field Crops Res. 250:107766)

Fig. 12.7 Generic parabolic and asymptotic response curves of yield versus density



Two types of relationships between yield and density are usually found: asymptotic and parabolic (Fig. 12.7). In the first type, yield increases with density, reaches a plateau, and does not decrease for very high densities. This case is also found when we plot biomass versus density. In the parabolic case, yield reaches a maximum at a given density and decreases for densities above or below.

The biomass production of any crop follows an asymptotic relationship with density. This is the response predicted by the Reciprocal Yield Law (Eq. 12.2). In crops harvested for their seed it used to be common to observe a decrease in yield for high densities (parabolic response), which implies that the *HI* is reduced. This was due to a direct effect of density (e.g. barrenness in maize) or as a result, of another limitation of resources such as water or nutrients. Thus, in situations of water deficit, the highest densities are at increased risk of not having sufficient water during grain filling. Evidence that a parabolic curve is the product of a limitation other than density may come from the observation that the density for maximum yield increases with increasing water or nutrient availability (Fig. 12.8). Additionally, within a species we can find various yield–density curves for the different cultivars, especially if they differ in cycle length. Very short cycles produce less biomass and yield at low densities. The maximum yield is achieved at a higher density if the cycle is shorter. A long cycle can fully exploit the available resources with low densities. It compensates for the low plant density with a longer vegetative period, which implies a higher growth potential for single plants. This is illustrated in Fig. 12.9 for two sunflower cultivars in Cordoba, Spain. In winter cereals, plant breeders have incorporated substantial plasticity in the response to density, and yields are the same over a wide range of densities as long as resources are not limiting (fully irrigated and fertilized conditions). Even in maize, modern varieties are quite resistant to barrenness and yields do not decline until very high densities are achieved (>150,000 plants/ha)

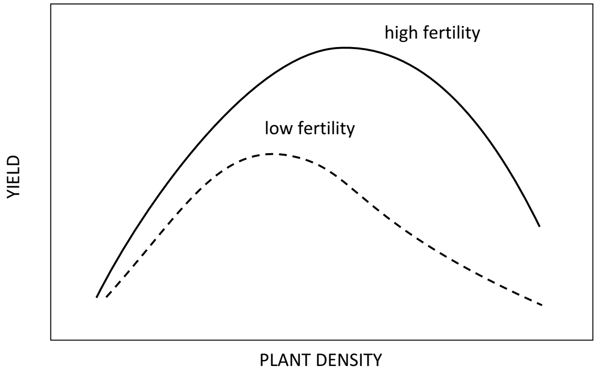


Fig. 12.8 Changes in parabolic response curves of yield versus density when resource availability is changed

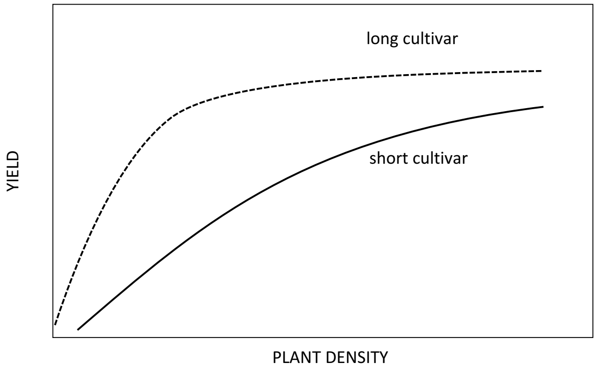


Fig. 12.9 Response of sunflower yield to density for short and long cycle genotypes

Using the Reciprocal Yield Law (Eq. 12.1), we can deduce at what density a particular fraction of maximum biomass ($r = B/B_{max}$) is achieved:

$$D_p(r) = \frac{r b_1}{(1-r) b_2} \tag{12.3}$$

Example 12.2

Two cultivars of sunflower differ in cycle. Under very low density, the shorter season cultivar produces 360 g/plant and the longer 1400 g/plant. In this environment, maximum biomass production is 1200 g m^{-2} and 1600 g m^{-2}, for the short and the long cultivar, respectively. We will calculate the densities required for these varieties to reach 90% of maximum biomass.

Short cultivar: b_2 = 1/1200 = 8.33 10^{-4} m^2/g
Long cultivar: b_2 = 1/1600 = 6.25 10^{-4} m^2/g

(continued)

Example 12.2 (continued)

Short cycle cultivar:

$1/W = b_1$ when D_p is very small --> b_1=1/W = 1/360 = 2.78 10^{-3} plants/g

$$D_p(r) = \frac{r\,b_1}{(1-r)\,b_2} = \frac{0.9 \cdot 2.78\,10^{-3}}{(1-0.9)\,8.33\,10^{-4}} = 30\,\text{plants m}^{-2}$$

Long cycle cultivar:

$1/W \approx b_1$ when D_p is very small --> b_1=1/W = 1/1400 = 7.14 10^{-4} plants/g

$$D_p(r) = \frac{r\,b_1}{(1-r)\,b_2} = \frac{0.9 \cdot 7.14\,10^{-4}}{(1-0.9)\,6.25\,10^{-4}} = 10\,\text{plants m}^{-2}$$

We see that to achieve yields close to the maximum, a much higher density is required for the short cultivar.

The yield–density relationships obtained experimentally should be used with caution because they depend on the limitations of water and nutrients and the cultivar considered. In any case, we should ensure a minimum planting density that should be increased for short growing cycles. Furthermore, if water or nutrients are scarce, we must avoid high densities that could reduce the harvestable fraction of biomass and therefore yield. The high density may cause other undesirable effects such as the increased risk of crop lodging by wind, which may decrease yield dramatically.

Parabolic responses to density are also observed for some horticultural crops where the product price is closely related to the size of the harvestable organ (e.g., garlic, onion, carrot). High densities lead to smaller and therefore lower selling prices, leading to yield–density curves of parabolic type when we express the yield in income/ha.

The relationship between density and yield mentioned above is obtained in experimental plots in which the crop density is uniform across the plot. However, in commercial plots, plants are not distributed evenly across the field. There is a spatial variability in density so there are areas where the density is high and areas where it is low. This may be due to variability in soil conditions (compaction, initial water), the presence of pests and soil diseases, or poor seed distribution at sowing.

In general, we may expect that the larger the variability in the density of plants the larger the decrease in yield. However, it depends strongly on the size of the gaps and the possibility of compensation, as indicated in 12.3. The negative effect of variability should be more pronounced when the response is parabolic as both lower and higher densities reduce yield below the optimum. In this case, if we cannot avoid a very high variability (soil or machinery problems, for example) we may reduce planting density below the theoretical optimum.

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Radiation Interception, Radiation Use Efficiency, and Crop Productivity

13

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Abstract

Photosynthesis is the set of processes whereby radiant energy is converted and stored as chemical energy in most plants, algae, and cyanobacteria. This process depends on radiation, temperature, and ambient CO_2 concentration. The maximum efficiency of the process is 6% but it is usually well below. The leaf-level photosynthesis can be described mathematically, and this analysis can be extended to the calculation of crop photosynthesis, as a function of leaf area index, and the coefficient of extinction as a shortcut to represent canopy architecture, and leaf photosynthetic parameters.

The respiration of the crop can be decomposed into a maintenance component that is dependent on biomass and temperature, and a growth component that is proportional to gross photosynthesis.

Crop yield can be expressed as the product of three factors, the amount of intercepted radiation, radiation-use efficiency (*RUE*), and harvest index (*HI*). Radiation interception depends on incident radiation, leaf area index, and the extinction coefficient. *RUE* is smaller for C3 than C4 crops and is smaller in crops with oil- and protein-rich seed in comparison to cereals. The *HI* depends on the species and its use. The main cause of genetic yield improvements in the

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past has been the increase in *HI*, which has been a remarkable success in the case of cereals; maize is the main exception to this trend. In some cases, such as high-yielding wheat in northern Europe, *HI* is reaching a biophysical limit hence further improvements in yield would require increasing *RUE* and biomass production.

13.1 Introduction

The input of energy to ecosystems is based on the process of photosynthesis by which sunlight is converted into chemical energy. Photosynthesis is the primary process of producing carbon compounds necessary for the construction and maintenance of crop biomass. Here, the focus is on leaf-level photosynthesis with a brief scaling-up exercise to crop-level photosynthesis, which links with crop traits developed in Chap. 3. When we measure the rate of CO_2 exchange of a single leaf, this rate is the net photosynthesis (P_n), which results from the total or gross photosynthesis (P_g) minus respiration (R). We use a convention that fluxes from air to leaf are positive, whereas fluxes from leaf to air are negative. Emphasis is placed on how radiation, CO_2, and temperature modulate leaf photosynthesis. Other factors affecting photosynthesis, such as plant water status and nitrogen nutrition are discussed in other chapters.

In the second part of this chapter, we discuss the relation between biomass production and the amount of radiation absorbed by photosynthetically active tissues, i.e. the efficiency in the use of radiation for biomass production. Absorbed radiation is closely related to intercepted radiation, i.e. the difference between incoming radiation and that reaching the soil surface (Chap. 3). Radiation-use efficiency varies between crop types with both photosynthetic metabolism (C4-C3) and seed composition (cereals, legumes, and oilseed crops); there is also moderate variation among cultivars that can be exploited in plant breeding. Plant age, source–sink ratio, dry matter, and nitrogen allocation also affect crop radiation-use efficiency. Nitrogen, water, and temperature are major environmental factors with effects on both radiation interception and radiation-use efficiency.

13.2 Leaf-Level Photosynthesis

Most (85–90%) of the dry matter accumulated in a crop derives from photosynthesis, which can be decomposed into the following three processes:

(a) Diffusion of CO_2 from the atmosphere to the chloroplasts, following the concentration gradient:

$$P_n = g_{sc}\left(C_a - C_i\right) \tag{13.1}$$

where P_n (μmol m^{-2} s^{-1}) is the net flux of CO_2 entering the leaf, g_{sc} is the stomatal conductance for CO_2 (mol m^{-2} s^{-1}), and C_a and C_i are the concentrations (μmol mol^{-1}) of CO_2 in the air surrounding the leaf and in the substomatal cavity, respectively.

(b) Absorption of radiation by the photosynthetic pigments and photolysis of water. The amount of radiation absorbed depends on the concentration of pigments, mostly chlorophylls, present in the chloroplasts. In this stage, O_2 is released and energy compounds (*ATP* and *NADPH*) are generated. This process does not depend on temperature or CO_2 concentration.

(c) Reduction of CO_2 using the compounds generated in the photolysis of water. Between 8 and 12 light quanta are required for each molecule of CO_2 reduced. The reduction can occur in the dark and is very sensitive to temperature.

The components of photolysis of water and CO_2 reduction may be calculated using the model of Farquhar:

$$P_n = \frac{a_c\left(C_i - \Gamma\right)}{b_c\, C_i + d_c} - R_d \tag{13.2}$$

Where a_c, b_c, and d_c depend on the process (photolysis or CO_2 reduction), temperature (both processes), and absorbed radiation (photolysis), Γ is the compensation point, and R_d is the leaf respiration. Nevertheless, the coefficient a_c is proportional to the leaf N content as N is the main component of chlorophyll and photosynthetic enzymes (e.g., Rubisco). Actual photosynthesis will occur at the equilibrium of Equations 13.1 and 13.2.

In summary, the photosynthesis of a leaf of a healthy, well-watered, and well-fertilized plant depends on irradiance, CO_2 concentration, and temperature.

The energy efficiency of photosynthesis, i.e. the ratio of energy stored in chemical form and incoming solar radiation, has a maximum value of around 6%, but actual efficiency in agricultural species usually does not exceed 2–3%. We can calculate the relative importance of photosynthesis in the energy balance equation (Chap. 7) as follows. Net radiation (R_n) above a crop is equivalent to 60–80% of solar radiation (R_s) depending mostly on cloud cover. On a clear day, we can assume R_n= 0.6 R_s so that the energy stored with 6% efficiency represents 10% of net radiation. However, the energy spent in photosynthesis also includes a fraction that is lost by respiration. If that fraction is one-third, then 15% of net radiation may be spent in photosynthesis. Therefore, the common assumption of neglecting energy use in photosynthesis may be wrong particularly when productivity is high (e.g., greenhouse crops) and irradiance is low. The partitioning of net radiation to photosynthesis may be even higher in protected cultivation with *LED* lights, as most of the radiation will be photosynthetically active radiation (*PAR*). In this case, with almost nil turbulence and zero balance of longwave radiation, we can assume equilibrium evaporation so transpiration is proportional to solar radiation. We can expect an efficiency of 20% over incoming *PAR* (including respiration) so around 25% of net radiation would be spent in photosynthesis (assuming an albedo of 0.2).

13.3 Plant Types According to Photosynthesis Mechanisms

Higher plants have developed three different photosynthetic systems (C3, C4, and CAM) that have distinct chemical and anatomical features. Terrestrial plants evolved from algae and initially were all C3. Subsequently, there has been a shift toward C4 and CAM systems. Agricultural species and natural flora show mostly the C3 system. Few but important cultivated species have the C4 system (maize, sorghum, millet, sugar cane, and some tropical grasses such as *Paspalum spp*), whereas the CAM system is rarer and less important in crops (agave, pineapple). C3 plants originate mostly in high to intermediate latitudes and high altitudes, whereas C4 are more typical of subtropical to tropical regions. C4 photosynthesis is a complex evolutionary trait that resulted from a major reorganization of leaf anatomy and metabolism leading to a CO_2-concentrating mechanism that counteracts the inhibitory effects of low atmospheric CO_2 on photosynthesis. The C4 pathway evolved independently at least 66 times within the past 35 million years. The main features of the three systems are as follows:

(a) C3 plants: The first compound formed in the process is phosphoglyceric acid (3 C atoms) by the combination of ribulose diphosphate (5C) with CO_2. The enzyme responsible is the ribulose-bisphosphate carboxylase (*Rubisco*). Although primarily serving for carboxylation, *Rubisco* can also act as an oxygenase. Thus, in the presence of light, O_2 competes with CO_2 at the enzyme active sites which leads to a loss of CO_2 (photorespiration). In addition to its enzymatic role, the large amount of *Rubisco* in plants means it plays a major role as a reserve of reduced nitrogen. This is most evident during grain filling and senescence of annual crops, where a significant part of the nitrogen, stored as *Rubisco*, is transported and contributes to the protein content in grain.

(b) C4 plants: The first compound formed in the process is oxaloacetic acid (4 carbons) by combining phosphoenol-pyruvate (*PEP*) with CO_2. The enzyme responsible is the phosphoenol-pyruvate carboxylase. C4 plants have higher photosynthesis per unit of energy and per unit of water than their C3 counterparts and this contributes to their adaptation to dry environments.

(c) CAM (Crassulacean Acid Metabolism) plants: This system is predominant in the *Crassulaceae* family that includes numerous cactuses. CO_2 fixation occurs during the night by the formation of *PEP* that is converted to organic acids that are stored in the vacuoles. During the day, malate enters the chloroplasts where *PEP* is regenerated. CAM plants behave as C3 if the water supply is adequate. In drought situations, CAM plants have reduced rates of water use as compared to C3 and C4 plants.

13.4 Effects of Environmental Factors on Photosynthesis

The main environmental factors affecting photosynthetic rate are solar radiation, temperature, and CO_2 concentration. Diseases, water and nutrient deficits may limit strongly photosynthesis as discussed in Chaps. 14 and 15.

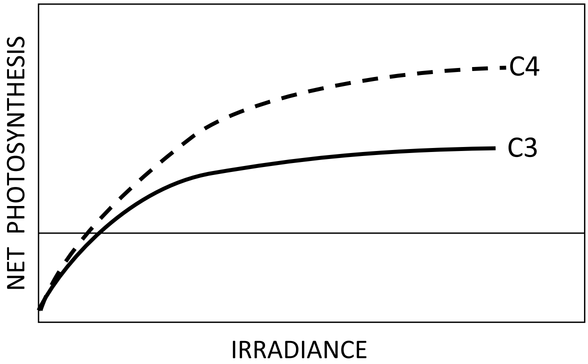


Fig. 13.1 Relations between leaf net photosynthesis and irradiance for C3 and C4 plants

13.4.1 Radiation

The net photosynthesis of a leaf (P_n) responds to irradiance (I) as shown in Fig. 13.1. For $I = 0$, the leaf loses CO_2 at a rate R_d (dark respiration). Assimilation is zero at the so-called light compensation point where gross photosynthesis is equal to the respiration rate. With higher I, P_n grows rapidly to a maximum at which the system reaches light saturation. For many species, P_n is saturated well below the typical radiation of clear days, which is particularly true of most C3 plants. The maximum P_n varies greatly between the C3 and the C4 groups and also within each group. However, the initial slope of the relationship $P_n = \mathrm{f}\,(I)$ is relatively constant for all species.

If R_d is constant, gross assimilation is defined as $P_g = P_n + R_d$. The gross assimilation rate increases with irradiance along a curve, which can be fitted to a hyperbola of the type:

$$P_g = \frac{\varepsilon\, I\, P_{gx}}{\varepsilon\, I + P_{gx}} \tag{13.3}$$

where P_g is the rate of gross photosynthesis (μmol m^{-2} s^{-1}), I is the irradiance (W m^{-2}), ε is the initial slope of the curve $P_g = \mathrm{f}\,(I)$, and P_{gx} is the asymptote of P_g when I tends to infinity. C3 plants have P_{gx} in the range 10–40 μmol m^{-2} s^{-1} while C4 show a range 18–55 μmol m^{-2} s^{-1}. The initial slope of the curve is similar for C3 and C4 species. When I is expressed as absorbed *PAR* (mol photons m^{-2} s^{-1}), the initial slope is called quantum efficiency of photosynthesis, which is a measure of the intrinsic efficiency of the photosynthetic system. In the range 20–25°C, both C3 and C4 plants have quantum efficiencies around 0.06 mol CO_2 E^{-1}. For lower temperatures, C3 plants perform better and for higher temperatures, the opposite occurs.

C3 plants reach their P_{gx} with much lower irradiance than C4 plants. Under optimal conditions, C4 plants show higher P_{gx} than C3 plants, although the differences are attenuated as we scale up from leaf to plant community. Thus, the maximum biomass produced by C3 and C4 crops differs much less than the maximum rates of photosynthesis at the leaf level.

The irradiance under which leaf growth occurs also affects its response to radiation. When a leaf has grown in the shade, P_{gx} is lower than when it has grown under high radiation. This process of acclimation is due to the increased accumulation of proteins (photosynthetic enzymes) in the leaves under high irradiance.

13.4.2 Temperature

The maximum photosynthesis responds to temperature following a bell-shaped curve with a maximum between 15 and 25°C for C3 plants and between 25 and 35°C for C4 plants (Fig. 13.2). Very few C4 species perform well under low temperatures, whereas most of these species suffer irreversible damage with temperatures between 10 and 12°C (chilling injury). Many C3 plants such as cotton and sunflower perform well with high temperatures (30–40°C) although some C3 are sensitive to low temperatures (e.g., banana). However, the leaves of most C3 plants can withstand temperatures down to 0°C.

13.4.3 Concentration of CO_2 and Endogenous Factors

Photosynthesis increases as CO_2 concentration increases because of the larger concentration gradient between the atmosphere and the leaf mesophyll (Eq. 13.1). The relation is hyperbolic (Eq. 13.2) for C3 plants. Leaves of C3 species lose CO_2 (P_n is negative) for CO_2 concentrations below 50–100 ppm. The concentration of CO_2 for which $P_n = 0$ is called CO_2 compensation point. C4 plants show little response to CO_2 concentration above 200–400 ppm.

In addition to the environmental effects, the photosynthesis rate can be affected by the existence of sinks capable of accumulating carbohydrates. For example, suppression of the tubers of potato plants leads to a decrease in the rate of leaf photosynthesis.

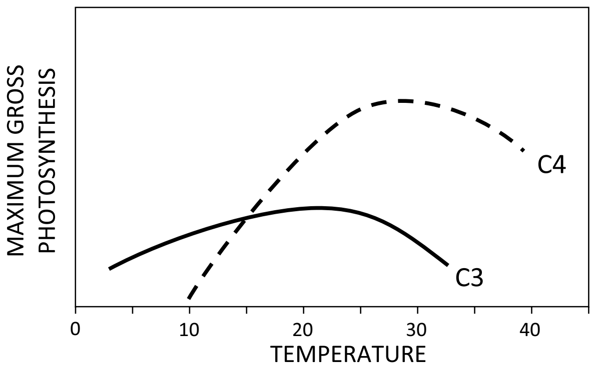


Fig. 13.2 Response of maximum gross photosynthesis to temperature for C3 and C4 crops

13.5 Respiration

Respiration (oxidation of carbohydrates and other compounds to produce energy) in plants can be decomposed into two main categories: growth respiration (R_g) which is proportional to gross photosynthesis and maintenance respiration (R_m), proportional to crop biomass (B):

$$R_d = R_g + R_m = a\,P_g + b\,B \tag{13.4}$$

Growth respiration is the energy cost involved in synthesizing plant tissues from glucose, which is the building block of plant tissues. For example, 1 g of glucose allows the building of approximately 0.65 g of leaves (or vegetative tissues in general). The energy cost depends mainly on tissue composition: synthesis of fats and proteins involves a higher R_g than that of carbohydrates (see Sect. 13.12).

Maintenance respiration is the energy cost associated with maintaining the organization and functioning of the crop tissues. The fundamental processes in which R_m is invested are protein turnover and keeping active ion transport mechanisms. For this reason, N-deficient plants or older plants with lower nitrogen concentration have lower maintenance respiration per unit of dry matter as illustrated in Fig. 13.3. The R_m per unit biomass increases exponentially with temperature up to 40–50°C, depending on the species. For higher temperatures, irreversible damage occurs. Indicative values of R_m at 20°C range between 0.01 and 0.035 g glucose/g of dry matter/day.

13.6 Crop Photosynthesis

The response of photosynthesis of a crop to environmental conditions is in principle more complex than that of its leaves. A crop is a set of leaves of different ages and nitrogen concentrations, subjected to different radiation intensities that change

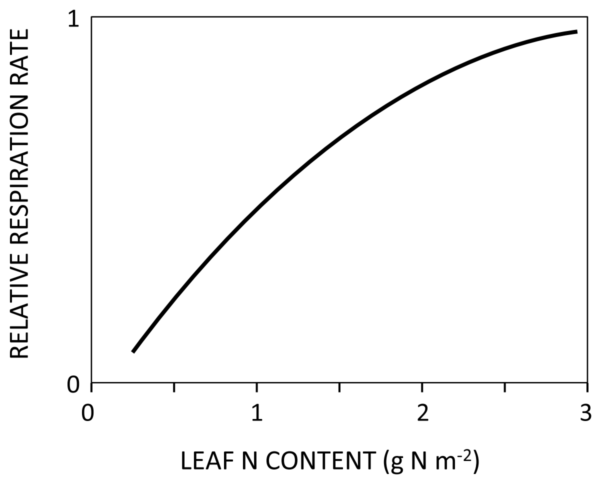


Fig. 13.3 Leaf respiration at 30°C as a function of leaf N concentration per unit leaf area

throughout the day. As will be seen later, crop photosynthesis is often linearly related to irradiance (or better, to intercepted radiation).

Considering the extinction of radiation within the canopy (Chap. 3) and the response of leaf assimilation to irradiance (Eq. 13.3), we can integrate assimilation for all the leaves and arrive at an equation for the rate of net photosynthesis of the crop:

$$P_{nc} = \frac{P_{gx}}{k} \ln\left(\frac{\varepsilon\, k\, I_0 + 1.2\, P_{gx}}{\varepsilon\, k\, I_0 e^{-kL} + 1.2\, P_{gx}} \right) - L\, R_d \tag{13.5}$$

where I_0 is the incident radiation, k is the extinction coefficient (see Chap. 3), L is the Leaf Area Index, and R_d is the dark respiration per unit leaf area. The main determinants of canopy photosynthesis are discussed using Eq. 13.5 in the examples below.

Example 13.1

Figure 13.4 shows the net photosynthesis of C3 crops with extinction coefficients of 0.5 (vertical leaves) and 0.9 (horizontal leaves) as a function of *LAI*. The maximum crop photosynthesis occurs for *LAI* around 3 for horizontal leaves and *LAI* close to 5 for vertical leaves. When *LAI* is low, horizontal leaves are more efficient for crop photosynthesis. Vertical leaves show a clear advantage for large *LAI*.

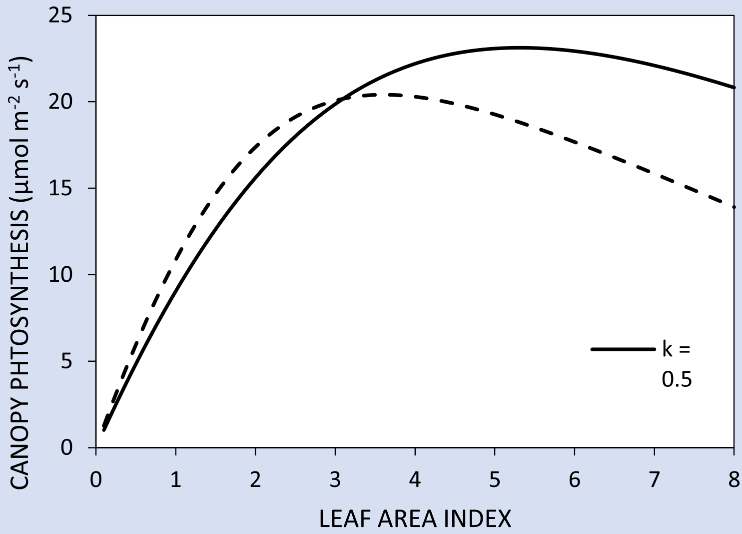


Fig. 13.4 Net photosynthesis of C3 crops with extinction coefficients 0.5 (vertical leaves, continous line) and 0.9 (horizontal leaves, dashed line) as a function of *LAI*

Example 13.2

Figure 13.5 shows the net photosynthesis of C3 crops with *LAI* = 1 and *LAI* = 4 as a function of incoming radiation. The response is closer to linear than that shown by leaf assimilation to irradiance (Fig. 13.1). When irradiance is low, the crop with *LAI* = 1 assimilates more CO_2 which is explained by the smaller respiration loss.

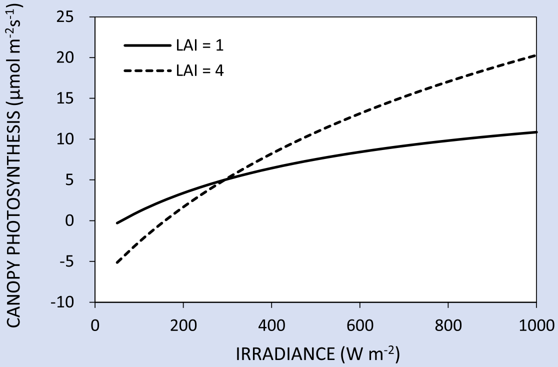


Fig. 13.5 Net photosynthesis of C3 crops with *LAI* = 1 and *LAI* = 4 as a function of incoming radiation

Example 13.3

The effect of leaf photosynthetic capacity on canopy photosynthesis is shown in Fig. 13.6 for crops of different *LAI*. The range in maximum leaf gross photosynthesis goes from the low range in C3 species to the high range of C4. We have assumed that respiration is 10% of P_{gx} and solar radiation is 500 W m^{-2}. The importance of leaf photosynthetic capacity is reduced as the canopy grows. For very high *LAI*, crop photosynthesis is almost independent of P_{gx}. This may explain why breeding for high leaf P_{gx} has not been successful in enhancing biomass production at the canopy level.

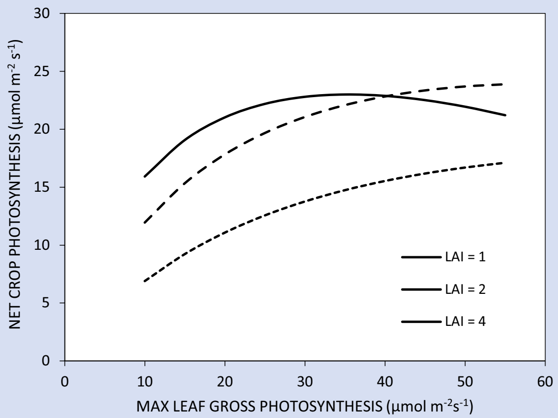


Fig. 13.6 Effect of leaf photosynthetic capacity on net canopy photosynthesis. The range in maximum leaf gross photosynthesis goes from the low range in C3 species to the high range of C4. We have assumed that respiration is 10% of P_{gx} and solar radiation is 500 W m^{-2}

13.7 Intercepted Radiation

We analyzed radiation interception by crops in Chap. 3. Actual interception depends on *LAI*, leaf angles, and the geometrical distribution of incoming radiation (sun angle, fraction of diffuse radiation). Models of radiation interception may be quite complex to include the actual 3D distribution of foliage elements in the canopy, which is required for tree orchards or forests.

A simpler approach uses the relationship between crop coefficients and radiation interception seen in Chap. 10. The FAO method for calculating K_c divides the crop cycle into four stages (initial, rapid growth, maximum, and declining). Rapid growth starts when ground cover is around 0.2 and ends at ground cover 0.8–0.9. Full radiation interception corresponds to K_c around 1.2, which leads to the simple model:

$$f_i = K_c - 0.3 \tag{13.6}$$

where f_i is the fraction of intercepted PAR. This should be valid for the third and fourth stages. In the initial stage, when we move from zero to 20% interception, we may assume an average value of $f_i = 0.1$. Values of interception for the rapid growth stage may be calculated by linear interpolation (Fig. 13.7). Note that in this simple model, intercepted radiation in the fourth stage, when leaves are old and the canopy

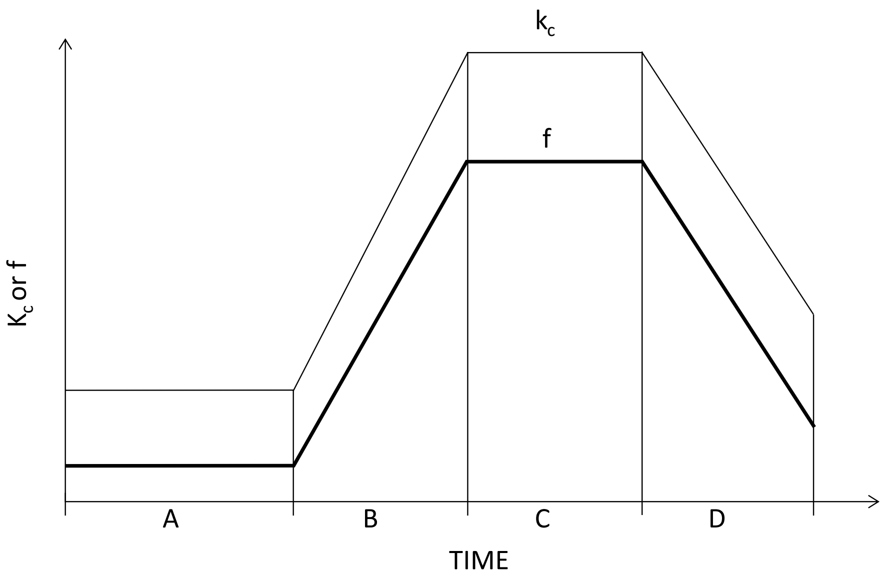


Fig. 13.7 Time course of crop coefficient and the fraction of intercepted PAR for an annual crop

is senescing, is a surrogate for absorbed radiation by pigments. In other words, dead leaves do not contribute to photosynthesis or transpiration, so the estimated intercepted radiation refers only to functional leaves.

13.8 Radiation Use Efficiency

The relationship between crop growth rate (increase in shoot biomass per unit land area and time) and intercepted radiation is approximately linear (Fig. 13.8). Therefore, the relationship between biomass production (B) and the sum of intercepted radiation should be linear:

$$B = RUE \sum_{\text{emergence}}^{\text{harvest}} f_i \, R_{sp} \tag{13.7}$$

where the proportionality coefficient is the RUE (Radiation-Use Efficiency, units of g/(MJ PAR)) and R_{sp} is the incoming PAR. The first to propose such a relation was Monteith in 1977, who plotted biomass versus accumulated solar radiation intercepted by different C3 crops (sugar beets, potatoes, barley, apples) and found

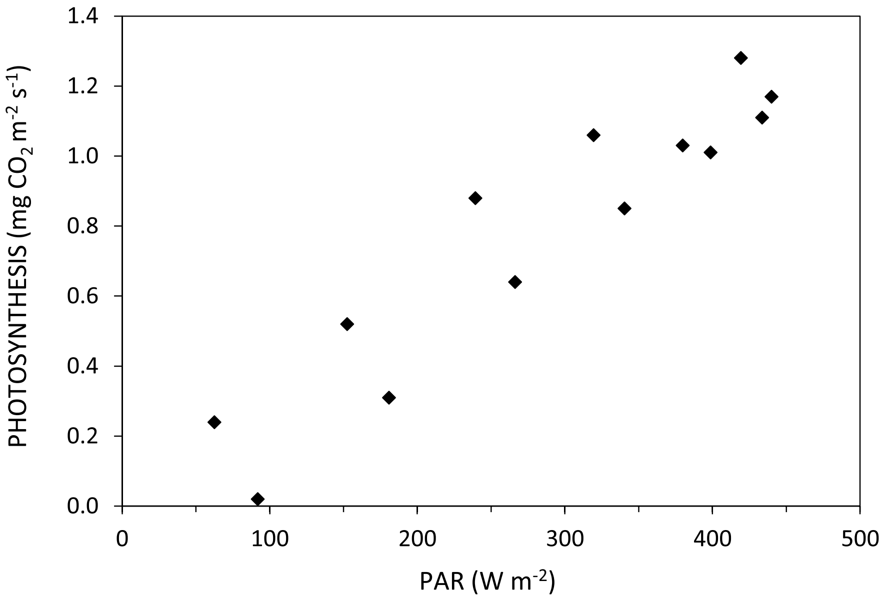


Fig. 13.8 Relationship between hourly crop photosynthesis and intercepted *PAR* in a cotton crop. Cordoba, Spain. June 23, 2003. For the same radiation, photosynthesis is higher during the morning than during the afternoon

similar linear relationships with a slope around 1.4 g dry matter/MJ solar radiation despite the obvious differences among these crops. The *RUE* of C3 plants inside greenhouses is higher than outdoors, with values in the range (2.2–2.5 g/(MJ PAR), which is explained by the higher proportion of diffuse radiation, the favorable thermal environment, and lack of wind that promotes higher shoot:root ratio. The biomass usually refers to the aboveground parts as quantifying the belowground biomass is much more difficult and uncertain.

The slope of the relation between biomass and intercepted radiation represents *RUE*, provided the intercept of the regression is zero; this is normally the case when the calculation spans the sowing to harvest period (eq. 13.7). Radiation-use efficiency can also be calculated for shorter periods during the season (see below). Where the intercept departs from zero, *RUE* is more reliably estimated as the ratio between biomass and intercepted radiation.

13.9 Crop Potential Productivity

We can calculate crop yield (*Y*) as the product of biomass and harvest index (Box 13.1), and further express biomass as the product of *RUE* and total intercepted *PAR* (Eq. 13.7):

$$Y = HI\ RUE \sum_{\text{emergence}}^{\text{harvest}} f_i\, R_{sp} \tag{13.8}$$

Assuming crops grown under ideal conditions that maximize capture and efficiency in the use of radiation and harvest index, we can calculate the potential dry matter yield of a crop in a given environment. Abiotic and biotic stress factors can reduce the harvest index and the components of crop biomass (Sect. 13.10). It is important to keep in mind that a fraction of the mass harvested by farmers is water. Therefore, the commercial or fresh yield can be calculated using Eq. 13.8 as:

$$Y_{\text{fresh}} = \frac{1}{1-w} HI\ RUE \sum_{\text{emergence}}^{\text{harvest}} f_i\, R_{sp} \tag{13.9}$$

where w is the fraction of water over fresh mass. Values of w for different species are shown in Table 26.1 and Annex 26.1. The difference between Y and Y_{fresh} is small for crops that are harvested dry (cereals, grain legumes) but it is very large for some species (e.g., potato, tomato).

The fraction of biomass that is harvested is called the Harvest Index ($HI = Y/B$). Biomass usually refers only to the aboveground fraction, unless the harvested organ is underground, in which case it is included in the biomass. The *HI* of fodder crops is very high (up to 0.9), as we may harvest and use almost all the aerial biomass (see Table 13.1). Small grain cereals like wheat can reach *HI* near 0.50, and many legume

Table 13.1 Harvest index (%) of crop species

	HI_{min}	HI_{max}
Alfalfa	90	90
Apple	60	70
Barley	40	50
Cassava	30	65
Chickpea	30	35
Citrus	50	60
Cotton	30	45
Cowpea (determinate)	45	60
Cowpea (indeterminate)	15	30
Bean (dry seed)	25	45
Faba bean	25	40
Garlic	50	55
Grain sorghum	40	50
Grapevine	40	60
Lentil	35	50
Lupin	30	50
Maize	40	55
Oats	40	50
Oil palm	40	45
Olive	50	70
Onion	60	85
Opium	30	40
Pea	35	45
Peanut	35	42
Pepper	40	60
Potato	50	80
Rapeseed	30	35
Rice	40	55
Safflower	25	35
Soybean	35	50
Sugar beet	50	70
Sugarcane	60	80
Sunflower	25	40
Tobacco	60	80
Tomato (industry)	45	60
Triticale	40	50
Vetch	40	50
Wheat	40	50

The typical intervals for commercial crops are shown. These values may be taken as representative of crops not suffering from extreme biotic or abiotic stress

and oilseed crops show *HI* in the range of 0.30–0.40. Crops with subterranean harvestable organs show high *HI* like sugar beet (up to 0.7) and potato (up to 0.8). It should be remembered, however, that the values shown in Table 13.1 correspond to "normal" cropping conditions, and that in extreme situations the *HI* may go down to zero, for example, if a crop fails to set grain due to untimely frost or heat.

13.10 Dry Matter Partitioning and Harvest Index

The dry matter accumulated during the crop cycle is partitioned among plant organs. In determinate annual crops, there is a distinct vegetative growth phase where assimilates are partitioned into leaves, stems, and roots. This phase is followed by a reproductive phase when inflorescences, flowers, seeds, and supporting structures grow while vegetative growth stops. In plants with an indeterminate growth habit, vegetative and reproductive growth overlap for much of the cycle. The difference between determinate and indeterminate growth is relative in the sense that there will always be some overlap between vegetative and reproductive growth even in determinate crops. The shorter the overlap is, the more determinate the growth habit. Interestingly, genetic variability exists for growth habits, which has been exploited to develop determinate cultivars that allow mechanical harvesting (e.g., processing tomato).

The fraction of dry matter that goes to each plant organ is called the partition coefficient. Part of the dry matter may be remobilized later and transported from one organ to another. This typically occurs with reserve carbohydrates in the stem, which support partially seed growth during the seed-filling period. In crops like sunflower and wheat, stem reserves can contribute significantly to grain yield, in particular under conditions that constrain photosynthesis during grain filling such as drought and foliar diseases.

The general trend over the XX century was the increase in the Harvest Index of the different species, which has enabled significant increases in yield without major improvements in biomass production. One example is that of the wheat cultivars obtained by the International Center for Improvement of Maize and Wheat (*CIMMYT*) in which improved *HI* was associated with short-stature plants, which enabled increasing N fertilization without increased risk of lodging. Maize is an exception to this trend, as improvement in yield has been primarily achieved by increasing crop biomass mediated by tolerance to crowding, in turn allowing higher sowing densities with a more efficient canopy architecture. For the last fifty years, plant breeders have focused on increasing *HI* to the point that the major crops are now approaching their biophysical limits in terms of *HI*.

Harvest index depends mainly on the developmental pattern of the crop, on the distribution of assimilates among plant organs, and on the ability to translocate assimilates to the harvestable organ. In particular, in determinate crops (e.g., sunflower) the reproductive phase is separated in time from the vegetative phase. Failure in setting seeds (or harvestable organs in general) may be a primary cause for reduced *HI*. Later, low post-anthesis assimilation or poor translocation of assimilates may reduce further the *HI*. Therefore, several critical periods for determining the *HI* may exist (flower initiation, flowering, pollination). A greater flexibility of the *HI* may be expected for indeterminate crops (e.g., cotton) as both vegetative and reproductive growth overlap during most of the crop cycle.

Nutrient and water deficits have variable effects on the harvest index. This relates to the definition of harvest index as a ratio of yield to biomass. Stress may reduce

Table 13.2 Effect of nitrogen supply on harvest index (relative to a maximum value of 0.47) of wheat at three locations in Australia

N rate (kg N/ha)	Ginninderra	Pucawan	Wagga
0	0.94	0.89	0.72
200	1.00	0.85	0.55

Adapted from van Herwaarden et al. 1998. Austr J Agri Res 49:1067–1082

both biomass and yield in equal proportion with no consequence for harvest index, or reduce biomass proportionally more than yield hence increasing *HI*, or reduce yield proportionally more than biomass, thus reducing the *HI*. The actual response of the *HI* to stress is thus contingent on the nature of the stress, and its timing, intensity, and duration. Table 13.2 illustrates all three possibilities. In comparison to unfertilized crops, well-fertilized crops had similar, lower, or higher harvest indexes depending on location-specific growing conditions. The seasonality of rainfall in dryland systems often has an impact on yield mediated by harvest index. In Mediterranean environments with winter rainfall that favors biomass growth and scarce rainfall during reproductive stages, the harvest index is often much lower than its potential. In irrigated systems, strategies of deficit irrigation may be used to improve *HI* by reducing water use during specific periods that favor reproductive over vegetative growth (see Chap. 22).

13.11 Alternate Bearing and Harvest Index in Fruit Tree Crops

The concept of *HI* also applies to fruit tree species, but its determination requires specific considerations. In trees, *HI* is the fraction of annual dry matter production allocated to fruits. It is very hard to measure by destructive sampling as we cannot separate the biomass produced over a year from that already in place at the start of the season (i.e., trunks, branches, and long-lived leaves in the case of perennials). On the other hand, yield and *HI* often vary substantially from one year to the next, as most tree crops alternate years with high and low fruit numbers. This “alternate bearing” can persist over time even under optimal growing conditions and implies that annual *HI* estimates provide limited insight into the “average” performance of the crop. Most importantly, yield oscillations challenge the experimental evaluation of management alternatives. Besides, in some tree crops like olive and pistachio, alternate bearing is usually synchronized over entire orchards, areas and even regions, eventually causing major labor and marketing problems apart from threatening farm sustainability in low bearing (“off”) years.

Our understanding of this phenomenon is still poor, although the competition for assimilates between developing fruits and vegetative growth is considered the main cause (see Box 13.1). As inflorescences or flowers appear on reproductive buds formed on shoots grown in previous seasons, any reduction in carbon partitioning to shoots sets a limit on the potential number of reproductive buds (and so fruits) that could be formed in the next season. That happens in high bearing ("on") years because fruits exert a strong sink effect on assimilates, so a heavy fruit load limits or even suppresses shoot growth. Meanwhile, most assimilates are allocated to vegetative growth in off years, increasing the number of potential reproductive buds. The onset of yield oscillations may be associated with the occurrence of adverse conditions during critical stages of the reproductive cycle leading to an "off" year.

Box 13.1: Alternate Bearing in Olive Trees

In this species, inflorescences appear on axillary buds of shoots grown in the previous season. In an experiment, we harvested trees of three cultivars either in June (just after fruit set), September (around veraison), or December (typical harvest date for oil production). The later the harvest date, the longer the overlap—and hence the competition—between reproductive and vegetative growth. This resulted in a lower production of axillary buds and inflorescences in the following spring. The treatments did not show a consistent effect on the ratio of inflorescences per bud, which shows that competition between fruit and shoot growth is the major determinant of alternate bearing in olive trees.

		Fruit removal treatment		
Cultivar	Variable	June	September	December
"Picual"	Buds/tree	4598	3059	2752
	Inflorescences/bud	0.36	0.50	0.28
"Arbequina"	Buds/tree	4542	2655	1727
	Inflorescences/bud	0.56	0.43	0.65
"Arbosana"	Buds/tree	3720	2846	2158
	Inflorescences/bud	0.52	0.42	0.36

13.12 Crop Factors Affecting Interception and Efficiency in the Use of Radiation

Chapter 3 discussed crop traits affecting radiation interception, including optical and geometrical properties of leaves and canopies. The *RUE*, which is the amount of dry matter produced per unit of intercepted *PAR*, depends on the crop species. Under optimal temperature and water supply, C3 plants produce between 2.0 and 2.5 g/MJ PAR and C4 plants produce between 2.5 and 3.0 g /MJ PAR.

Differences in seed composition explain the higher *RUE* of cereals in comparison to both oilseed crops and grain legumes. Following the analyses of Penning de Vries, the amount of glucose required to build 1 g of dry can be calculated as:

$$\frac{g\,\text{glucose}}{g\,\text{dry matter}} = 1.24\,FC + 1.70\,FP + 3.11\,FF + 2.17\,FL + 0.93\,FO + 0.05\,FM \quad (13.10)$$

where *FC*, *FP*, *FF*, *FL*, *FO*, and *FM* represent the fractions of carbohydrates, protein, fat, lignin, organic acids, and minerals in the dry matter being formed. With these values, we derive an approximate method to calculate the *RUE* of a crop based on biomass composition, assuming that the harvested product consists of carbohydrates, proteins, and fats, and the crop residues contain carbohydrates only:

$$RUE = \frac{RUE_c}{(1 - HI) + HI\,(FC + 1.4\,FP + 2.5\,FF)} \quad (13.11)$$

where RUE_c is the *RUE* for production of carbohydrates. Appendix 34.1 (Chap. 34) presents data of composition of harvested parts of many agricultural species.

Example 13.4
Winter cereals have a seasonal *RUE* of around 2 g/(MJ PAR) which may be taken as the reference RUE_c. Then for oilseed sunflower with *HI* = 0.35 and seeds containing 45% fat and 20% protein, RUE will be:

$$RUE = \frac{2}{(1-0.35) + 0.35(0.35 + 1.4\,x\,0.2 + 2.5\,x\,0.45)} = 1.58\,\text{g}/(MJ\ PAR)$$

Example 13.5
We will calculate the potential yield (without limitation of water and nutrients) of castor bean (*Ricinus communis*) in Cordoba, (Spain). The crop is sown on April 1 and harvested on September 30. The average fraction of intercepted radiation is 0.2 in April, 0.4 in May, 0.9 in June, July, and August, and 0.2 in September. The harvest index is 0.25. The seed water content is 5%. The castor seed contains 50% fat and 15% protein (dry mass basis). We also assume that temperature does not affect crop productivity. Solar radiation data and PAR interception calculation are shown in Table 13.3. Seasonal intercepted *PAR* is 1106 MJ m^{-2}.

First we calculate *RUE* using Eq. 13.10 and assuming RUE_c = 2 g/(MJ PAR), which yields

RUE = 1.66 g/(MJ PAR)

And now we calculate yield applying Eq. 13.9:

$$Y_{\text{fresh}} = \frac{1}{1-w} HI\ RUE \sum_{\text{emergence}}^{\text{harvest}} f_i\,R_{sp} = \frac{1}{1-0.05} 0.25 \cdot 1.66 \cdot 1106 = 483\,\text{g}\,\text{m}^{-2} = 4830\,\text{kg}/\text{ha}$$

(continued)

Example 13.5 (continued)

Table 13.3 Calculation of intercepted radiation for a castor bean crop in Cordoba (Spain)

Month	R_s	PAR	Days /month	f_i	Intercepted PAR per month
	MJ/ m²/d				MJ/m²
1	8.8	4.0	31		
2	9.9	4.4	28		
3	11.7	5.2	31		
4	16.9	7.6	30	0.2	45.7
5	20.1	9.1	31	0.4	112.3
6	23.8	10.7	30	0.9	289.7
7	25.1	11.3	31	0.9	315.4
8	23.5	10.6	31	0.9	295.4
9	17.8	8.0	30	0.2	48.0
10	10.9	4.9	31		
11	8.0	3.6	30		
12	6.3	2.8	31		
Season					1106.4

Variations in *RUE* due to the composition of the harvested product and loss of photosynthetic capacity that occurs in many crops during the final phase of the cycle reduce seasonal *RUE* below the maximum values. Thus, for seasonal calculation, we propose intervals of *RUE* of 1.6–2.0 g / (MJ PAR) for non-leguminous C3 plants, 1.5–1.8 for C3 leguminous plants, and 2.2–3.0 g/(MJ PAR) for C4 plants. These *RUE* values represent "well-adapted" crops under normal cropping conditions, so they include the effect of temperature and assume a good supply of water and nutrients. However, *RUE* is expected to change under cooler or hotter environments, and when water and nutrients are in short supply, as explained in the next section.

Some species show low *RUE* due to their low leaf photosynthesis; for example, olive *RUE* is 1.3 g/(MJ PAR) for nonbearing trees and 0.9 g/(MJ PAR) for bearing trees. This difference is due to the higher cost of biomass production of olive bearing trees as fruits accumulate oil. In citrus, the *RUE* of adult trees is 1.3 g/(MJ PAR).

The intra-specific variation in *RUE* is smaller than the differences between crop types associated with photosynthetic metabolism and seed composition. Nonetheless, selective pressure for yield has improved the radiation-use efficiency of wheat in both favorable (UK) and stressful (Australia) environments (Fig 13.9). The improvement in pre-flowering *RUE* of Australian wheat was associated with higher nitrogen uptake (i.e., greener leaves), and changes in canopy architecture that favored greater *PAR* penetration in the canopy; effectively, modern varieties have a greater proportion of leaves contributing to total crop photosynthesis, whereas the photosynthesis per unit leaf area remained unchanged. The role of nitrogen in crop photosynthesis is discussed in the next section.

A single *RUE* value is useful for comparisons between contrasting crop types (C3 v C4, cereal v oilseed) and also captures large environmental effects, such as

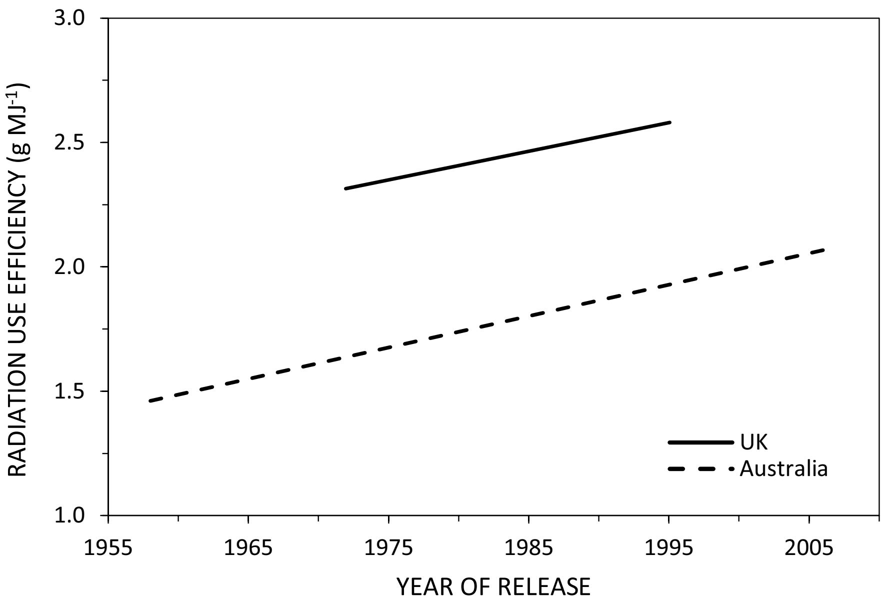


Fig. 13.9 Selection for yield indirectly improved the pre-flowering radiation-use efficiency of wheat varieties in UK and Australia. (Adapted from Evans JR. 2013. Plant Physiol 162:1780–1793)

shortage of water or nitrogen (next section). However, *RUE* changes with crop age, developmental stage, and the pattern of nitrogen and dry matter allocation. For example, studies of *RUE* in sunflower distinguished three phases: establishment (sowing to 47 days after sowing), rapid growth (47 days after sowing to anthesis), and grain filling (anthesis to maturity). Radiation-use efficiency was highest during rapid growth (2.4 g/MJ) and lower during crop establishment (1.0 g/MJ) and grain filling (1.3 g/MJ). The low *RUE* during establishment was associated with a large proportion of leaves exposed to high radiation, and the intrinsically lower efficiency of leaves at saturated light regimes. The low *RUE* during grain filling was related to high respiration and high synthesis cost of oil and protein in the seed (see Eq. 13.10) and to leaf senescence.

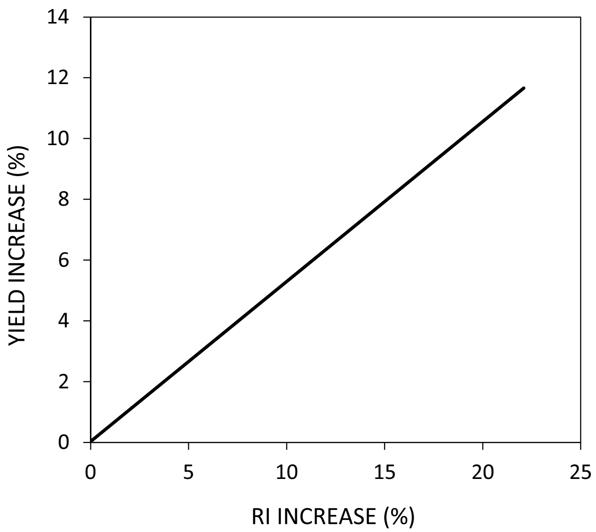
The concept of source and sink is useful to understand the physiology of the crop, despite some problems in definitions. A mature leaf is a net source of carbon, whereas the growing seed is a sink. A leaf however transitions from sink at early stages of development to source at later stages. Likewise, wheat and sunflower stems are sinks of carbohydrates during early growth stages but become sources for grain filling. The source:sink ratio can be manipulated experimentally by increasing source activity (e.g., increasing ambient CO_2 concentration or radiation), reducing source activity (e.g., defoliation, shading), reducing sink activity (e.g., removal of maize ear, cooling of potato tubers), or increasing sink activity (e.g., applying gibberellic acid). Experiments where the source:sink ratio is diminished often show an increase in photosynthesis, whereas increasing source:sink ratio may reduce photosynthesis. With high source:sink ratio, the plant has a relative excess of photosynthates, and the accumulation of starch in leaves can trigger the feedback-inhibition of photosynthesis usually mediated by reduction in stomatal conductance. Conversely, leaf photosynthesis may be stimulated if the capacity of the source to meet the carbohydrate requirements of the sink is restricted. These source:sink interactions are agronomically important. For example in pasture species such as alfalfa or grasses, browsing by animals reduces the size of the canopy relative to root biomass, hence reducing the source:sink ratio. After browsing, the rate of photosynthesis of remanent leaves may increase in response to the low source:sink ratio, hence contributing to re-growth. This “compensatory photosynthesis” has also been recorded in plants after damage by insects that reduce source:sink ratio (e.g., defoliators). In wheat varieties developed in *CIMMYT* (International Centre for Improvement of Maize and Wheat), increased seed number in modern varieties, compared with older ones, has increased RUE during grain filling; this increase in crop photosynthesis has been interpreted in terms of reduced source:sink size, as grain number increased without a proportional increase in canopy size. Effectively, more grains are “pulling” photosynthesis up.

13.13 Environmental and Management Factors Affecting Interception and Efficiency in the Use of Radiation

Effects of temperature on biomass production and its components, radiation interception and *RUE* are twofold. First, and most important, temperature changes the duration of the period from sowing to harvest, setting the limits of integration in Eq. 13.8. At high latitudes in Europe, Asia, and North America, warming over recent decades has extended this period, with positive implications for crop growth and yield (Chap. 11). In contrast, increasing temperature in subtropical and temperate environments may shorten season length, with potentially negative effects on crop yield. A caveat to the correlation between yield and season length in grain crops is that the association is causal only when temperature or other factors affect the duration of the critical period of grain set. Second, *RUE* is non-linearly related to temperature, an effect that is mediated by the effects of temperature on lower-level processes such as leaf gross photosynthesis, respiration, and dry matter partitioning. For example, field pea *RUE* is reduced with average ambient temperatures below 12 °C or above 22 °C.

Row spacing is manipulated to improve capture and efficiency in the use of resources, and to accommodate practices such as weed control and tillage (Chap. 17). The best row spacing for a combination of crop, soil, climate, and cropping system is usually determined empirically. Alternatively, we can apply the physiological concepts developed in this chapter to predict the responses of crop yield to row spacing as illustrated in Fig. 13.10. For the well-watered crops in this study, no yield gains are expected from narrowing the space between rows when wide-row crops intercept 90% of incident radiation in the critical period of yield

Fig. 13.10 Relationship between percentage yield increase in response to increase in radiation interception due to reduction in row spacing for maize, soybean, and sunflower. (Adapted from Andrade et al. 2002. Agron J 94:975–980)



determination but gains up to 12% can arise if wide-row crops intercept 60–90% of radiation. The gain in yield with narrowing row distance is proportional to the gain in intercepted radiation. In recent decades, even though row spacing has been diminishing to increase radiation interception, sowing machinery and tillage/traffic practices are the major determinants of row spacing.

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Effects of Water Stress on Crop Production

14

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Abstract

Water stress is due to a low water potential in the plant caused by low soil water potential, high evaporative demand, and/or a high resistance to water flow through the plant. The water deficit affects many crop processes, although most are related to the reduction in expansive growth, the most sensitive process, and stomatal closure. Mild to moderate deficits do not generally affect the harvest index, and in some species, they may increase it. However, severe water deficits reduce the harvest index (*HI*). The effect of water stress on crop yield can be quantified by Stewart's equation, which establishes that the relative yield reduction is directly proportional to the relative reduction in evapotranspiration (*ET*), with an empirical coefficient (K_y) which ranges between 0.8 and 1.5. More mechanistic models may be used to characterize the yield responses to variable water supply, but they need local calibration for accuracy.

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14.1 Introduction

Cultivated plants require a continuous water supply to replace that lost by evaporation from the aerial organs, particularly from the leaves. This requirement is due to the high evaporative demand (solar and thermal radiation and warm, dry air) experienced by the leaves while their substomatal cavities are saturated with water vapor. The gradient in water potential between the substomatal cavity and the leaf surface thus drives the evaporation process. Leaf cuticles, however, are significant barriers to evaporation, forcing most transpiration to flow through the stomata. For carbon dioxide to enter into the leaves, the stomata must be open, allowing water vapor to escape in response to the vapor pressure gradient. To maintain water flow without tissue desiccation, terrestrial plants have developed elaborate systems for the uptake and transport of water. Water flows from the soil into the root system and then is carried by xylem vessels to the leaves, where they replace the water evaporated into the atmosphere. Thus, from a physical point of view, the plants transport water from a source, the soil, to a sink, the atmosphere. These systems can transport large quantities of water, equivalent, in a typical summer day to a water depth of 6 to 8 mm in the field, which involves several times the total plant weight. However, a small, hardly detectable imbalance in the transport process in response to changes in the water supply from the soil or in atmospheric demand causes a water deficit in the plant. These mild deficits that are often harmful to crop growth and yield may occur despite the large amounts of water used by the plants. In this chapter, we outline the concepts of the energy status of water in the plant and its role in driving water flows. Then we look at the responses of crop processes to water deficits and the mechanisms of crop regulation of transpiration. After establishing these principles, we analyze the links between water and crop production from an agronomic viewpoint.

14.2 Energy Status of Water in the Plant

As we have seen for the soil (Chap. 8), the energy status of water in the plant may be characterized in terms of water potential. To do this we must go down to the cellular level since water status varies between subcellular compartments.

Schematically a plant cell is a protoplast (nucleus, cytoplasm, and vacuoles) surrounded by a membrane (plasmalemma) that presses on a semi-rigid cell wall. This pressure, called turgor, reflects turgor potential (Ψ_p). The osmotic potential (Ψ_o) due to solutes is the other main component of total water potential (Ψ) in the protoplast. In the cell wall, a porous structure composed of microfibers and polysaccharides, the solute concentration is much lower, so Ψ_o is very small and Ψ_p is zero. Thus, the major component of potential outside the protoplast is the matrix potential (Ψ_m) due to the adsorption forces that the porous cell wall matrix exerts on water. Another component of the potential, the gravitational, is negligible in plants except for very tall trees.

Example 14.1
In an equilibrium situation, the water potential in the vacuole is −0.5 MPa with components $\Psi_p = 0.2$ MPa and $\Psi_o = -0.7$ MPa. The total potential in the cell wall is also −0.5 MPa. Its components are $\Psi_m = -0.48$ MPa and $\Psi_o = -0.02$ MPa.

Outside the cell, in the xylem, for the same water potential, its components will be different from in the cell. The Ψ_o is much lower and Ψ_p is negative since water in the xylem is under tension. Turgor in the protoplast and tension outside create a large pressure gradient that would tear the plasmalemma if not for the rigidity of the cell wall containing it.

The pressure potential is the main driver of the expansive growth of plant shoots and leaves and is largely responsible for the proper functioning of some basic processes for growth and crop production.

14.3 Causes of Water Deficits

From the soil to the substomatal cavities, water moves in the liquid phase, whereas the flow from the substomatal cavities to atmosphere is in the vapor phase. Transpiration (E_p) is the water vapor flux from the substomatal cavities into the atmosphere following a vapor pressure gradient. This water loss from the plant is compensated by the inflow of root water absorption from the soil. The water flow can be expressed in terms of the water potential gradient between the soil and the leaves:

$$E_p = \frac{\Psi_s - \Psi_l}{R_{sl}} \tag{14.1}$$

where Ψ_s is the soil water potential, Ψ_l is the leaf water potential, and R_{sl} is the resistance to flow between the soil and the leaves. Rearranging Eq. 14.1:

$$\Psi_l = \Psi_s - R_{sl} \; E_p \tag{14.2}$$

That is, the leaf water potential, which is always lower than Ψ_s, is a function of soil water potential, flow resistance, and transpiration rate. A low leaf water potential is required for water to move from the soil, so leaves are under a water deficit as long as transpiration occurs. However, it is considered that a plant is water-stressed when the water potential in its tissues decreases enough to affect physiological processes. Thus, the causes that can lead to low leaf water potential and therefore to water deficit are:

(a) Low soil water potential (low water content and/or high salt concentration in the soil solution)
(b) High evaporative demand (high E_p)
(c) High resistance to water flow (high R_{sl}) in the soil (low hydraulic conductivity, dry soil) or in the plant associated with low root length density, vascular diseases, etc.

These processes can act simultaneously and in the same or in opposite direction. For instance, low soil water potential increases the soil-root resistance, while increases of transpiration may be accompanied by a reduction in resistance.

Water deficits may occur in the short term in plants with good water supply during the middle of the day, in response to high evaporative demand. By contrast, long-term water deficits are commonly associated with the progressive depletion of soil water.

We have seen then that the water status of the plant is the result of interactions between atmospheric demand (E_p) and the ability of the plant to meet this demand, which depends on the soil water content and the flow resistance. Transpiration rates and soil water uptake follow similar diurnal patterns with a maximum in the middle of the day, due to the high evaporative demand, but are offset in time (Fig. 14.1).

The role of R_{sl} is critical in regulating the water flow between the soil and the atmosphere. The resistance between the soil and the leaves can be separated into several components, as indicated in Fig. 14.2. The resistance between the soil and the root depends on the soil's hydraulic conductivity (K), root length density (L_v), and root resistance. As the soil dries, K decreases exponentially and R_{sl} increases. The root length density (root length per unit volume of soil) usually decreases exponentially with depth. A higher L_v implies a shorter average distance between the soil and the root surface and thus a lower R_{sl}.

Cereals have higher root length density than dicots for crops of similar size (Fig. 14.3), reaching L_v between 3 10^4 and 10 10^4 m m^{-3} in the surface layer (0–30 cm). The low root length density of dicots, which can support similarly large canopies, is compensated by larger and more abundant metaxylem vessels and smaller axial resistance to water flow. Numerous studies have shown that L_v around 10^4 m m^{-3} is enough for full soil water extraction down to the Permanent Wilting Point. Some crops such as sunflower can extract all subsoil water with L_v of about

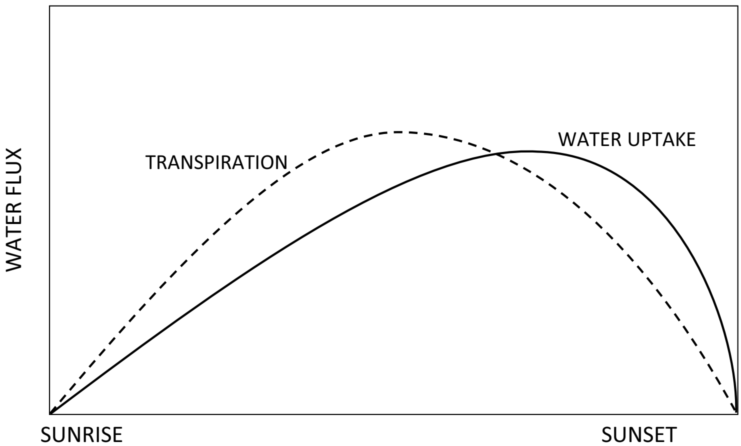


Fig. 14.1 Diurnal variation of transpiration and water uptake

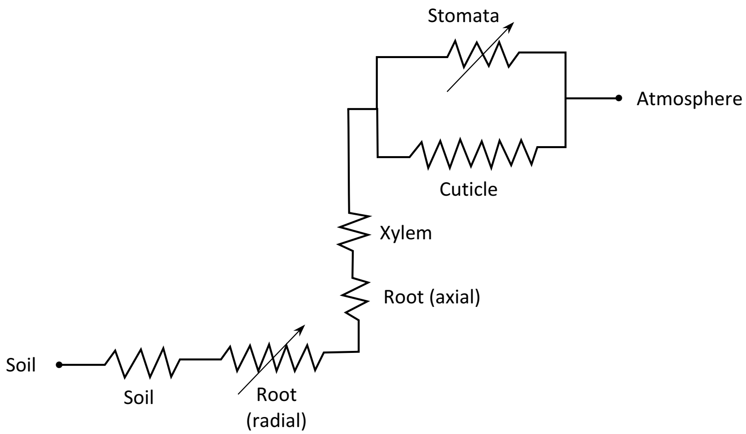
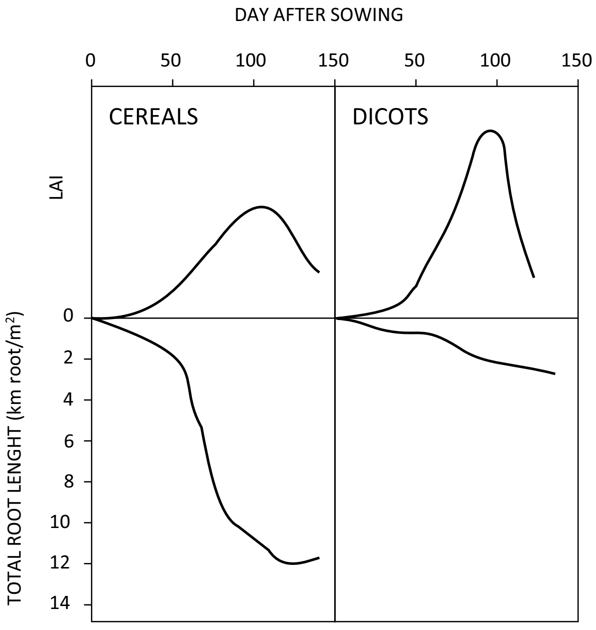


Fig. 14.2 Diagram of the soil–plant–atmosphere water flux

Fig. 14.3 Cereals (e.g., wheat) have a much higher root length density than dicots (e.g., lupin) in crops of similar leaf area index. (Adapted from Hamblin and Tennant. 1987. Aust J Agric Res 38:513–527)



0.5 10^4 m m^{-3}. The adaptive value of L_v well above 10^4 m m^{-3} is probably related to the extraction of immobile nutrients such as P, rather than to the absorption of water.

After penetrating the surface of a root, water must overcome a significant radial resistance before reaching the xylem vessels. This resistance is mostly due to the suberization of a layer, the endodermis, which prevents water from flowing through the apoplast hence forcing water flow through cell membranes. The lipid bilayer of cell membranes is a significant resistance to water flow in roots. However, membranes contain certain proteins, the aquaporins, that control water flow across membranes by changes in their abundance, by opening and closing the channel (gating), or both. Therefore, stomata and aquaporins both provide mechanisms for changing the plant's resistance to water flow. In some cases, there is a good correlation between the expression of aquaporins and physiological traits, e.g. aquaporin expression follows a day/night cycle consistent with the daily changes in root hydraulic conductivity coupled with transpiration. After reaching the xylem, the axial resistances from the root to the base of the stem and from the stem to the leaves are much smaller (Fig. 14.2).

Water in the leaves finds two resistances in parallel: the stomatal resistance determined by the degree of stomatal opening and the much greater cuticular resistance, highly variable among crops, with rice having half the value of corn or sorghum.

Although the crop is a simple intermediary for water transport between the soil and the atmosphere, the modulation of the resistances described above allows the matching, within certain limits, of the soil water supply to the evaporative demand of the atmosphere.

14.4 Effects of Water Deficits

Water stress can affect virtually all crop morphological and physiological processes if its duration and severity are intense enough. The general response is reflected in reductions in plant size, leaf area, and harvestable yield.

The main effects of water stress on crops can be explained largely through the impact on two processes: expansive growth and stomatal functioning.

14.4.1 Expansive Growth

Expansive growth, e.g. leaf elongation, is very sensitive to water deficit, particularly in comparison to other processes such as photosynthesis per unit leaf area. Mild water deficits, therefore, decouple growth from photosynthesis, with the consequent accumulation of labile carbohydrates not used in the slowed-down growth.

Turgor is responsible for the plant form and is a prerequisite for cell expansion since the increase in size requires both new cell wall synthesis and turgor pressure against the wall. The relative growth rate of the cell may be related to Ψ_p by the following equation:

$$\frac{dV}{dt}\frac{1}{V} = \varepsilon\left(\Psi_p - \Psi_{pu}\right) \tag{14.3}$$

where V is the cell volume, ε is the cell wall extensibility, and Ψ_{pu} is the threshold turgor potential, below which the expansion is stopped. The value of Ψ_{pu} is high, which means that with a small reduction in Ψ_p, expansion may cease and this would occur much sooner than wilting ($\Psi_p = 0$).

In general, if the crop is subjected to a progressive water deficit, acclimation occurs by increasing ε and/or reducing Ψ_{pu}, which conditions the future plant responses to water deficit. These acclimations occur differentially in the expansion of roots and aerial parts so that shoot growth is much more sensitive to water stress than root growth. In roots, Ψ_{pu} is reduced rapidly and solutes accumulate so that Ψ_o is reduced (osmotic adjustment), allowing root growth to continue under low soil water potential.

The great sensitivity of expansive growth to water deficits leads to expansion reductions for all organs growing when the water deficit occurs, which causes varying effects at the crop level depending on the timing of the water deficit.

14.4.2 Stomata Functioning

In terms of evolution, stomatal closure prevents desiccation and death of the plant in the aerial environment, especially when water is scarce. The trade-offs of stomatal closure are the reduction in the flux of CO_2 into the leaves and thus in assimilation, and the increase in canopy temperature. Stomatal closure under high vapor pressure deficit or drying soil favors a higher photosynthesis/transpiration ratio, which is related to water-use efficiency as discussed in Sect. 14.5.

The stomata are formed by two guard cells of kidney shape that are welded at their ends. The stoma opening occurs when the guard cells are turgid. If their turgor is reduced, the guard cells approach and the stoma closes. Therefore, stomatal resistance is a function of the pressure potential of guard cells, which is regulated by leaf water potential and other factors in a rather complex way. The complexity of stomatal behavior arises from several causes. First, stomata respond to many environmental (CO_2 concentration, temperature, vapor pressure deficit, radiation, and light quality) and plant factors (e.g., leaf age, source–sink ratio, see Chap. 10). Second, because of the rapid changes in the environment, the process of stomata regulation is highly dynamic; for example, stomatal resistance increases when evaporative demand increases, but the increased resistance improves hydration and thus leaf water potential, which in turn stimulates stomata opening. In short-time scales (minutes), the size of the stomata pore changes continuously, and there is also variation among stomata in the same leaf. Third, there are genotype-dependent differences in stomata response to soil and atmospheric dryness. In some species such as maize and soybean, stomata tend to close when leaf water potential drops; this allows for the maintenance of leaf water potential and for this reason, this strategy has been called "isohydric." In other crops such as sunflower, stomata are more likely to remain open at low water potential; this response is called "anisohydric." There is, however, intra-specific variation in these strategies and a wide range in responses between the extreme isohydric and anisohydric behaviors (Fig. 14.4), Growing conditions, which influence the rate of development of water stress, also affect such behavior, slow stress development is more conducing to isohydric behavior. Fourth, there are adaptive trade-offs in stomatal behavior. To understand these trade-offs, we need to recognize three functions of stomata: regulate the ratio

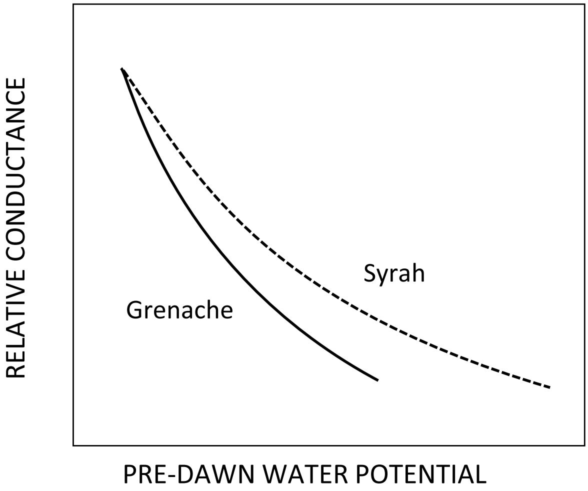


Fig. 14.4 Stomatal conductance declines with increasing water deficit but their response is stronger in Grenache (continuous line) than in Shiraz (dotted line). (Adapted from Schultz HR. 2003. Plant Cell Environ 26:1393–1405)

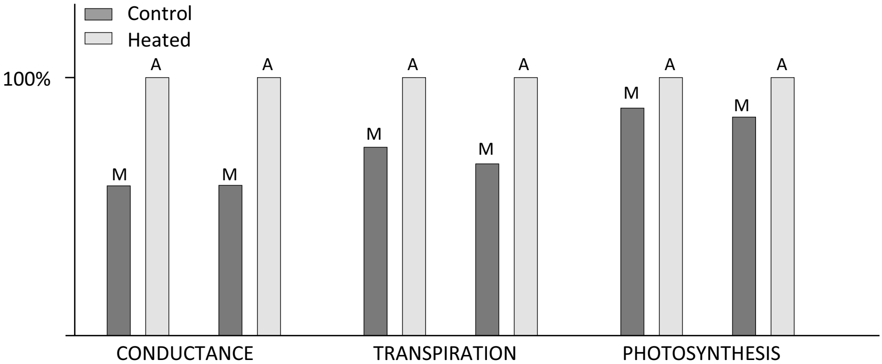


Fig. 14.5 Comparison of stomatal conductance, transpiration, and net photosynthesis in well-watered Shiraz vines grown under ambient (control) and elevated (heated) temperature. The elevated temperature increased stomatal conductance and transpiration and to a lesser extent photosynthesis. Evaporative cooling maintained the difference in canopy temperature between heated and control vines below 1 °C, at the expense of lower photosynthesis/transpiration ratio. M (morning), A (afternoon). (Adapted from Soar et al. 2009. Functional Plant Biol 36:801–814)

between photosynthesis and transpiration, prevent cavitation, and regulate canopy temperature. Stomata closure in drying soil or under high evaporative demand favors the photosynthesis/transpiration ratio and prevents cavitation. However, stomata closure increases canopy temperature. This trade-off means that stomata physiology cannot always be optimized. In wheat, cotton, and Shiraz grapevines, heat stress favors stomata opening and evaporative cooling at the expense of photosynthesis/transpiration, suggesting that keeping the canopy cool is, under some conditions, more important than saving water (Fig. 14.5). The role of stomata in regulating canopy temperature is crucial in warm regions where heat waves, compounded with dry soil, can cause severe damage (see Sect. 15.3.1).

14.4.3 Crop Regulation of Transpiration

Crop transpiration (E_p) can be analyzed as the product of three factors: total transpiring area, approximated by the leaf area index (*LAI*), intercepted radiation (*IR*) per unit *LAI*, and transpiration per unit of intercepted radiation:

$$E_p = LAI \frac{IR}{LAI} \frac{E_p}{IR} \tag{14.4}$$

A small canopy is the most effective means of transpiration control. Indeed, *LAI* components including tillering or branching, and the area of individual leaves are very responsive to water deficit. For a given *LAI*, the amount of radiation intercepted, which provides the energy for water evaporation, depends on canopy architecture. Figure 15.3 (Chap. 15) shows how wilting can transiently reduce *IR*/*LAI* and therefore reduce transpiration. Transpiration per unit intercepted radiation is related to the conductance of crop canopies, which is related to both its aerodynamic properties and stomatal conductance (Box 14.1).

The relative importance of the factors in Eq. (14.4) changes with crop development (Table 14.1). In general, tissue expansion is much more sensitive to water deficit than stomatal conductance, and regulation of *LAI* is the main control of transpiration. Figure 14.6 illustrates this idea with experimental data of sunflower in Cordoba in 1991. In summer, the expansion rate decreases when the relative soil water content is 0.8, while stomatal conductance is affected when the relative soil water is 0.2–0.3. In spring, expansion is reduced after half of the soil water is depleted, which is explained by the better water status of plants under lower evaporative demand. Thus, during the period of leaf growth, reduction in *LAI* is the main control of transpiration. However, in annual crops, *LAI* peaks around flowering, when the number and individual size of leaves are fixed; canopy expansion is therefore no longer relevant during grain filling. In this stage, leaf senescence is the only possible regulation of *LAI*, and often water deficit accelerates this process (Table 14.1).

Table 14.1 Relative importance rated from greatest (+++) to negligible (−) of mechanisms regulating transpiration of sunflower in pre- and post-anthesis

Process	Mechanism	Result	Pre-	Post-
↓ intercepted radiation	↓ leaf growth rate	↓ *LAI*	+++	−
↓ intercepted radiation	↑ leaf senescence		+	++
↓ intercepted radiation	↓ extinction coefficient (wilting)	↓ *IR/LAI*	+	++
↓ transpiration per unit *IR*	↓ stomatal conductance	↓ E_p /*IR*	−	++

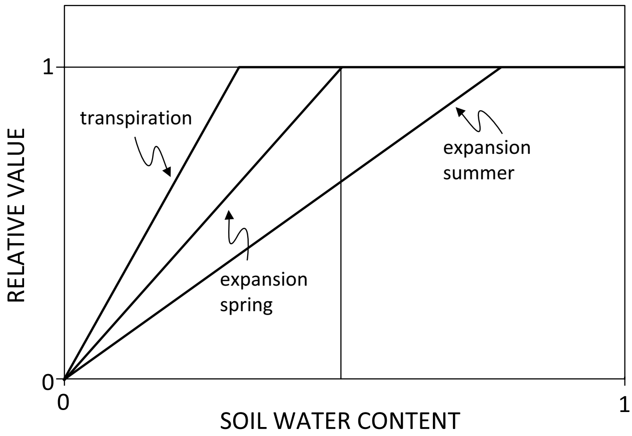


Fig. 14.6 Relations between expansive growth or transpiration and soil water content for sunflower in spring and summer. Soil water content is relative so the values in Permanent Wilting Point and Field Capacity are 0 and 1, respectively. (Adapted from Sadras et al. 1993. Agron J 85:564–570)

Box 14.1: Canopy–Atmosphere Coupling

Figure 14.2 represents the flow of water from the soil to the atmosphere at the level of the plant. At the crop level, however, there is an additional resistance located between the canopy and the atmosphere, the aerodynamic resistance. With increasing aerodynamic resistance, the canopy and the atmosphere become increasingly decoupled (see Sect. 9.4). In these cases, the impact of stomatal resistance in modulating crop transpiration is less than in cases where the aerodynamic component represents a smaller resistance. In tall, aerodynamically rough vegetation such as conifer forests, the aerodynamic resistance is small, canopies and atmosphere are closely coupled, and the stomata regulation has a significant impact on transpiration. In contrast, in short (aerodynamically smoother) vegetation, such as grassland, the aerodynamic resistance is higher, the canopy and atmosphere are less coupled, and the stomata regulation has less impact on transpiration.

14.4.4 Effects on Other Processes and Interactions

The effects of water stress depend on its timing, duration, and severity. A very severe stress affects almost all crop processes and may lead to total crop loss. Crops do not usually suffer such severe deficits as to threaten their survival, so we will only consider the effects of mild to moderate water deficits. The effects can be defined and investigated at different levels of organization. For example, water deficit can reduce the rates of cell division and expansion and induce abnormal cell differentiation, which can result in flower primordia and/or flower abortion. Water

Table 14.2 Ear damage (%) caused by heat stress in rainfed wheat crops grown under two sowing densities and several nitrogen rates

N rate	Half density	Normal density
Nil	10	22
Low	23	32
High	33	60

Adapted from Rodriguez et al. 2005. Aust J Agric Res 56:983–993
No ear damage was observed when the same treatments were applied under irrigation

stress can cause hydrolysis of proteins and accumulation of amino acids which, at the leaf level, reduces CO_2 fixation by a direct effect on photosystems. Water deficit increases levels of abscisic acid and ethylene and reduces levels of indole acetic acid, cytokinins and gibberellins. These hormonal changes can lead to accelerated senescence. Water stress has little effect on the respiratory processes, the transport of assimilates, and the rate of development.

Water stress under field conditions, however, does not occur in isolation. In arid and semi-arid environments, low soil fertility interacts with low rainfall leading to water-nutrient co-limitation. Water and nitrogen co-limitation is particularly important for the yield of cereals in Mediterranean environments, where water stress is also combined with heat stress. In wheat crops in South-Eastern Australia, ear damage caused by a heat episode close to flowering was significant in rainfed crops but not in irrigated crops (Table 14.2). Conditions that favored vigorous growth and faster soil water depletion, including excessive nitrogen supply and higher sowing density, compounded the effects of heat in the rainfed crops (Table 14.2).

The sensitivity of crops to insects and diseases can increase, diminish, or remain unchanged in water-stressed plants. Water-stressed cotton, for example, was less susceptible to spider mites than their well-watered counterparts. This was because water deficit increased leaf thickness and hardness, making them less palatable to mites. In choice tests, mites showed a marked preference for leaves from well-watered plants. By contrast, water stress in almond trees makes them more susceptible to mite infestations. Root diseases can compound the effect of water deficit, particularly those that cause xylem blockage.

14.5 Coupling of Photosynthesis and Transpiration

The flow of CO_2 into the leaf follows the same path as the flow of water vapor out of the leaf (transpiration). Any opening or closing of the stomata affects the two processes.

The flux of transpiration (E_p, mol m^{-2} s^{-1}) may be expressed as:

$$E_p = 1.6\, g_{sc} \frac{e_i - e_a}{P_{at}} \tag{14.5}$$

Where g_{sc} (mol m^{-2} s^{-1}) is the stomatal conductance for CO_2, e_i and e_a (both in kPa) are the vapor pressure in the substomatal cavities and the air outside the leaf, respectively, and P_{at} (kPa) is the atmospheric pressure. The factor 1.6 is the ratio of diffusion coefficients for water vapor and CO_2 in air at 25 °C. A similar equation (Eq. 14.1) is used for photosynthesis.

Air within the substomatal cavities is usually close to saturation ($e_i = e_s$ at leaf temperature), so by adding and subtracting e_s at air temperature, we may write:

$$e_i - e_a = e_s\left(T_c\right) - e_a + e_s\left(T_a\right) - e_s\left(T_a\right) = VPD + \Delta\left(T_c - T_a\right) \tag{14.6}$$

where VPD is the Vapor Pressure Deficit (Chap. 5), T_c and T_a are the leaf (crop) and air temperature, respectively, while Δ (kPa K^{-1}) is the slope of the saturation vapor pressure function versus temperature.

Therefore, the ratio of net photosynthesis and transpiration will be:

$$\frac{P_n}{E_p} = \frac{\left(C_a - C_i\right)P_{at}}{1.6\left[VPD + \Delta\left(T_c - T_a\right)\right]} \tag{14.7}$$

Several authors have shown that the ratio C_i/C_a tends to fairly constant values of 0.7–0.8 (C3 plants) and 0.3–0.4 (C4 plants). More exactly, the value of C_i that satisfies the photosynthesis equations (13.1 and 13.2, Chap. 23) increases exponentially with g_{sc}, so we may write:

$$\frac{C_i}{C_a} = 1 - k_1 \exp\left(-k_2 g_{sc}\right) \tag{14.8}$$

Therefore, water-use efficiency will be:

$$\frac{P_n}{E_p} = \frac{g_{sc}\, C_a \left(1 - \frac{C_i}{C_a}\right) P_{at}}{1.6\, g_{sc}\left[VPD + \Delta\left(T_c - T_a\right)\right]} = \frac{C_a\, k_1 \exp\left(-k_2 g_{sc}\right)}{1.6\left[VPD + \Delta\left(T_c - T_a\right)\right]} \tag{14.9}$$

This equation shows that the photosynthesis/transpiration ratio (also called Water-Use Efficiency, *WUE*) depends mainly on the vapor pressure deficit: the amount of carbon fixed per unit of water lost will decrease as the atmosphere is drier or warmer. This is illustrated in Fig. 14.7 that shows hourly values of cotton *WUE* as a function of *VPD* during summer days in Cordoba, Spain. Here, *WUE* was calculated as the ratio of canopy photosynthesis and *ET*. Equation 14.9 also indicates that the photosynthesis/transpiration ratio increases as C_a increases and with stomatal closure, i.e. a reduction in g_{sc}. This last effect may be offset by the increase in T_c caused by stomatal closure.

If we assume a constant ratio C_i/C_a and T_c=T_a, Eq. 14.9 can be simplified to:

$$\frac{P_n}{E_p} = \frac{\alpha_w}{VPD} \tag{14.10}$$

For a value of C_a = 417 µmol mol^{-1}, the coefficient α_w would be 5331–7997 µmol mol^{-1} kPa for C3 plants and 15,993–18,659 µmol mol^{-1} kPa for

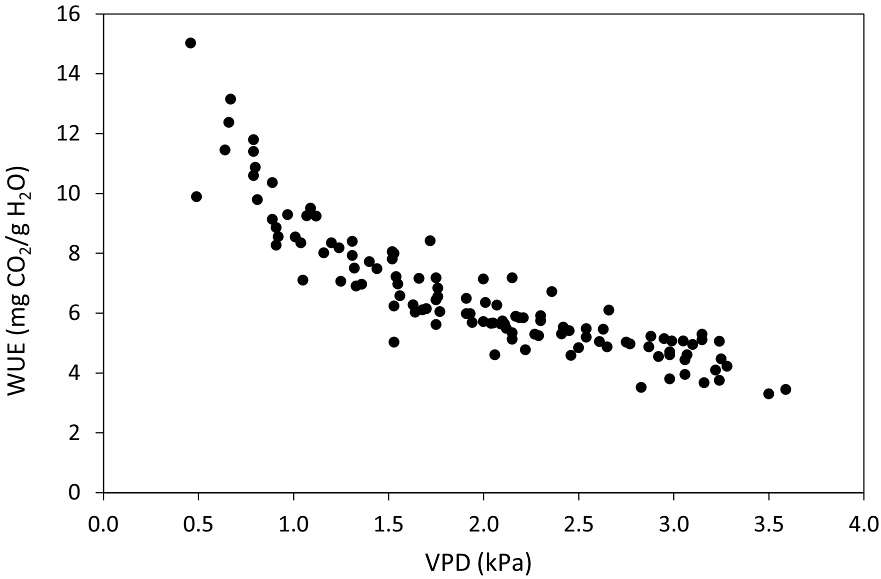


Fig. 14.7 Relationship between the *WUE* (ratio of canopy photosynthesis/*ET*) and *VPD* for cotton in Cordoba (Spain) during the summer days of 2003.

C4 plants. If we convert these values to biomass production of carbohydrates and take into account the relation between daytime *VPD* and mean *VPD*, the coefficients would be 5.4–8 g dry matter L^{-1} kPa for C3 and 16.2–18.9 g dry matter L^{-1} kPa for C4. If we consider also night respiration, the coefficients would be reduced to around 60% of the previous values for seasonal estimates.

Therefore, biomass accumulation (g m^{-2} day^{-1}) can be calculated as:

$$\Delta B = E_p \frac{\alpha_w}{VPD} \tag{14.11}$$

The same equation applies to isolated trees or plants, but then transpiration is expressed in L/tree/day and the increase of biomass in g/tree/day.

Example 14.2

Typical seasonal values of *WUE* (g dry matter/kg water transpired) for various C3 species in Southern Spain are: olive (3.4), sunflower (3.5), and wheat (5.3).

The higher value of wheat is due to lower *VPD* during its cycle from December to May (average 0.7 kPa) as compared with sunflower (February to July, 1.3 kPa) and olive (January to December, 1.2 kPa). The theoretical estimates, taking $C_i/C_a = 0.75$, would be:

Wheat: 6.5 g dry matter L^{-1}kPa/0.7 • 0.6 = 5.6 g dry matter/kg water
Olive: 6.5 g dry matter L^{-1} kPa/1.2 • 0.6 = 3.25 g dry matter/kg water
Sunflower: 6.5 g dry matter L^{-1}kPa/1.3 • 0.6 = 3.0 g dry matter/kg water

Example 14.3
In Example 9.5, we calculated transpiration of an olive tree with radius 0.5 m in Cordoba, Spain on 21 March with ET_0 of 3 mm day^{-1}. Calculated E_p is 2.07 L/day.

If average VPD is 1.5 kPa, the increase of biomass would be:

$$\Delta B = E_{p\,\mathrm{tree}} \frac{\alpha_w}{VPD} = 2.07 \frac{L}{\text{tree day}} \frac{6.5 \frac{\text{g kPa}}{\text{L}}}{1.5\,\text{kPa}} = 9 \frac{\text{g}}{\text{tree day}}$$

14.6 Quantifying the Impact of Water Deficit on Crop Production

The impact of water deficit on crop production can be quantified using models of different complexity. Here we illustrate the simple model of Stewart and the more complex *AquaCrop* model.

14.6.1 Stewart Model

The model is based on the empirical relations between crop evapotranspiration and yield, which derive from the association between transpiration and photosynthesis. These two processes are linked for two reasons. First and most importantly, both are driven by radiation that provides the energy for water evaporation and CO_2 reduction. Smaller canopies capture less radiation, fix less carbon, and transpire less. Second, the flows of both water and CO_2 between the crop and the atmosphere are partially regulated by stomata. These two mechanisms account for the correlations between biomass and transpiration (see Sect. 14.5). Therefore, if the harvest index is known, yield can be calculated as a function of seasonal transpiration using Eq. 14.11:

$$Y = HI \sum_{t=\text{emergence}}^{t=\text{harvest}} WUE_i\, E_{pi} \tag{14.12}$$

where WUE_i is the biomass produced per unit transpiration (g dry matter/kg water) for day i, which depends mainly on VPD and the crop species (Eq. 14.10). For simplicity, we will assume that WUE is constant throughout the season and that HI is not affected by water deficit, but see Box 13.1 for a more realistic discussion. As evapotranspiration of day i is the sum of soil evaporation and transpiration:

$$Y = HI \;\; WUE \left(\sum_{t=\text{emergence}}^{t=\text{harvest}} ET_i - \sum_{t=\text{emergence}}^{t=\text{harvest}} E_{si} \right) \tag{14.13}$$

We arrive at a linear relationship between yield and total evapotranspiration (*ET*). The intercept is negative, and the x-intercept is seasonal soil evaporation (E_s) while the slope is the product of *HI* and *WUE*.

We are interested in computing yield as a function of water used (*ET*). A simple approach that requires a priori estimates of *ET* and yield in unstressed crops (ET_x and Y_x) is the model of Stewart, which calculates the relative reduction in yield as a linear function of the relative reduction in seasonal *ET*:

$$1-\frac{Y}{Y_x}=K_y\left(1-\frac{ET}{ET_x}\right) \tag{14.14}$$

where K_y is a coefficient of sensitivity to water stress. If *HI* is not affected by water stress and we change *ET* while keeping soil evaporation constant, K_y will depend only on the ratio of soil evaporation:transpiration:

$$K_y=1+\frac{E_s}{E_p} \tag{14.15}$$

On the other hand, if soil evaporation is proportional to *ET*, K_y should tend to 1. These relations are not valid for severe water stress that reduces *HI* (see Sect. 13.10). In general, the empirical values reported for K_y are in the range of 0.8–1.5.

The Stewart model, adopted by the FAO Manual 33 of Doorenbos and Kassam, has been used as a first approximation for calculating yield as a function of *ET* but has a number of limitations:

- Variation in *WUE*: For a given environment mean *WUE* will depend on when actual transpiration occurs due to the inverse dependence of *WUE* on *VPD*. Under water stress, the pattern of water use will change as compared to the unstressed situation, which may lead to important changes in *WUE*.
- Calculation of unstressed yield: In the absence of local data, a good alternative would be to use a crop simulation model, calibrated and verified for local conditions.
- Irrigation method: The irrigation method affects evaporation from the soil surface. A different E_s leads to different *ET* for the same transpiration (the variable directly related to biomass and yield). The K_y coefficient of Eq. 14.14 can be considered constant only if E_s and E_p are affected equally by a reduction in the supply of irrigation, which is very unlikely.
- Acclimation: Crops' responses to water stress are conditional to the previous history of stress. In addition, the effect of water deficit in perennials can be carried over from one season to the next.

These limitations are common to any empirical model used to generate universal production functions. However, their use can be advantageous when high accuracy is not required and when they are the only available alternative for practical purposes.

14.6.2 The *AquaCrop* Simulation Model

AquaCrop (www.fao.org/nr/water/aquacrop.html) is a dynamic simulation model of herbaceous crops that predicts yield as a function of water supply. It is based on the relation between *B* and E_p and on the constancy of *WUE* (for a given species) if normalized by the evaporative demand (reference *ET*). After seedling emergence, the model calculates the rate of canopy expansion and the components of *ET* (E_p and E_s) by computing soil water extraction daily. Based on the transpiration, the model then calculates the increment of *B*, which is accumulated until harvest. As the canopy develops and the crop grows driven by thermal time, different developmental stages occur depending on the crop. The *HI* is built up during the pertinent period and enters in the computation of yield at the harvest date.

Water stress affects the simulations first via reductions in canopy expansion, followed by reductions in stomatal conductance and acceleration of canopy senescence. Different crop-specific thresholds in root zone water content are defined for each process, and the *HI* is also modulated by water deficits, generally decreasing under severe stress. The model gives an estimate of water-limited potential yield without any other limiting or yield-reducing factors. It has a soil fertility module to consider non-optimal fertility conditions common in many agricultural systems.

To obtain accurate predictions, *AquaCrop* should be calibrated and validated with experimental data obtained in the environment where it will be utilized. Its description and numerous applications may be found in FAO manual ID 66 and the *AquaCrop* website.

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Abiotic and Biotic Stress Limitations to Crop Productivity

15

Victor O. Sadras, Francisco J. Villalobos, and Elias Fereres

Abstract

Environmental factors including water stress, nutrient deficiency, high or low temperatures, chemical (Al-toxicity, salinity) and physical soil constraints (e.g., compaction), and biotic factors reduce crop yield. Deficit of water and nitrogen, and soil constraints have a larger impact on canopy size and duration, hence growth reductions are closely linked with reduced intercepted radiation; radiation use efficiency is generally less responsive to stress. Extreme temperatures at critical stages usually reduce harvest index and yield. Other stresses can be neutral, positive, or negative for the harvest index; this depends on the nature, timing, intensity, and duration of stress and its relative impact on total and harvestable biomass. Biotic agents such as pests, diseases, and weeds can reduce crop yield substantially, hence the importance of appropriate crop protection practices.

15.1 Introduction

In Chap. 13, we analyzed crop yield as a function of temperature and radiation interception. This "potential" yield will be higher than actual yields as other biotic and abiotic factors affecting the crop come into play. The main abiotic factors that reduce crop yields are excess or deficit of water (reviewed in Chap. 14); nutrient deficit; soil chemical (salinity, acidity) or physical (e.g., compaction) constraints;

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and meteorological events including extremely high or low temperatures, hail, and wind. Biotic factors are weeds, animal pests, and diseases.

In this chapter, we will revise the main impact of these factors on crop yield. Some of them have been discussed (water in Chap. 14) while others (salinity, nutrient deficits, frost) will be treated in more detail in specific chapters of this book.

15.2 Nutrient Deficiency and Soil-Related Limitations of Productivity

Deficits of water or nutrients reduce biomass by primarily reducing leaf area index and radiation interception; under severe stress, radiation use efficiency is also reduced. This is because tissue expansion is more sensitive to water and nutrient deficit than leaf photosynthetic rate (Chap. 14). Indeed, a common short-term response of water and N-stressed plants is to accumulate carbohydrates as the restriction in expansion is more severe than in photosynthesis, leading to a transient excess of reduced carbon.

The effects of N supply on crop growth and yield can thus be explained in terms of radiation interception and its use efficiency. Nitrogen deficit reduces crop *LAI* by reducing tillering or branching, and leaf expansion (Fig. 15.1). Reduced leaf size of nitrogen-deficient crops is associated with reduced cell division and expansion (Table 15.1). Nitrogen deficit can accelerate leaf senescence (Fig. 15.2), further contributing to reduced radiation interception and photosynthesis. *Rubisco* and light-harvesting proteins involved in photosynthesis represent 60% of the leaf N

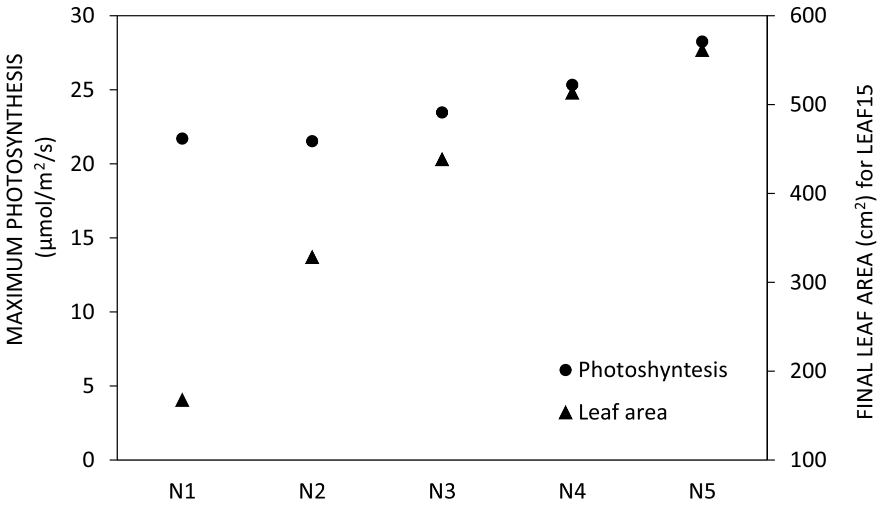

Fig. 15.1 Nitrogen deficit reduces photosynthesis and leaf size. Sunflower plants were grown under five N regimes, with extreme treatments receiving 0.25 (N1) and 7.5 g N per plant (N5). (Adapted from Connor et al. 1993. Aust J Plant Physiol 20: 251–263)

Table 15.1 Nitrogen deficit reduces cell number and size, hence the leaf area of sunflower

	Number of cells	Area per cell	Leaf area
	$\times 10^6$	μm^2	cm^2
High N	56	554	302
Low N	33	443	147

Data are for leaf number 10 at full expansion under high or low N supply. Adapted from Trapani et al. 1999. Ann Bot 84:599–606

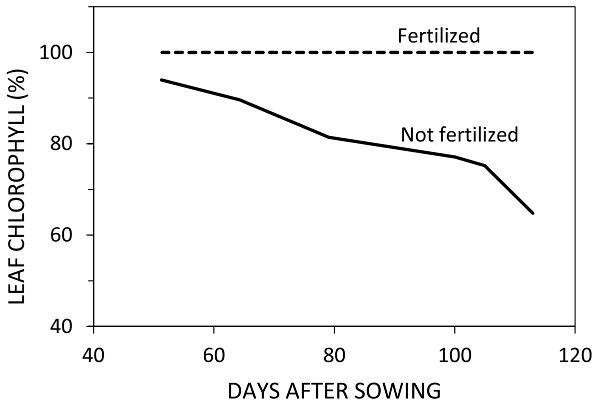

Fig. 15.2 Nitrogen deficiency accelerates leaf senescence of wheat. Leaf chlorophyll, measured in the youngest expanded leaf, is expressed as a percentage of that of fertilized crops. (Adapted from Caviglia and Sadras. 2001. Field Crops Res 69:259–266)

content, hence the link: shortage of nitrogen ➔ less *Rubisco* ➔ less photosynthesis.

The effects of water supply on crop growth and yield (Chap. 14) can also be explained in terms of interception and efficiency in the use of radiation. Water deficits cause irreversible responses such as reduced tillering or branching, and reduced leaf expansion. Reduced stomatal conductance and wilting are transient crop responses to water deficit that reduce crop water use and photosynthesis. Figure 15.3 illustrates the sawtooth pattern of radiation interception in alternating dry-wet periods with transient wilting and recovery after irrigation. In addition to the individual effects of nitrogen and water, these resources often interact in complex ways. In wheat crops growing under a combination of irrigation and fertilizer regimes, *RUE* was 1.8 g/MJ in rainfed, unfertilized crops and increased to 2.1 g/MJ with N fertilization. Weekly irrigation did not improve *RUE* in unfertilized crops, but irrigation combined with N fertilization increased efficiency to 2.5 g/MJ.

In common with water and nitrogen deficits, physical and chemical soil constraints reduce canopy size and interception of radiation, whereas radiation use efficiency is less affected. This is illustrated in the cases of soil compaction and aluminum toxicity.

Soil compaction is a common problem, often caused by tillage, machinery traffic, and loss of organic matter, reflected in increased soil bulk density. Its effects on the crop are two-fold: it hinders the emergence and establishment of seedlings and slows down the growth of the root system and the shoot. The effect of compaction on root growth is quantified by the penetration resistance, which can be measured

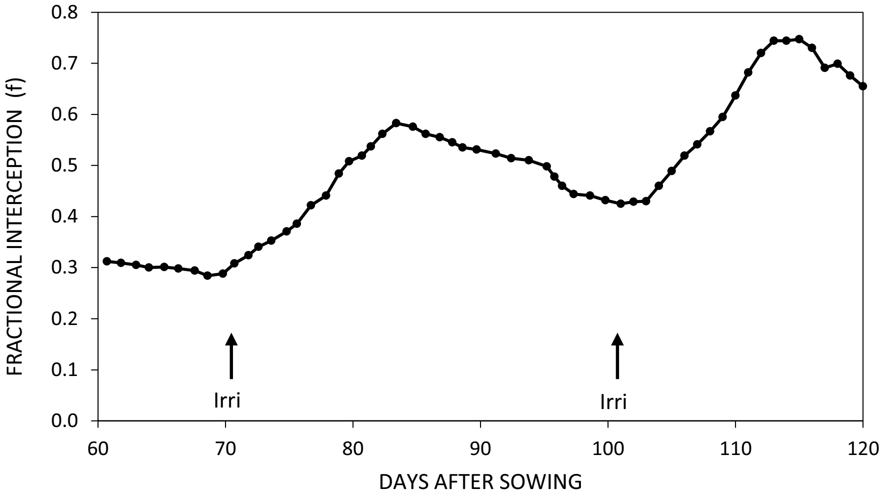

Fig. 15.3 Dynamics of fractional radiation interception of peanut crops. The sawtooth curve of radiation interception results from transient wilting and recovery after irrigation. During this period, *LAI* increased from 0.5 to 2. Arrows mark irrigation events. (Adapted from Matthews et al. 1988. Exp Agric 24:203–213)

with a penetrometer. For a particular soil, penetration resistance is directly proportional to the apparent density and inversely proportional to the water content of the soil. Therefore, the effects of compaction are much more severe when the soil is dry (Chap. 17). In the Mallee region of South-Eastern Australia, sandy soils often develop a compacted layer at 0.2–0.3 m depth, thus restricting root proliferation and water and N uptake below this depth. Crops in compacted soil were compared with crops in soils where compaction was removed by deep ripping (subsoiling). Wheat yield in compacted soil ranged from 1.2 to 2.9 t/ha, and ripping improved yield up to 40%. The reduction in yield associated with compaction was fully accounted for by reduced leaf area index and intercepted radiation, whereas radiation use efficiency was unaffected by soil condition.

Aluminum toxicity reduces yield in acid soils (pH < 5.8), about 30% of agricultural soils worldwide. Growth analysis of Al-tolerant and Al-sensitive wheat cultivars in southern Chile showed a marked reduction in intercepted radiation with soil Al, a largely unresponsive *RUE* in the tolerant wheat and reductions in *RUE* in sensitive wheat only at high Al concentrations (Fig. 15.4).

15.3 Climatic Accidents

We will consider the effect of extreme low temperatures in Chap. 32 and the effects of wind in Chap. 31.

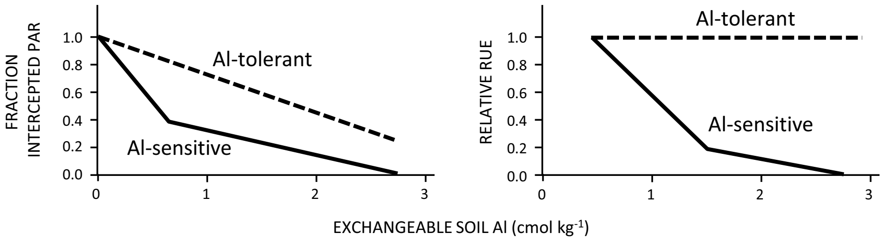

Fig. 15.4 Effects of soil aluminum toxicity on (**a**) intercepted radiation and (**b**) radiation use efficiency of wheat crops. (Adapted from Valle et al. 2009. Field Crops Res 114:343–350)

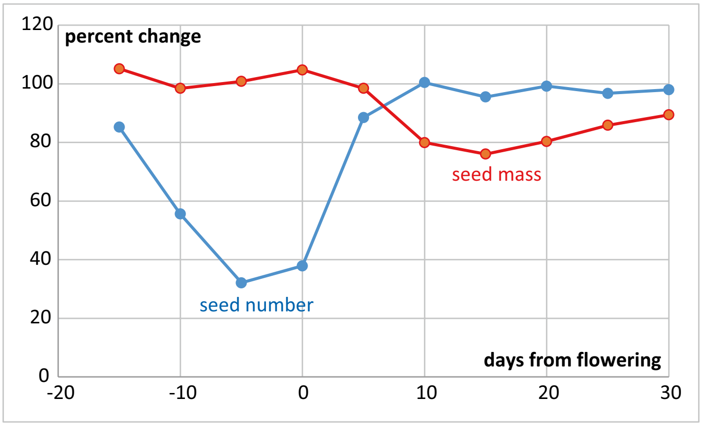

Fig. 15.5 Influence of high temperature stress (36/25 °C during 5 days) at different times relative to flowering on wheat grown at 25/15 °C. Floret fertility (% of control), grain weight (% of control). (Adapted from Prasad PVV, Djanaguiraman M. 2014. Funct. Plant Biol. 41:1261–1269)

15.3.1 High Temperature

The effect of heat depends on the timing, duration, and intensity of the stress. Yield reductions are more severe for heat events during a critical period, with the consequent reduction especially in grain number while grain size is less affected, as illustrated in Fig. 15.5. Late-season high temperatures can reduce grain size by shortening the grain growth period and indirectly, by accelerating leaf senescence. In Mediterranean climates, low water availability is coincident with high temperature so low transpiration due to water stress amplifies heat stress as canopy temperature increases due to stomatal closure.

Maximum canopy temperature differs from maximum air temperature. Turbulence is a main determinant of that difference that decreases as wind speed increases. On the other hand, water deficits that induce stomatal closure decrease transpiration cooling and thus increase canopy temperature. Therefore, the impact of high temperatures on crops is amplified by water deficits. Here we present a simple procedure for calculating the expected maximum crop temperature from standard weather data.

Using Eqs. 9.8 and 9.10, we compute the maximum canopy temperature as:

$$T_{cx} = T_{ax} + \left[\left(1 - f_G\right) R_n - LE\right] \frac{r_{aH}}{\rho C_p} \tag{15.1}$$

where T_{cx} and T_{ax} are the maximum canopy and air temperature (°C), respectively, f_G is the fraction of net radiation invested in soil heat flux (taken as 0.1 during the daytime), LE is the latent heat flux, r_{aH} is the aerodynamic resistance for heat exchange, ρ is the air density, and C_p is the specific heat of air.

This equation is evaluated at the time of maximum temperature, which is assumed to occur 3 h after solar noon. At that time, solar radiation on sunny days is approximately 84% of the value at solar noon. We also assume that on average on sunny days, net radiation is 60% of solar radiation, so:

$$R_{nx} = 0.6 \cdot 0.84 \cdot \frac{\pi}{2} \cdot \frac{10^6 R_{sd}}{3600 N_s} \tag{15.2}$$

where R_{nx} is the net radiation (W m^{-2}) at the time of maximum temperature, R_{sd} is the daily solar radiation (MJ m^{-2} day^{-1}), and N_s is the day length (hour).

The time course of latent heat flux (LE) in the daytime is assumed to follow a sine function, with the maximum occurring at the time of maximum air temperature. Therefore, the maximum LE (LE_x, W m^{-2}) is:

$$LE_x = \frac{\pi}{2} \cdot \frac{2.45 \, ET}{10^{-6} \, 3600 \, N} \tag{15.3}$$

where ET is the daily actual evapotranspiration (mm day^{-1}).

Calculation of r_{aH} for unstable conditions may be performed using a simplified equation derived from the model of Thom and Oliver as a function of wind speed over grass at 2 m height (U_{2g}):

$$r_{aH} = \frac{25.9}{1 + 2.3 \, U_{2g} / c_w} \tag{15.4}$$

The coefficient c_w depends on crop height (h) and lies between 7.3 (h = 0.5 m) and 5.5 (h = 3 m).

Wind speed at the time of maximum temperature is calculated by assuming that the mean daytime wind speed is twice the mean value during the nighttime and that the value during the day is a sine function. Therefore, at the time of maximum temperature, wind speed at the weather station is:

$$U_{2gx} = \left(1 + \frac{\pi}{2}\right) \frac{U_{2gm}}{1 + N/24} \tag{15.5}$$

where U_{2gm} is the mean (24 h) wind speed at the weather station.

For field crops, typical values of r_{aH} are between 6 (high wind speed) and 12 s/m (moderate wind speed) with only a minor effect of crop height.

These equations show how water deficit interacts with air temperature and wind to determine crop temperature (see Example 15.1).

Example 15.1

Wheat at flowering stage at Cordoba, Spain.

11 April 2014. c_w=6.6, day length = 13 h

Maximum air temperature 29.7 °C, Reference ET = 5.1 mm/day, R_{sd} = 22.7 MJ m^{-2} day^{-1}

Mean wind speed (weather station) = 2.3 m/s

The maximum crop coefficient of wheat during this period is 1.1 (Chap. 10) so:

$$ET = 1.1 \times ET_0 = 56\text{mm / day}$$

Maximum wind speed (weather station):

$$U_{2gx} = \left(1 + \frac{\pi}{2}\right)\frac{U_{2gm}}{1 + N/24} = 1.667 \cdot 2.3 = 3.84\,\text{m / s}$$

Aerodynamic resistance:

$$r_{aH} = \frac{25.9}{1 + 2.3 \cdot 3.84 / 6.6} = 11.1\,\text{s / m}$$

Maximum net radiation and LE over the canopy:

$$R_{nx} = 0.6 \cdot 0.84 \cdot \frac{\pi}{2} \cdot \frac{10^6 R_{sd}}{3600\,N} = 384\,\text{W m}^{-2}$$

$$LE_x = \frac{\pi}{2} \cdot \frac{2.45 \cdot ET}{10^{-6}\,3600 \cdot N} = 460\,\text{W m}^{-2}$$

So maximum canopy temperature will be:

$$T_{cx} = T_{ax} + \left[\left(1 - f_G\right)R_{nx} - LE_x\right]\frac{r_{aH}}{\rho C_p} = 29.7 + \left[\left(1 - 0.1\right)384 - 460\right]\frac{11.1}{1184}$$
$$= 29.7 - 1.1 = 28.6\text{°C}$$

(continued)

Example 15.1 (continued)

If water deficit occurs and actual *ET* is 50% of maximum *ET* ($LE = 460/2 = 230$ W m^{-2}):

$$T_{cx} = 29.7 + \left[(1-0.1)384 - 230\right]\frac{11.1}{1184} = 29.7 + 1.1 = 30.8°\text{C}$$

If the crop had maximum stress (zero *ET*):

$$T_{cx} = 29.7 + \left[(1-0.1)384 - 0\right]\frac{11.1}{1184} = 29.7 + 3.2 = 32.9°\text{C}$$

15.3.2 Hail

Hail is a form of solid precipitation consisting of ice balls or lumps that originate in strong thunderstorm clouds (cumulonimbi). The diameter of hailstones is typically between 5 and 12 mm. Hail occurrence is localized over areas from a few to hundreds of hectares.

Hail is more common in mid-latitudes (inland areas, elevated regions) than in the tropics despite the higher frequency of thunderstorms in the latter. Hailstorms are common in Northern India and parts of China and Central Europe. During the year, hail will occur mostly during spring and summer.

Hail crop damage is due to the impact of hailstones whose velocity is proportional to size. For a 1 cm diameter hailstone, terminal velocity could reach 9 m/s while an 8 cm hailstone would fall at 48 m/s. Apart from the direct physical damage that destroys leaves or reproductive structures, wounds facilitate infection by pathogens. The effect of defoliation due to hail on crop yield depends on the development stage when hail occurs and the level of defoliation. Partial early defoliation may be compensated by increased dry matter allocation to leaves resulting in a small reduction in yield. Full defoliation before anthesis may be catastrophic for yield. Damage to reproductive structures leads to a reduced harvest index in proportion to the number of structures affected. Partial damage to fruits greatly reduces their commercial value.

High-value crops may be protected with anti-hail nets. In field crops or extensive fruit production, nets are not feasible so the best option is crop insurance. Silver iodide is also used with anti-hail rockets or ground generators. This compound increases the number of deposition nuclei within the cloud, so more hail particles with smaller sizes will form.

15.4 Waterlogging

High soil water content implies a limited oxygen supply for root respiration, so root function (absorption, growth) is impaired. If the soil is saturated, the roots decompose starting from the tips, and the plant stops growing and eventually dies. Most often, crops suffer from temporal waterlogging events and recover partially afterward, but the poor root system may compromise water and nutrient absorption at high-demand periods. This is particularly important in some cropping systems as in the high-rainfall areas of Victoria, Australia or in the clay soils of Southern Spain where drought late in the season follows early-season waterlogging.

Waterlogging contributes to N losses by denitrification (see Chap. 26), the conversion of nitrate to volatile N compounds. Low N uptake will cause symptoms of N deficiency.

Waterlogging may be prevented by improving the field drainage or using raised beds at planting.

15.5 Biotic Factors

Biotic agents causing crop damage (generically known as pests) are weeds, animal pests (arthropods, nematodes, gastropods, rodents, and birds), and pathogens (fungi, bacteria, and viruses).

The effect of pests and diseases on crop growth can also be analyzed in terms of capture and efficiency in the use of radiation, and harvest index (Eq. 13.3). Insects that feed on reproductive structures, such as cotton bollworms, have a primary effect on harvest index. In extreme cases of uncontrolled infestation, cotton crops can accumulate large amounts of biomass with little fruit set, i.e. low harvest index and yield. Defoliators reduce leaf area and intercepted radiation, whereas some diseases can also reduce the photosynthetic rate of individual leaves and *RUE*. Spider mites, for example, pierce the leaf epidermis with needle-like mouthparts and feed on mesophyll and palisade cells, thus reducing leaf photosynthesis and *RUE* (Fig. 15.6).

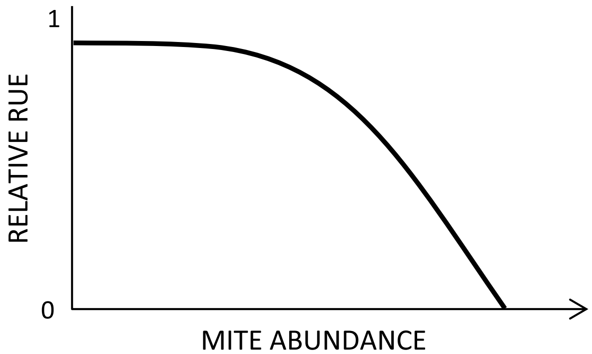

Fig. 15.6 Spider mites feed on mesophyll and palisade cotton leaves, reducing leaf photosynthesis and radiation use efficiency. (Adapted from Sadras and Wilson. 1997. Crop Sci 37:481–491)

Comparisons of wheat crops protected with fungicides and unprotected crops exposed to damage by foliar pathogens showed that growth reduction was mostly associated with reduced healthy leaf area, with a secondary contribution of reduced radiation use efficiency.

15.5.1 Arthropods

Many species of insects and other arthropods are present in the agro-ecosystem but only a few are important pests, causing severe yield loss. Insects are six-legged invertebrates that usually undergo metamorphosis during development. Adult insects have three body regions (head, thorax, and abdomen), three pairs of legs, one pair of antennae, complex mouthparts, and frequently two pairs of wings. The skin of an insect is the exoskeleton, which covers the whole body.

All insects have an egg and an adult stage. Complete metamorphosis includes 4 stages (egg, larva, pupa, and adult). The most common, foliage-eating insect pests are larvae of *Lepidoptera* (butterflies and moths) and larvae and adults of *Coleoptera* (beetles). Aphids, leafhoppers, and thrips not just feed on the crop but are also transmission vectors of bacteria and virus diseases. Recent episodes of bacteria and virus diseases transmitted by leafhoppers are affecting the citrus and olive industries worldwide.

Many insect species are predators or parasites of other insects and are, thus, beneficial, so pest control should avoid damaging them.

15.5.2 Plant Pathogens

Plant pathogens (fungi, bacteria, and viruses) affect crop plants by altering the following processes:

– Photosynthesis: Destruction of photosynthetic tissue, degradation of chloroplasts, leaf senescence, yellowing, etc.
– - Water and nutrient transport: Destruction of roots, formation of root galls and root knots, impaired root absorption, destruction or blocking of xylem tissue, damage to leaf cuticles or stomatal function (higher transpiration), and altered phloem transport.
– Plant respiration may increase after infection and reduce growth and plant reserves.
– Membrane permeability may increase causing leaf damage by nutrient losses and entry of toxins.
– Changes in transcription and translation of nucleic acids, which alter plant function and structure and the synthesis of enzymes or substances involved in plant resistance.

The disease starts with a primary infection (first in the season) due to primary inoculum (spores or fungal mycelium) that overwinters, i.e. survives from one growing season to the next.

The probability of a disease epidemic is proportional to the amount of inoculum and the proximity to its host. Primary infection occurs when the pathogen is in contact with a susceptible host under suitable conditions. The pathogens enter directly through the plant's surface, wounds, or natural openings. Bacteria and fungi require free water for spore germination, so infection is favored by wet periods with high air humidity and by wet canopies.

Dissemination of the pathogen from an inoculum source to a host can occur by wind, rain splash, runoff, insects, infected seeds or seedlings, etc. Fungi grow and spread within their host employing mycelium, and eventually produce spores on or within the infected tissue. These spores lead to secondary infections during the season. Bacteria spread in the plant by rapidly increasing the population. Then, when fissures develop on infected tissue, the cells (secondary inoculum) are exposed to the environment and thus, dissemination may proceed.

The secondary infection cycle can be repeated many times during the growing season, depending on the biology of the pathogen and its host and environmental conditions.

15.5.3 Yield Losses Due to Pests

The crop yield loss due to pests may be characterized by an actual and a potential value. The *potential yield loss* occurs with no pest control and the *actual loss* is that observed despite the crop protection practices. The *efficacy* of the crop protection practices may be quantified as a percentage of potential losses prevented. The potential and actual losses vary with crop species, pest, and environment. The total loss potential of all biotic factors worldwide varies between 50% (wheat) and more than 80% (cotton). Actual losses are estimated at 26–31% for soybean, wheat, maize, and cotton, and 37–40% for potatoes and rice, respectively (Table 15.2).

Table 15.2 Yield losses due to pests at a global scale

		Wheat	Rice	Maize	Potato	Soybean	Cotton
Weeds	Potential	23	37	40	30	37	36
	Actual	8	10	10	8	7	9
	Efficacy	67	73	74	73	80	76
Animal pests	Potential	9	25	16	15	11	37
	Actual	8	15	10	11	9	12
	Efficacy	9	39	40	29	18	67
Pathogens and viruses	Potential	18	15	12	29	12	9
	Actual	13	12	11	21	10	8
	Efficacy	30	20	9	28	19	15
Total	Potential	50	77	68	75	60	82
	Actual	28	37	31	40	26	29
	Efficacy	43	51	54	46	56	65

Adapted from Oerke EC (2006)

Potential and actual yield losses (%) are those occurring in a no-control and a current control scenario, respectively. The efficacy of control is the percentage of losses prevented by current control measures

Overall, weeds have the highest loss potential (23–40%) with animal pests and pathogens being less important and of similar weight (9–37% and 9–29%, respectively). Although viruses cause serious problems in potatoes and sugar beets in some areas, worldwide losses due to viruses average 6–7% on these crops and <1–3% on other species. The efficacy of crop protection lies between 43% and 65% for the different crops. Global efficacy in weed control (67–80%) is much higher than that of animal pests (9–67%) or diseases (9–30%). These values have to be taken only as indicative as they are based on estimates of reference yields (not affected by pests).

Table 15.2 shows also the possible impact of restrictions on pest control brought about by environmental concerns. If we abandoned pest control, we would have an impact on yields equal to the difference between potential and actual yield loss, i.e. between 22 (wheat) and 53% (cotton).

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Part III

Crop Management

Sowing and Planting

16

Francisco J. Villalobos, Francisco Orgaz, and Elias Fereres

Abstract

Successful crop establishment depends on several factors at the time of sowing (soil water content, soil structure and soil temperature, seed viability, presence of pests). Therefore, decisions regarding the date and depth of sowing, planting density, spatial arrangement of plants, and other cultural techniques (irrigation, fertilization, application of pesticides) will be critical. The sowing date should match the growing cycle to the best possible environmental conditions for the crop. Early spring sowings improve water use efficiency in Mediterranean areas but increase the risk of attacks by biotic factors. The seeding rate is a function of single seed mass, desired planting density, seed viability, and expected fraction of emerged plants. Trees and some annual species are sown in nurseries where they grow for some time until they are transplanted to the field. The best time for planting trees is autumn when they are dormant and the risk of desiccation is minimal.

16.1 Introduction

By sowing or planting the farmer intends to ensure good crop establishment and get the right conditions for growth, development, and yield. For many crops, the establishment phase (germination, emergence, and early seedling growth) is the most

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critical phase of the cycle. To succeed, the farmer must make a series of decisions related to the amount of seed to be used, the method of planting and the spatial distribution of seeds, the planting date, the application of pesticides, or performing additional tasks like irrigation.

16.2 Crop Emergence

Soon after sowing the seeds, the seedlings will emerge from the soil. The duration of this period and the success, i.e., the fraction of seeds leading to emerged seedlings, depend on several factors:

- Seed viability: A viable seed is one able to germinate under suitable conditions. Viability decreases with time from the harvest of the seeds and occurs in parallel to the loss of reserve substances (e.g., lipid oxidation in sunflower seeds). In some species, some mechanisms delay seed germination, such as the presence of germination inhibitors or waterproof coats. For these cases, germination may be improved by scarification (mechanical abrasion or chemical treatment with acids to increase the permeability of seed coats) or stratification (placing the seeds between layers of cold (1–5 °C) moist soil).
- Soil water content: Germination is a process that begins with water uptake by the dry seed (imbibition). If the soil is dry or the contact seed soil is loose, the water transport from the soil to the seed is prevented, and germination does not proceed. After germination, the radicle expands, which contributes to guaranteeing the supply of water to the seedling. The increase in depth of the radicle occurs in advance of hypocotyl growth, so that, at the time of emergence, root depth normally exceeds 10 cm.
- Temperature: Along with depth, temperature will determine the duration of the sowing-emergence period. If this period is too long, the likelihood of attacks by pathogens or soil insects increases. Table 16.1 shows the average values of thermal time from sowing to emergence and its base temperature for a series of annual crops.
- Soil structure: the presence of a surface crust or excessive soil compaction above the seed makes emergence difficult as they prevent the expansion of the hypocotyl, especially if the soil is dry (Chap. 17). A greater amount of seed or wetting of the soil can contribute to mitigating the effects of the surface crust.
- Presence of pests or pathogens: during emergence and initial seedling growth, attacks by insects or soil fungi can often lead to a failure of crop establishment. To avoid this problem, fungicides (seed treatment) and/or insecticides (seed and/or soil treatments) are applied.
- Oxygen concentration in the soil: the processes of germination and emergence use energy derived from the seed reserves through respiration, which is an aerobic process. This is why the fraction of emerged plants can be greatly reduced in waterlogged soils.

Table 16.1 Base temperature (T_b, °C) and thermal time (TT, °Cd) required to complete the phase sowing-emergence for different species

	Thermal time	T_b
	°C d	°C
Amaranthus	32	11.7
Barley	120	0
Bean	52	10.6
Buckwheat	37	11.1
Castor bean	95	12.5
Chickpea	94	4.5
Cotton	60	15.5
Cucumber	40	15.5
Faba bean	200	1.2
Lentil	90	1.4
Linseed	89	1.9
Maize	75	8
Melon	52	15.5
Millet (finger)	40	13.5
Millet (foxtail)	42	10.9
Millet (pearl)	40	11.8
Millet (proso)	45	10.4
Oats	132	1.6
Pea	110	1.4
Peanut	76	13.3
Pepper	135	13
Rapeseed	79	2.6
Rye	91	2.2
Ryegrass	130	2
Safflower	70	7.4
Sesame	21	16
Sorghum	74	8
Soybean	70	9.9
Sunflower	67	7.9
Tomato	57.5	9.3
Trifolium spp.	150	0
Watermelon	55	15.5
Wheat	110	0

Adapted from Angus et al. (1980) Field Crops Res 3:365–378 and Moot et al. (2000) New Zealand J Agric Res 43:15–25

These values were obtained under field conditions with high soil water content in the soil and a planting depth of about 3 cm

16.3 Decisions Related to Sowing

The farmer has to make a series of operational decisions before sowing the crop, such as date of sowing, amount of seed (seeding rate), sowing depth, and the planting pattern (row distance, plant spacing within the row). Additional operations may be required such as fertilization, irrigation, application of pesticides, or tillage.

The method of sowing, which may imply the selection of the planting machinery (e.g., seed drill), is a key strategic decision for the farmer.

16.4 Sowing Date

The choice of sowing date has to ensure that the crop cycle matches the most suitable period for growth and yield. The first limitation on the growth of a crop is its ability to survive when exposed to low temperatures. In mid-latitudes, this limitation allows classifying crops into two categories:

(a) Autumn sown crops: species able to withstand frost and grow at low temperatures (winter cereals, rapeseed, flax, faba beans, beets, etc.). They have a low base temperature.
(b) Spring plantings: species with high base temperature (corn, cotton, soybeans). They are damaged even by low temperatures above freezing.

Regardless of the type of crop, early plantings have several advantages:

(a) Water use efficiency is inversely proportional to the vapor pressure deficit (Chap. 14). If crops are grown under low evaporative demand (early planting date), they produce more biomass and will require less water in irrigated conditions. This is especially important in Mediterranean climates as rainfall decreases and evaporative demand increases from spring to summer.
(b) The grain-filling process is more efficient and longer if the temperature is not too high. If we prevent this process from occurring under high temperatures, the harvest index will increase, and so will yield.
(c) In some spring-summer crops, the cycle may be terminated by cold temperatures in autumn (e.g., cotton). Therefore, early sowing favors crop maturing before low temperatures stop crop development. Additionally, autumn precipitation may adversely affect crop quality.
(d) In some horticultural crops, the price is directly proportional to precocity (melon, watermelon, etc.); thus, early sowing allows increased revenue.

Early planting may be limited by possible negative effects later in the growing season. For winter cereals, it is critical to avoid frost during anthesis. This is achieved by preventing excessively early plantings and/or using longer-season cultivars such as winter types with large vernalization requirements. The environmental conditions at the time of sowing may also restrict early sowings:

– If the temperature is too low, the crop takes a long time to emerge and establish, allowing the attack of biotic agents and leading to a significant reduction in the fraction of established plants. Also under low-temperature conditions, weed competition will be more severe. We should sow when the temperature is such that the sowing-emergence period does not exceed 15–20 days. To calculate the time from sowing to emergence as a function of temperature for different crops, we can use the information presented in Table 16.1.

– Water content in the soil at the time of sowing should ensure seed imbibition and the water supply to the seedlings after they emerge. In Mediterranean areas, the autumn sowing is usually delayed until the rains have been sufficient and evaporative demand is low. Sowing over partially dry soil may cause relatively early emergence (with high evaporative demand), but seedlings may die if the rains do not continue.

16.5 Seeding Rate and Planting Density

The amount of seed to be applied per unit area (seeding rate) depends on the cost of the seed and the planting density desired.

(a) Cost of seed: In general, the cost of seed is a low fraction of total cultivation costs. However, the consequences of using a small amount of seed or low-quality seed may be extremely negative (see the importance of obtaining a suitable planting density in Chap. 12). We should use high-quality seeds. The indices used to characterize the quality of the seed are viability (germination percentage) and purity (proportion of the seed belonging to the acquired cultivar). The seed should be free of pests, diseases, and weed seeds and have a suitable size. The probability of emergence and the growth rate of the seedling afterward are both proportional to seed size.

(b) Density: The amount of seed used must be sufficient to ensure the emergence and establishment of a sufficient number of seedlings. The required excess of seed depends on various factors (seed viability, soil structure, pathogens, water content, etc.).

The seeding rate (QS, g m^{-2}) may be calculated as:

$$\mathrm{QS} = \frac{p_u D_p}{f_1 f_2} \tag{16.1}$$

where p_u is the mass of each seed (g/seed), D_p is the desired planting density (plants m^{-2}), f_1 is the viability (fraction), and f_2 is the fraction of viable seeds that become established plants. Seed mass (p_u) can be measured directly by weighing a known number of seeds or estimated using Table 16.2, which also shows intervals of D_p for various crops. Viability (f_1) depends largely on the quality of the seed and is usually above 0.9 for certified seed. The value of f_2 depends greatly on the state of the soil at planting, sowing depth, and environmental conditions after planting. Under adverse conditions, f_2 will be proportional to seed size.

Table 16.2 Mass per seed, planting density, and minimum amount of seed required for different crop species

Crop	Mass (fresh) per seed mg/seed			Planting density plants/m^2			Seed rate kg seed/ha		
	Min	Max	Average	Min	Max	Average	Min	Max	Average
Alfalfa	2.1	2.3	2.2	400	500	450	8	12	10
Cotton	100	120	110	5	10	7.5	5	12	8
Lupin (white)	200	320	260	30	60	45	60	192	117
Lupin (yellow)	100	130	115	30	60	45	30	78	52
Oats	30	45	37.5	130	250	190	39	113	71
Safflower	30	50	40	25	50	37.5	8	25	15
Barley	30	50	40	150	230	190	45	115	76
Rye	25	35	30	140	250	195	35	88	59
Rape	2.5	4	3.25	50	180	115	1	7	4
Chickpea	50	70	60	25	45	35	13	32	21
Sunflower (oil)	100	140	120	6	12	9	6	17	11
Sunflower (seed)	150	180	165	4	7	5.5	6	13	9
Pea	125	300	212.5	35	100	67.5	44	300	143
Faba bean	350	800	575	15	50	32.5	53	400	187
Bean	130	500	315	25	10	17.5	33	50	55
Lentil	20	80	50	100	150	125	20	120	63
Flax	5	7	6	100	400	250	5	28	15
Maize	350	400	375	7	10	8.5	25	40	32
Sugar beet	20	20	20	6	9	7.5	1	2	2
Soybean	100	200	150	15	60	37.5	15	120	56
Sorghum (grain)	20	30	25	10	13	11.5	2	4	3
Sorghum (forage)	20	30	25	80	140	110	16	42	28
Clover	0.6	0.8	0.7	500	900	700	3	7	5
Wheat	30	45	37.5	150	250	200	45	113	75
Triticale	30	50	40	180	220	200	54	110	80
Vetch	20	30	25	200	300	250	40	90	63
Potato	23000	30000	27000	7.5	13.3	10	1725	3990	2700
Garlic	1500	6000	3500	20	28	24	300	1680	840
Garlic white type	1000	8000	5000	20	28	24	200	2240	1200
Onion	4	10	7	60	90	80	2.40	9.00	5.60
Pepper	5	10	7	4	6	5	0.20	0.60	0.35
Tomato	2.2	3.3	2.8	2	6	4	0.04	0.20	0.11
Melon	29	47	38	0.4	1	0.7	0.12	0.47	0.27
Watermelon	35	60	47	0.25	1	0.75	0.09	0.60	0.35
Leek	2.5	3.2	2.8	16	38	25	0.40	1.22	0.70

Example 16.1

We will calculate the seeding rate for wheat to obtain a density of 150 plants m^{-2} if the percentage of viable seeds that emerge is 90% and the seed has a viability of 0.95.

In Table 16.2, we see that wheat seed mass is between 30 and 45 mg. If we take an intermediate value (37 mg/seed), the seeding rate should be:

$$QS = \frac{37\ 10^{-3} \cdot 150}{0.9 \cdot 0.95} = 6.5\ \text{g m}^{-2} = 65\ \text{kg/ha}$$

16.6 Sowing Depth

The more appropriate sowing depth depends on the temperature and water content of the soil. In general, soil water content increases with depth, while temperature and oxygen availability decrease. The greater the sowing depth, the greater expansion of the hypocotyl required to reach the soil surface. If the depth is excessive, reserves would be exhausted before emergence. Therefore, larger seeds allow deeper sowings. Large seeds (faba beans, beans) allow depths up to about 15 cm, while the medium-sized seeds (winter cereals, sunflower, cotton) should not exceed around 10 cm sowing depth, and small seeds (onion, carrot) allow less than 3 cm. In the latter case, it is difficult to ensure adequate soil water content in the surface layer, requiring irrigation for successful emergence.

The rules about sowing depth may show remarkable exceptions. For instance, in the dry inland area of the Pacific Northwest of the USA, winter wheat is sown in late summer at depths as large as 20 cm to ensure water supply to the seed and crop emergence.

16.7 Planting Pattern and Sowing Method

Crop plants are usually sown in rows at spacings between 0.15 and 0.20 m (cereals, rapeseed) and 1 m (e.g., cotton). Wide separations between rows were often required for mechanical control of weeds. The use of herbicides has allowed for narrowing the inter-row spacing, which contributes to increasing the radiation interception.

In many species, yield is relatively independent of the distance between plants (e.g., winter cereals). In some (garlic, beets), excessive crowding can lead to lower yield or poor quality of the harvested product.

The sowing method to be used depends on the crop type, soil conditions, and available machinery. The methods used are:

(a) Broadcasting: the seeds are randomly distributed in the field. The application can be done by hand, using centrifugal fertilizer broadcasters, or an airplane, as in the case of rice. Usually, broadcasting sowing requires further operations to bury the seeds and carries a high seed cost, poor distribution uniformity, and irregularity in sowing depth.
(b) Sowing in furrows: This is done by opening furrows in the soil and depositing the seeds inside, usually performed with a seed drill. This drill has the necessary equipment to open the furrow (shoe type, hoe type, or disk), deposit the seeds, and close the furrows (plank, disks). In some cases, to allow post-emergence tillage and achieve optimum planting density, crop rows are distributed non-uniformly as in the case of the paired lines, in which the lines are grouped in close pairs, separated from the next pair by enough distance to allow inter-row tillage operations.

Precision seed drills provide a better distribution of seeds, which saves seed and, in some cases, avoids the need for plant thinning (e.g., sugar beet).

16.8 Additional Operations

At the time of sowing, other farming operations that contribute to crop establishment may be performed:

(a) Irrigation: The application of irrigation may be needed to ensure germination and emergence. In soils that form surface crust, more than one irrigation application may be needed to prevent hardening of the crust.
(b) Tillage: Pre-planting tillage should form a suitable seedbed. This entails small aggregates on the surface and sufficient soil water content in the upper layer. In some sowing methods, the seed, once deposited in the soil, should be covered by harrowing. In other cases, it may be necessary to compact slightly the soil surface to ensure water supply to the seed (e.g., roller pass in small seed crops). Soil compaction after sowing also contributes to soil warming (Chap. 6) and thus to faster emergence.
(c) Fertilizers and pesticides: It is common to apply fertilizers (P, K, and some N) and other products (e.g., pesticides) while preparing the seedbed. Some seed drills allow localized fertilizer application at sowing time, which can be of interest in poor soils, especially for P and K (Chap. 28). Other products (soil insecticides, pre-emergence herbicides) may be applied along with the seed.

16.9 Transplanting of Annuals

In the case of some horticultural crops, seedlings are grown at a place (nursery) for some time and then transplanted to the field. The need for transplantation may be due to different causes:

(a) High seed cost, poor germination success, and/or delicate seedlings: The conditions in the nursery can be manipulated to provide a suitable environment for the seedlings. This can be achieved by soil heating or using plastic or glass covers. The associated cost will be acceptable in the nursery because of its small size.
(b) The need to shorten the cycle: In the nursery, we can maintain proper moisture and temperature, hastening the crop cycle when external conditions are unfavorable.

The structures used as nurseries range from natural shelters to greenhouses. In the nursery, seeds are planted at high density. Seedlings are maintained in the nursery until their final transplanting to the field. During that time, some thinning of plants may be required to avoid etiolation.

16.10 Transplanting and Grafting of Trees

Trees of agricultural interest are usually fruit trees with planting densities ranging from 50 to more than 1000 trees/ha. Some species with industrial interest (e.g., rubber tree, cork oak) and ornamental trees and shrubs may be also of commercial value. Plantations of fruit trees are established to last for long, typically more than 15–20 years. Fruit tree species may be evergreen (citrus, olive) or deciduous (pome fruits, stone fruits, nuts).

Plantations are established by transplanting young trees grown in nurseries. Trees may be planted at any time of the year if temperatures are not too low. However, successful establishment requires an adequate balance between root water uptake and water loss by transpiration to avoid desiccation and death. The best time for planting is autumn when the tree is dormant, the air temperature is low, and the soil temperature is still warm, which enhances root growth. Leafless trees of deciduous species may be planted as bare-root trees in autumn or spring. Evergreen species have active root systems, so they are transplanted directly from the pots where they have grown in the nursery.

A typical limiting factor for tree growth is soil compaction, so breaking any compacted soil layers by deep vertical tillage is common practice before transplanting.

Although not specifically planting operations, pruning allows renovating the tree structure, while grafting is used to change the cultivar (scion), which constitutes most of the tree shoot while keeping the rootstock.

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Tillage

17

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Abstract

Tillage has been developed in farming to improve soil conditions concerning water balance and crop growth, to incorporate crop residues, and for weed control and seedbed preparation. The effects of tillage depend greatly on the water content and the soil characteristics. Clay soils are rarely found under more suitable conditions for tilling, which are easier to find on medium- or coarse-textured soils. The main undesirable effects of tillage are soil compaction, which leads to lower crop yields and soil degradation, particularly due to water erosion (Chap. 18). Erosion of the surface soil layers reduces the natural fertility and water retention capacity of soils.

17.1 Introduction

From the point of view of farming, the soil has often been viewed as a mere medium on which the crop grows. Thus, soil structure should be suitable for germination of seeds and growth of roots and must have characteristics that enhance the storage and supply of water, nutrients, gases, and heat to the crop. From this perspective, tillage is inseparable from agriculture. The transformation of a natural ecosystem into an agroecosystem requires a mechanical intervention on the soil. Since hoe tillage, and later the Roman plow, followed the appearance of the moldboard plow and,

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finally, the development of mechanical traction, tillage and crop cultivation have been virtually synonymous.

Each soil-crop-climate system presents specific problems that require different tillage operations, which has led to the development of diverse machinery whose engineering is well known. Unfortunately, much less is known about the effects of tillage on physical, chemical, and biological soil properties and ultimately on the effects on crop yield. This limited knowledge is often translated into tillage practices whose only rationale is the habit or tradition from the times when tillage was performed using animal power.

In Western agriculture conventional tillage, which is characterized by a large number of operations, using diverse implements and powerful tractors is increasingly challenged by the high cost of energy expenditure and by soil degradation resulting in different environmental problems in numerous agricultural areas. The rationalization of tillage requires considering the soil as a valuable resource and should be based on a better understanding of the effects of tillage on soil properties and crop production, which is the objective of this chapter.

17.2 Objectives of Tillage

Traditionally tillage had three main objectives, seedbed preparation, improving soil conditions for crop growth, and controlling weeds. However, goals have changed with the appearance of new technologies (herbicides, seed drills), new issues or problems (compaction, erosion, offsite contamination), and a better understanding of the relevance of some soil functions (such as carbon sink or natural filter of water). In rainfed agriculture, tillage is also an essential tool to modify water balance to improve the availability of water for the crop.

17.2.1 Seedbed Preparation

This is a process that often requires the removal of the residues of previous crops. Removal can be done by burning the residues or burying them with certain operations. The burning of stubble is a fast and cheap method that has been widely used in the past and has some clear advantages, such as elimination of weed seeds, destruction of propagules of pathogens and insect eggs and larvae, and immediate release of some nutrients. But burning causes a loss of organic matter and N (lost as volatile N oxides), contributing to air pollution and anthropogenic CO_2 emissions. It also promotes soil degradation and increases wildfire risk.

After clearing the residues, we can prepare the seedbed, which ideally consists of a surface layer of granular structure with a high percentage of aggregates smaller than the seed. In general, this objective is achieved only when tillage is performed with a soil water content close to field capacity and is called optimum soil water content for tillage (*OPT*, e.g., Dexter & Bird, 2001) (see Sect. 17.3). In some cases, it is necessary to compact slightly the seedbed with a roller compactor to enhance seed-soil contact and hydration of the seeds. Furthermore, below the depth of planting, the soil must have a lower bulk density to allow root growth without restrictions, which is often achieved by previous deeper tillage.

17.2.2 Weed Control

Before the advent of herbicides, tillage was the only effective method for controlling weeds. The control may be direct by destroying the plants, cutting the roots or the stem, or burying them. The control may be indirect, by changing the position of weed propagules or changing the environmental conditions of the weed seed bank. For example, the moldboard plow buries many seeds below a certain depth, making them unable to emerge. In other cases, such as weeds that propagate through underground organs (tubers, rhizomes), tillage contributes to cutting such organs and therefore enhances the dispersion of the weed when the soil is wet, but it may have the opposite effect when the soil is dry as the weed propagules would desiccate.

In this tillage strategy for controlling weeds, it is essential to till immediately before planting to minimize weed-crop competition. This operation can reduce the water content of the seedbed and therefore cause poor seedling emergence in dry areas. This occurs, for example, in spring sown rainfed sunflower. This negative effect can be solved by replacing the tillage operation with a pre-plant herbicide application.

In those crops for which there are no selective herbicides or when they are not very effective against the weed community, inter-row tillage operations will be required after crop emergence. Although it is possible to control weeds only with tillage, herbicide use, at least partially, is often a much more effective alternative in terms of cost and time.

17.2.3 Modification of Water Balance

In rainfed crops, the main objective of tillage is to improve water balance to maximize the availability of water for the crop. In a natural ecosystem, with the soil covered by vegetation, the macropores formed by the roots and mesofauna allow high and stable infiltration rates even at relatively high bulk density. The situation is very different in an agroecosystem as seedbed preparation involves the traffic of machinery and the surface of the soil is kept bare. This kind of tillage results in a low bulk density but in a pore system in which many of the pores are less stable than the macropores formed by vegetation or soil fauna or are even occluded with no connection to the soil surface (Fig. 17.1). In this situation, the impact of raindrops breaks soil aggregates and causes the sealing of pores, thus reducing the infiltration rate. This is reversed after tilling, by breaking the surface crust and increasing soil porosity and surface roughness, but the effect is temporary, and the infiltration rate is reduced after new rain events occur. The velocity of the surface sealing process depends not only on the amount of precipitation but also on soil characteristics,

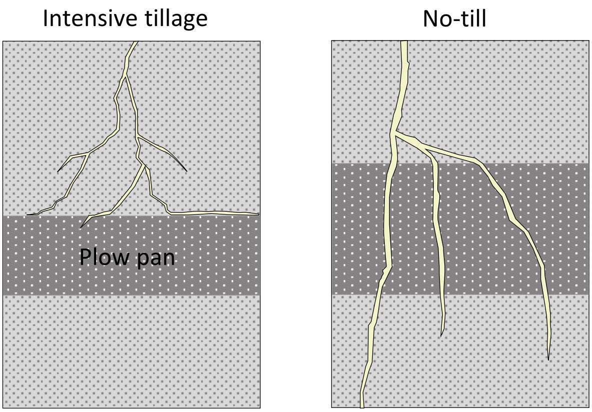


Fig. 17.1 Conceptual model of soil porosity in tilled and long-term no-till systems. (Adapted from Ontario Ministry of Agriculture and Food)

especially its structure (closely related to soil texture and organic matter content), being at its best state in undisturbed natural soils under grassland or forest plant cover.

Tillage thus serves to break the surface crust but also increases porosity, which improves water retention capacity and aeration, which in turn favors root growth.

In many rainfed areas, farmers consider tillage an effective method for reducing evaporation from the soil surface (E_s). Indeed, in soils prone to cracking, sealing the surface cracks by tillage helps reduce E_s. Large cracks increase evaporation in relatively deep sections of the subsurface soil in desert areas provided that transport of pore water from the sediment matrix to the crack walls is not a limiting factor. This would explain the adoption of inter-row cultivator passes in summer crops (e.g., cotton) in expansive soils. In many cases, however, tillage may increase soil evaporation. Evaporation from a dry soil surface is small (second-stage evaporation). If the soil is tilled, the dry surface layer mixes with moist soil from below, thus increasing evaporation. In Fig. 10.3 (Chap. 10), an increase in evaporation on day 157 was due to a pass of cultivator for weed control. In the long run, the impact of tillage on E_s is limited as most of the E_s takes place before the tractor with its tillage implements can enter the field. Thus, except for expansive soils, the effect of any tillage system on soil evaporation has much less impact on the water balance than on infiltration.

17.2.4 Other Goals

Tillage can serve other purposes such as modification of energy balance or incorporation of fertilizers or soil amendments. For instance, the reduction of bulk density and soil water content after tilling increases thermal diffusivity, which favors a faster warming of soil surface.

Sometimes, we find some tillage practices whose objectives are unclear and may be due more to tradition or aesthetic reasons. Traditionally, good farmers kept their fields "clean" of weeds at all times by excessive tillage and the adoption of unsustainable practices.

17.3 Influence of Soil Water Content on the Effects of Tillage

The energy required for tilling the soil and the effects of tillage depends on the soil water content. In medium- or fine-textured soils, the cohesive strength of soil aggregates decreases with increasing water content. The adhesion forces between the soil and the tools increase with water content up to a maximum, in which soil passes from the plastic, i.e., moldable, to the liquid state. In the liquid state, tillage causes the dispersion of the soil particles, and the soil loses its structure. The coherent state of the soil occurs with low water content and does not allow deformations without breaking of the aggregates. In this state, tillage generates large blocks of aggregates (lumps) with large gaps between them. Between the coherent and the plastic state, there is a point in which the sum of both adhesion and cohesion forces is minimal, which occurs with a medium content of water below the upper limit. At this state, called optimum soil water content for tillage (*OPT*), the soil crumbles after tillage (Fig. 17.2).

The water content of the soil not only determines the effects of tillage on soil conditions but also the degree of soil compaction due to the traffic of machinery. Soil compaction occurs mainly in the plastic state, but it is not likely to be important in drier soil, since in this case, the force causes breakage of aggregates. Within the plastic state, two zones may be distinguished above and below the adhesion point: above that point, the soil will adhere to a smooth surface cutting it, as is the case with implements. This implies a high energy expenditure for tilling and the danger of cementation once the soil dries.

The best condition for tilling occurs in a range of water contents below field capacity. This occurs approximately 2–3 days after rain or irrigation for medium-textured soils. In this zone, the energy required for tillage is minimal, and a granular structure is achieved, which is desirable for the seedbed, while the risk of compaction is moderate. Medium- and sandy-textured soils drain well and have a narrow plastic state, so they move quickly to the plastic state and reach the *OPT* soon after

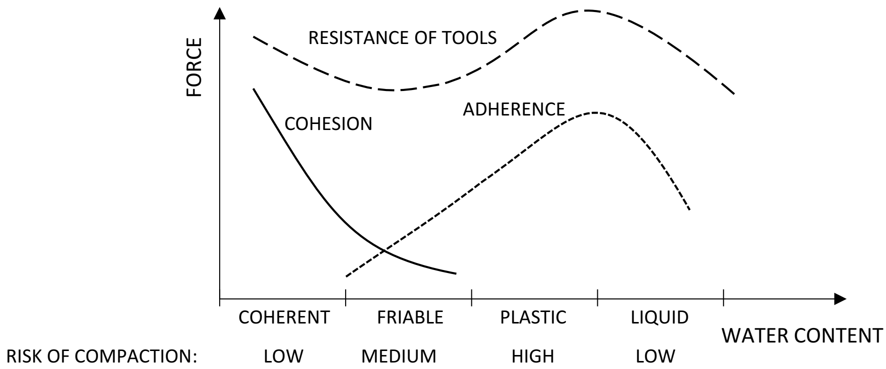


Fig. 17.2 Coherence and adhesion forces between soil and tillage tools as a function of soil water content

rain or irrigation, staying that way for a long time. That state, however, is not easy to achieve in clay soils where drainage is slow and the plastic state interval is wide. If we till in that state, the soil is cut into slices, which get extremely hard when dry and the tillage operation barely increases soil porosity. Besides, the risk of compaction is maximum when soil is tilled in the plastic state. To promote drainage in clay soils, it is necessary to till before the rainy season. Only so will it be possible to get a proper moisture condition before planting. The drawback is that tilling in the dry season, when the soil is in coherent state, requires much energy and generates large clods that must be disaggregated by additional secondary tillage operations. That subsequent disaggregation can be very difficult when rainfall is low. The disadvantages of tilling when the soil is dry do not occur in sandy soils as they do not show a coherent state.

17.4 Conventional Tillage

Maintenance of the infiltration rate, weed control, and seedbed preparation requires several tillage operations that vary widely across geographic areas, soil types, and crops. This set of operations, which we call conventional tillage, can be classified according to different criteria. In conventional agriculture, it is common to distinguish between primary and secondary operations. The primary operations are performed with a moldboard plow or a disc plow sometime after harvest and serve to incorporate crop residues and improve soil conditions. The moldboard plow cuts, lifts, and turns the soil down to 40 cm deep at most. This process improves infiltration, incorporates crop residues, and buries the weed seed bank. For the rupture of compacted deep layers, subsoilers are used, which can achieve greater depths (60–70 cm), performing a vertical cut so that residues are not incorporated. Subsoilers have replaced the moldboard plows in many areas, leaving 50–80% of the residues on the soil. The chisel plow performs a similar but shallower (less than 30 cm) vertical tillage than the subsoilers.

Secondary tasks are performed with harrows, cultivators, and other implements, affecting only the top 10–20 cm of the soil. They serve to refine the soil before sowing (reducing the size of the aggregates on the surface) and to control weeds. The primary operations often result in large aggregates, which are then broken down by harrowing. The finer structure is achieved with cultivators, also used for weed control before and after sowing (passes between rows). To finish the shredding of the aggregates and/or for compacting the soil surface layers, various tools can be used (e.g., compactor, harrow tines).

Example 17.1

Sunflower conventional tillage in a wheat-sunflower rotation in a Mediterranean area. After burning the wheat stubble in summer, a moldboard pass results in large aggregates and many gaps. After the first rains, we may use a cultivator or a disk harrow to reduce the size of the aggregates. Then two additional

(continued)

Example 17.1 (continued)
cultivator passes are needed in autumn-winter to remove weeds and another before planting. Additionally, one can have 1–2 cultivator passes between rows to control weeds during the campaign. Tillage costs in this case may account for over 60% of the total production costs of the sunflower crop.

17.5 Compaction and Plow Pan

Compacted layers may be due to natural causes (e.g., petrocalcic horizons), but it is a widespread phenomenon due to tillage. Compaction can occur in the uppermost soil layer (a few mm) due to the impact of rain. This surface crust hinders seedling emergence, especially if the soil is dry, and reduces infiltration (Fig. 17.3). Secondary tillage favors the formation of surface crusts when it leaves fine aggregates on the surface.

Another kind of compacted horizon may appear within the soil profile, which not only delays or prevents the growth of the root system but also leads to reduced growth of the aerial part of the plant and finally, to yield losses (Fig. 17.4), even when the supply of water and nutrients is not limited. Figure 17.5 shows the relationship between penetration resistance and soil water content for loamy soil with or without compaction. As penetration resistance of 3.2 MPa reduces root growth strongly, the growth conditions for roots in the compacted soil were greatly restricted. Compaction has other side effects such as waterlogging, which promotes denitrification (see Chap. 24), root anoxia, and a higher incidence of soil diseases (e.g., *Phytophthora*).

Compaction is caused by the weight of the implements (plow, disk) at the depth on which they act resulting in a plow pan and/or by the wheels of the tractor or other machines that compact the entire surface horizon. In either case, the magnitude of the compaction depends on the pressure applied (regulated by axel load and tire

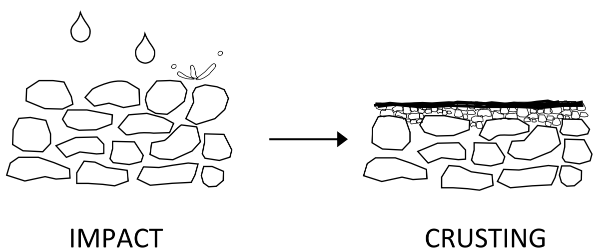
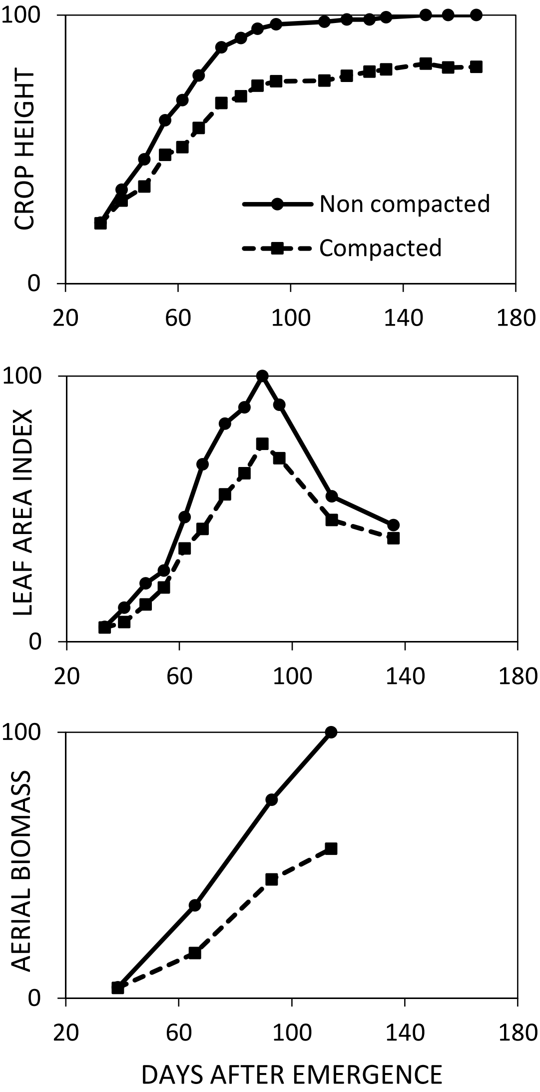


Fig. 17.3 Schematic representation of the formation of a depositional crust on a soil with sand, silt, and clay-sized particles. (Adapted from Cattle et al. 2004. In: SuperSoil 2004: 3rd Australian-New Zealand Soils Conference, Dec 2004, Univ Sydney, Australia (on CDROM))

Fig. 17.4 Time course of *LAI* and biomass of cotton on non-compacted (solid line) and compacted (dotted line) soil. (Adapted from Coelho et al. 2000. Soil Tillage Res 57(3):129–142)



type and pressure) and the water content of the soil at the time of the operation; thus, traffic should be avoided if the soil is in the plastic state. This is why compaction risk is very high in clay soils where the plastic state promotes the transmission of compaction in depth. By contrast, in medium-textured soils, the risk of compaction is lower and generates a compacted layer below the tilled depth (Fig. 17.1). This is why subsoiling to relieve compaction problems is more effective in medium-textured soils than in clay soils.

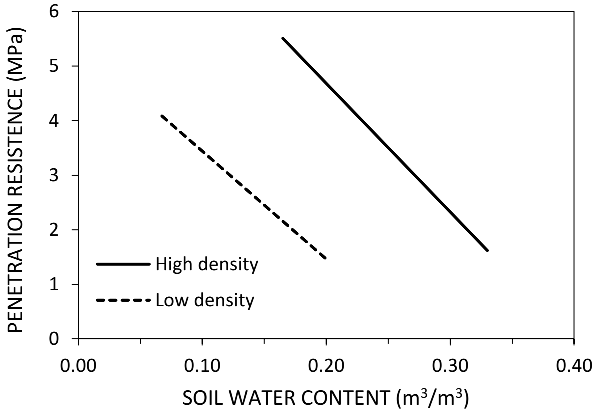


Fig. 17.5 Relationship between soil bulk density, soil water content, and soil resistance to penetrometer. Sandy loam soil. (Adapted from Coelho et al. 2000. Soil Tillage Res 57(3):129–142)

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Soil Conservation

18

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Abstract

Tillage is used to improve soil conditions for water storage and crop growth, incorporate crop residues, control weeds, and prepare the seedbed. However, tillage and other bare soil management systems using herbicides significantly increase the risk of soil erosion. These problems have led to the development of conservation tillage techniques that typically rely on keeping plant residues on the ground and reducing tillage operations. When conservation tillage is combined with crop rotations or cover crops in woody crops, it is termed conservation agriculture. Conservation tillage usually requires herbicides and, in the case of annual crops, specific direct drills for sowing. The transition from conventional to conservation tillage is dynamic and should be gradual as different problems may arise as the adoption progresses (e.g., compaction). In this case, sporadic tillage or controlled traffic could then be adopted. In woody crops, there are some options for soil conservation, such as introducing no-tillage and cover crops controlled by herbicide or mowing. In tree orchards in the Mediterranean region, conservation agriculture may be implemented with temporary cover crops that protect the soil during the rainy season and are killed in the early spring to avoid competition for water with the trees.

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18.1 Introduction

Soil erosion is the main threat to the sustainability of agricultural systems in many parts of the world. The development of powerful tractors in the last century allowed rapid mechanization of tillage operations but also resulted in a reduction of ground cover by vegetation and stubble, a decrease in soil organic matter, and a deterioration of soil structure and, therefore, in an increased risk of water and wind soil erosion. The "Dust Bowl" period in the USA in the 1930s exemplifies the relevance of this problem.

Conserving the soil in agricultural lands is not straightforward. Success requires adapting new management practices to local conditions and considering costs and profitability. The recommended approach is to develop a good understanding of the system and monitor the adoption of practices for conservation tillage, aimed at minimum soil disturbance, maintenance of soil cover with vegetation and/or residues, and spatiotemporal diversification of cropping systems.

18.2 Soil Erosion

Erosion is the process of soil loss. Firstly, energy is required to remove the particles, and then some transport medium will be needed. The energy is obtained from the impact of raindrops and the transfer of momentum from water (surface runoff) or wind, although at the hillslope scale, the energy is also provided by gravity, which moves downslope soil particles destabilized by tillage (called tillage erosion). The transport medium will be the fluid (water or air). Water erosion is proportional to runoff, the difference between precipitation and infiltration (Chap. 8) and a parameter (Erodibility) that reflects the ease with which the soil is eroded. Erodibility depends mostly on the soil's structural stability, which is related to the organic matter content and soil texture. In degraded silty soils with poor soil aggregation and low infiltration, soil erodibility is the highest.

Erosion has two major effects on the agricultural system: soil loss results in a decrease in soil depth, which in turn involves a reduction of the water storage capacity, and therefore a reduction in long-term yield. Moreover, the surface soil lost is often the richest in nutrients; thus, erosion involves a loss of fertility (and yield potential) and causes an environmental problem (sediment and pollutants accumulate in surface waters). Unfortunately, erosion is hard to control as it is ephemeral and, often, occurs in a few episodes of torrential rain. In any case, excessive tillage destroys the soil structure and keeps its surface exposed to wind and rain for prolonged periods, making it the leading cause of erosion in many agricultural systems. Although tillage initially increases water infiltration, its effect is temporary, and in some silty fine-texture soils, it can favor the rapid formation of surface crust after the subsequent rainfall. This illustrates the paradox of keeping bare soil free of weeds with tillage, as a viable and safe short-term solution, while irreversibly reducing the productivity of soils.

On a larger scale, erosion is a process with feedback: soil loss implies a reduction of vegetation that favors intensified erosion, which finally leads to desertification.

This process, the loss of vegetation and water bodies of dryland regions, advancing in some areas, is fueled by soil erosion.

Several methods have been proposed to quantify soil erosion, among which the most popular is *USLE* (Universal Soil Loss Equation) and its revised version, *RUSLE* (Renard et al., 1997). Both were designed to predict the effect of different soil management on average annual erosion rates at the hillslope scale from empirical factors that can be calibrated from physically based variables. According to the *RUSLE*, the average soil loss by erosion (*SLE*, t/ha/year) is calculated as the product of six factors:

$$SLE = R\,K\,L\,S\,C\,P \tag{18.1}$$

When using *USLE/RUSLE*, a major source of confusion is units, as some sources use the International System (*SI*) and others the Imperial. It is necessary to ensure that when using Eq. 18.1, all the non-dimensionless factors (*R* and *K*) are in a coherent set of units. In this chapter, all factors are in the *SI*. The factor *R* (MJ mm ha^{-1} h^{-1} year^{-1}) is the average annual rainfall erosivity, which is a measurement of the rainfall energy available for water erosion; it depends on the amount and intensity of the rainfall, and its calculation is explained in detail by Renard et al. (1997). Several equations can be used as a regional approximation, such as Eq. 18.2 for the USA, based on the monthly rainfall distribution (Bergsma, 1981. ITC Journal 4:460–483):

$$R = 10\left(4.17\sum_{1}^{12}\frac{P_i^2}{P_y} - 152\right) \tag{18.2}$$

where P_i is the precipitation (mm) of month i and P_y is the annual precipitation in mm. Nevertheless, databases and maps are available to determine the average *R* in any agricultural area of the world.

K is the soil erodibility factor, soil loss that would occur in standard conditions, that is, if the land is kept as clean fallow, and has a slope of 9% and a length of 22 m. It depends on soil texture, soil organic matter, soil structure, and infiltration class. Suggested values of *K* appear in Table 18.1.

L and *S* are factors that include the effect of the slope length (*L*) and steepness (*S*). In its most basic form, *L* and *S* are combined to represent the ratio of erosion in a given situation and that happening in standard conditions (22 m long, 9% slope), and their product is calculated as:

$$LS = \left(0.065 + 0.0456\,p_t + 0.006541\,p_t^2\right)\left(\frac{l_t}{22.1}\right)^{NT} \tag{18.3}$$

where p_t is the slope (%) of the land, l_t is the length (m), and *NT* is a factor that depends on the slope (Table 18.1).

C is the factor that reflects the effect of cover and management and their interaction with the rainfall erosivity distribution during the year. Its proper calculation requires calibration of several subfactors (see Renard et al., 1997). It can be approximated from tables developed for local management and climate conditions as presented in Table 18.1.

Table 18.1 Parameters for calculating soil loss using the *RUSLE*

	K (t h MJ^{-1} mm^{-1})		
Soil texture	Low OM	Medium OM	High OM
Clay	0.02	0.017	0.013
Fine sand	0.016	0.014	0.01
Fine sandy loam	0.035	0.03	0.024
Loam	0.038	0.034	0.029
Loamy fine sand	0.024	0.02	0.016
Loamy sand	0.012	0.01	0.016
Loamy very fine sand	0.044	0.038	0.03
Sand	0.005	0.003	0.002
Sandy clay loam	0.027	0.025	0.021
Sandy loam	0.027	0.024	0.019
Silt loam	0.048	0.042	0.033
Silty clay	0.025	0.023	0.019
Silty clay loam	0.037	0.032	0.026
Very fine sand	0.042	0.036	0.028
Very fine sandy loam	0.047	0.041	0.035

Tillage and cropping practice	Crop sequence	C
Forest	Permanent	0.0005
Pasture	Permanent	0.005
Rotation 1/6	Z-G-M-M-M-M	0.011
Rotation 2/5	Z-S-G-M-M	0.027
No till cover crop after soybean	Z-S	0.0027
Chisel, 50% residue on contour	Z-S	0.16
Chisel, little residue	Z-S	0.35
Moldboard plow, spring	Z-S	0.35
Moldboard plow, fall	Z-S	0.39
Bare soil	none	1

Slope %	NT
<1	0.2
1–3	0.3
3–5	0.4
>5	0.5

Direction of tillage	P
Same as slope	1
Contour lines	0.5

Sources: For *K* and *NT*: Stewart et al. 1975. US EPA Report No. 600/2-75-026 or USD. Rep No. ARS-H-5-1. Converted into *SI* by authors.
For *C* and *P*: Franzmeier et al. (2009) Indiana Soils. Evaluation and Conservation. Purdue University
Z maize, *M* meadow (forage crop), *G* small grains, *S* soybean

Finally, the factor *P* indicates the effect of conservation practices on erosion control (Table 18.1) such as contour plow or terraces.

The value calculated using Eq. 18.1 is compared with the tolerable soil loss rate (Table 18.2). This is the maximum erosion rate tolerable before the soil productivity is severely affected in the medium term. This tolerable level is higher than the natural rate of soil formation or the threshold to reduce water quality in the streams

Table 18.2 Soil loss tolerance rates for comparison with values derived from RUSLE

Soil erosion class	Potential soil loss (t/ha/year)
Very low (tolerable)	<6.7
Low	6.7–11.2
Moderate	11.2–22.4
High	22.4–33.6
Severe	>33.6

receiving the sediments from the fields. The tolerance level varies depending on the type and depth of the soil. Deep soils not previously eroded are assumed to have a higher tolerable soil loss rate than shallow and/or previously eroded soils.

Example 18.1

Let us calculate the average soil erosion on a farm in Flint, Michigan, with 5% average slope and slope length 50 m. The soil is loam with average OM (2%), and the crop is a rotation of maize and soybean with moldboard plow in the fall, which is made on contour.

Monthly rainfall values are:

Month	1	2	3	4	5	6	7	8	9	10	11	12	12
Precipitation mm	35	32	55	75	67	81	69	89	90	55	66	53	53

Therefore, rainfall erosivity is:

$$R = \left(4.17\,\Sigma\left(P_i^2 / P\right) - 152\right)10 = 1360$$

Now, in Table 18.1, we see that for a loam soil with medium OM content $K = 0.034$ and with slope 5%, $NT = 0.4$. As $p_t = 5$ and $l_t = 50$, we can calculate the product LS as:

$$\begin{aligned} LS &= \left[0.065 + 0.0456\,p_t + 0.006541\,p_t^{\,2}\right]\left(1_t / 22.1\right)^{NT} \\ &= \left[0.065 + 0.0456 \times 5 + 0.006541 \times 5^2\right]\left(50 / 22.1\right)^{0.4} = 0.63 \end{aligned}$$

According to Table 18.1, with contour tillage, we have $P = 0.5$, and the maize-soybean rotation with fall plow has $C = 0.39$. Therefore, the estimated soil loss due to erosion is:

$$SLE = R\,K\,L\,S\,C\,P = 1360 \times 0.034 \times 0.63 \times 0.39 \times 0.5 = 5.7\,\text{t ha}^{-1}\,\text{year}^{-1}$$

According to Table 18.2, this value is tolerable. However, for this specific field, if tillage direction was that of the slope, the estimated soil loss would double, as P would be 1 instead of 0.5. Then the estimated soil loss (11.4 t ha^{-1} year^{-1}) would be classified as moderate.

18.3 Conservation Tillage

As discussed above, conventional tillage has several disadvantages:

(a) The increased infiltration due to tillage is only temporary and promotes a surface crust for some soil types.
(b) The traffic of machinery and tillage implements can lead to soil compaction and a subsurface plow pan.
(c) Tillage prevents the accumulation of organic matter in the soil surface, which is necessary to protect the soil and stabilize its aggregate structure. Organic matter generates aggregating agents (especially polysaccharides) that promote the cohesion of the aggregates.
(d) Tillage has high economic and energetic costs and promotes the emission of greenhouse gases from soils. The use of fossil fuels also contributes to anthropogenic CO_2 emissions.
(e) Tillage favors erosion, although some operations may temporarily reduce it and runoff.

All these disadvantages, plus the emergence of new technologies, have driven the search for alternative systems for managing agricultural soils. These systems range from reducing the number of operations (reduced tillage) to eliminating tillage (no tillage). However, not all of them contribute to soil conservation. To avoid confusion, conservation tillage was defined by ASAE in 2005 as tillage operations (or no tillage) that leave enough residues to cover 30% of the surface after sowing and at least 110 g/m^2 of organic material during the critical periods of erosion risk. Conservation agriculture (CA), as defined by FAO in 2016, adds a third component to minimum soil disturbance and maintenance of residues: the use of more than one crop in the rotation.

Adopting CA by farmers is not straightforward, and the dynamic and complex interactions limit acceptability in Europe. The CA effects on the system performance and interactions will be discussed while considering its adoption in three main steps (Fig. 18.1) (1) changing from conventional to no tillage, (2) maintaining a mulch on the ground, and (3) introducing a crop rotation. Some changes have immediate effects, while others appear in the long term only, particularly those related to soil characteristics. These long-term benefits are hardly appreciated by farmers unless they have good knowledge and understanding of the system. There is not a single recipe for a successful CA system, and it usually requires an adaptation process and special attention to solve problems as they appear.

Step 1. Switching from conventional tillage to no tillage. Simply ceasing to disturb the soil can have more negative than positive effects on crop productivity. A major concern is the impossibility of decompacting the plow layer, particularly when heavy direct-drill seeders enter a field with wet soil. Compacted soil will reduce root and shoot growth, whereas compacted superficial soil will result in

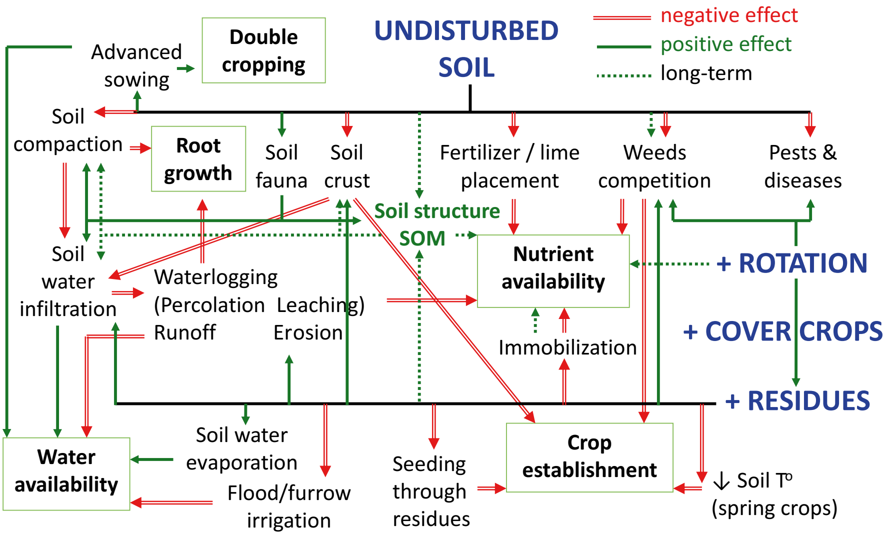

Fig. 18.1 Main pathways through which a change in management from conventional to conservation agriculture may impact key drivers (highlighted in green boxes) of crop yields. A single dark-green arrow and a double red arrow indicate positive (beneficial) and negative (constraining) effects, respectively, on yield drivers and component attributes. A dotted line indicates a beneficial effect expected over the long term. (Adapted from Brouder and Gomez-Macpherson. 2014. Agric Ecosys Environ 187:11–32)

lower water infiltration and soil water content; waterlogging and even seedling death may then occur. Another major concern when adopting no tillage is the potential increase of weeds, diseases, and pests. Adopting no tillage requires attentive weed control, especially when perennial weeds appear. On the other hand, a major advantage of no tillage is the possibility of entering earlier in the field for sowing. This is particularly relevant to adjusting the crop to a narrow cropping season window or for crop sequence intensification, e.g., allowing two crops per season.

Traffic of agriculture machinery, like heavy drills or harvesters, leads to soil compaction, particularly when the soil is wet. The introduction of *controlled traffic* will reduce this problem. Controlled traffic implies that wheels will pass over the same tracks in all operations while the crop is grown in the non-trafficked zone. Wheels operate then more efficiently on this firm soil. In CA systems, the adoption of controlled traffic can minimize the negative impact of compaction on crop performance and soil water infiltration (Fig. 18.2). Nevertheless, occasional deep ripping or subsoiling of the traffic tracks may be needed. The success and costs of adopting controlled traffic will depend on the possibilities of adapting the machinery and the accessibility to GPS guidance.

Example 18.2
In Southern Spain, a ridge planting system combined with controlled traffic has been developed successfully to deal with soil compaction and excessive residues produced by an irrigated maize-cotton rotation (Boulal and Gomez-Macpherson, 2010. Agric Ecosyst Environ 139: 284–292). Irrigation was applied from a central pivot, but ridges were formed to facilitate controlled traffic and to have residues in the furrows rather than on the beds where crops are sown. Applied irrigation was reduced by 17% since the introduction of the system, without yield loss, but most importantly to the farmer, the costs were also reduced.

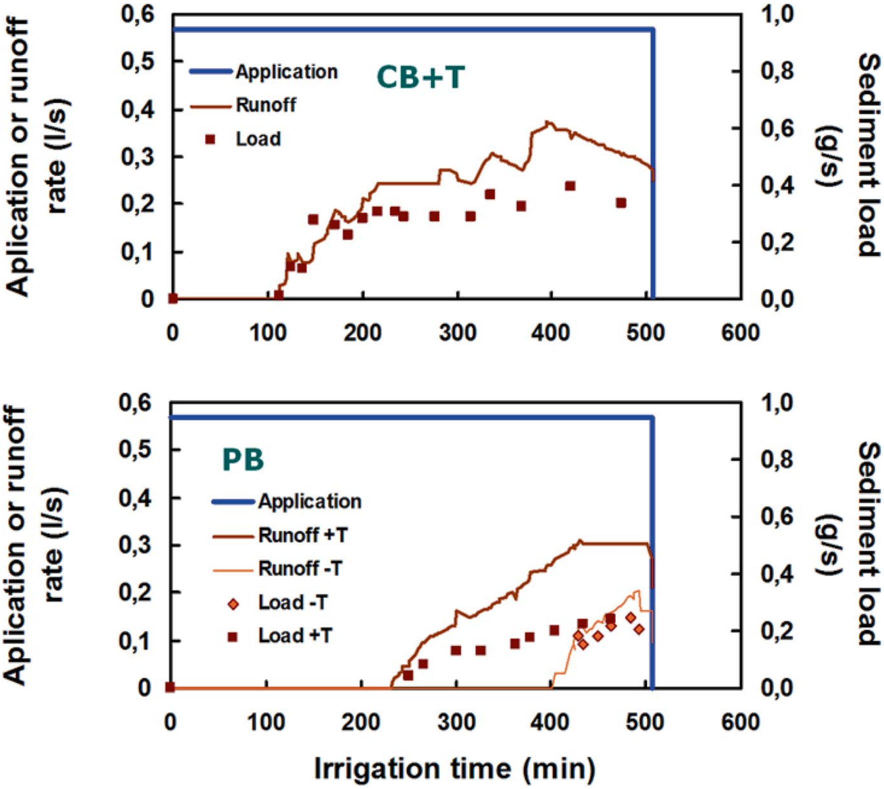

Fig. 18.2 Time course of runoff rate and sediment load in runoff water during rainfall simulations in conventional ridge system (CB) and in furrows of permanent ridge system (PB), with (+T) and without (−T) traffic

Step 2. Mulching. Most negative effects derived from no tillage may be offset by maintaining crop residues on the soil surface after harvest (Fig. 18.1). As discussed in the previous section, crop residues on the ground protect the soil from the direct impact of rain and wind. The presence of decomposing plant material from the previous crop also favors the structural stability of the soil surface layers and thus reduces erosion. Another positive effect of maintaining residues is the increased surface roughness, which implies an increase in the water held on the surface that is retained until it infiltrates. In the longer term (2–5 years), leaving crop residues and roots of previous crops without disturbing the soil can increase soil organic matter content and the activity of the soil mesofauna (generating macropores) and the soil flora, which are further enhanced as surface temperature fluctuations are reduced. All these processes contribute to the improvement of infiltration. Furthermore, the favorable microclimate near the soil surface promotes the proliferation of roots that will compete for water with direct evaporation from the soil surface.

The effect of residues on evaporation from the soil surface depends on the frequency of rainfall events. If they are frequent, the soil is kept in evaporation stage 1 (Chap. 9), so the residues will reduce evaporation in proportion to the radiation they intercept, although it will depend also on the amount and capacity of residues to retain water. If rainfall is infrequent, the soil remains in phase 2 (limited by hydraulic conductivity), so the presence of residues has little effect on evaporation. If the amount of residues is sufficient to cover the ground, the water balance is expected to improve due to enhanced rainfall infiltration and, to a lesser extent, less evaporation. The improvement of yields due to CA (relative to conventional tillage) is higher in rainfed systems of semiarid zones than in other environments where water is not limiting.

Maintaining residues may also have negative short-term effects on plant growth (Fig. 18.1). In the initial phase of adopting no-tillage and mulching, high amounts of residues may result in N immobilization. More N fertilizer will then be required to compensate for the immobilization until soil fertility is increased and the system is balanced. Additionally, non-mobile soil nutrients, like phosphorus, cannot be incorporated into the soil unless the fertilizer is placed next to seeds during sowing. Residues also reduce radiation absorption by the soil, delaying soil warming during the early establishment of spring crops when temperatures are low. In the tropics, lower temperatures may benefit nutrient cycling and plant growth. Leaving residues on the ground also requires specific drills to sow through them and makes difficult flood or furrow irrigation or herbicide application.

Step 3. Crop rotation. In CA, crop rotation has the main role of facilitating weed control and reducing the risk of pests and diseases (Fig. 18.1), particularly in the soil. For example, in Australia, higher incidences of soil-borne fungal diseases were observed in no-tilled wheat monoculture systems. However, the incidence decreased when rapeseed was included in the rotation. The crop rotation can also help maintain the optimum amount of residues in the system by alternating high- and low-residue-producing crops, which is particularly relevant under irrigation.

There are differential responses to tillage systems in the different agricultural areas. No tillage reduces crop yields as compared to conventional tillage, but the difference decreases if residues are maintained. While CA has been widely adopted in North and South America, it has been scarcely adopted in Europe (except for cover crops in orchards). The reasons limiting CA adoption in Central and Northern Europe include technical problems with crop establishment in cold and wet soils, high natural organic matter content of many soils, flat topography, and low erosion risk, and management problems with crop residues and weed control.

Example 18.3: Some CA Systems Around the World
Rice-wheat cropping system in the Gangetic Plains. Rice is the main crop grown during the monsoon period. In the conventional system, rice stubble is removed or burned after harvest, and the soil is then prepared for sowing wheat. This preparation usually takes 2–3 weeks, which in turn causes the wheat crop to be sown later than the optimum period for avoiding high temperatures during flowering and grain filling. However, in the CA system, thanks to the direct seeder, wheat can be sown the day after rice harvest and through the remaining stubble, thus advancing sowing time and increasing grain yield. Wheat crops are irrigated, and soil moisture facilitates root growth in the compacted soil.

Maize-based and soybean-based cropping systems in North and South America. The adoption of glyphosate-resistant transgenic maize and soybean cultivars has greatly improved weed control, a major limitation in CA systems. In these cultivars, the total herbicide can be applied after crop establishment without major damage. The CA expansion in America has been accompanied by the manufacture of machinery adapted to the demands of local farmers.

Wheat-based cropping system in Australia. Over the past decades, most Australian wheat farmers have adopted conservation agriculture practices. Adapted rotations including break crops and improved fertilization and weed control. Farmers have a flexible vision and can perform sporadic targeted tillage or crop residue removal. Part of the success derives from the innovative and adaptive capacity of farmers, researchers, advisors, and industry.

The transition from conventional tillage to conservation tillage should be a gradual process, and adjustments will be needed to cope with the specific problems of the soil and crops and techniques to be adopted. For instance, no tillage has fewer problems adapting to medium- or light-textured soils because of their lower risk of compaction, while in heavy clay soils, it may aggravate soil compaction and cause yield reductions. Furthermore, in heavy soils, no tillage seeders may leave the sowing furrow slightly open, which results in poor seed-soil contact. These problems can be solved in part by changes in the implements of the seeder. For example, in *strip tillage*, several blades can be installed to prepare a 10-cm-wide band of soil in front of the sowing boot favoring the seed contact with the soil. This system also allows the localized application of P and K fertilizers in the same strips and the

Fig. 18.3 Ridge tillage: direct sowing of maize over cotton stalks

warming of that area without residues as radiation can reach the soil surface (important in cold conditions).

In *ridge tillage* or *permanent bed planting* (Fig. 18.3), the soil is left undisturbed from harvest to planting except for nutrient injection. Ridges are rebuilt annually. Planting is completed in a seedbed prepared on ridges with sweeps, disk openers, coulters, or row cleaners. Residues are left on the surface between ridges. Weed control is accomplished with herbicides and/or light cultivation. The beds or ridges, on which the rows of plants are sown, have the advantage of drying sooner and warming faster in spring.

18.4 Soil Conservation Systems in Orchards and Vineyards

In permanent woody crops, the objectives of soil management differ from those in arable crops because sowing is not required. Traditionally, tillage in orchards targeted the elimination of weeds, incorporation of fertilizers, and improvement of water balance. The wide availability of herbicides or mowers to control weeds allows conservation agriculture techniques that enhance ground cover and restrict tillage while ensuring an adequate water balance and erosion control.

Soil management options used in orchards can be summarized as follows:

– Conventional tillage. It maintains the soil bare by periodic surface tillage (cultivator, disc harrow) to increase infiltration and control weeds. It is the system used traditionally and is still widespread in rainfed orchards (olive, almond, vineyards).

This has a broad variability depending on the number and timing of the tillage operations and the tools used. This system tends to generate compaction, keeps soil organic matter low, and increases erosion risk.
- Minimum tillage. The weeds are controlled with herbicides. Tillage operations are limited to a cultivator pass in summer-autumn to improve infiltration.
- No-tillage with bare soil. The soil is kept bare by using herbicides. In the long term, infiltration is reduced due to unavoidable traffic (application of herbicides and fertilizers and harvesting). For rainfed systems, the lower infiltration reduces soil water availability and, thus, yield. In sloping areas, no tillage favors gully erosion due to higher runoff coefficients.
- Permanent cover crops. A cover crop is sown, or the weed community is managed by periodic mowing when needed. It is not advisable in dry areas, due to the competition for water with the trees.
- Temporary cover crops. Cover crops may be sown (degraded soils with a depleted seed bank) or generated by the weed community. In Mediterranean conditions, the cover crop is established in the fall before the rainy season and removed early in the spring to prevent competition for water during spring and summer. This can be done by tillage, herbicides, or mowing, with the residues serving as a mulch until the next fall. Mowing may be performed more than once during the season depending on the rainfall patterns. Cover crops can occupy the whole area or just part of it (cover crops in strips).

The date of removal of the cover crop should be late enough to protect it from erosion by rainfall and early enough to prevent excessive use of soil water. Delaying the removal also allows seed production to improve the soil seed bank. The right date is not easy to determine as it depends on many factors (actual rainfall, tree water use, fraction area covered by cover crop). The analysis may be performed using simulation models like the results shown in Fig. 18.4 obtained using *OliveCan*.

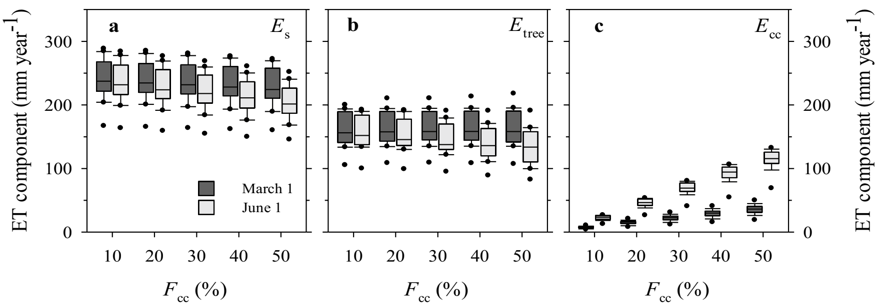

Fig. 18.4 Evaporation from trees, soil, and cover crop in a rainfed olive orchard in Cordoba (Spain) for different values of fraction of area covered by the cover crop and two possible mowing dates. (Adapted from Lopez-Bernal et al. 2023. J Forestry Res 34:283–295)

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Irrigation Systems

19

Luciano Mateos

Abstract

Irrigation methods are classified into surface irrigation, sprinkler irrigation, and localized irrigation (drip/micro irrigation). Surface irrigation uses gravity: the water is distributed over the field as it infiltrates. With sprinkler irrigation, water is distributed across the field using pressurized pipes and sprinkled over the soil through nozzles. Drip/micro-irrigation systems are conceived to localize the water to parts of the field and apply it frequently. The factors to be considered when selecting an irrigation method are project goals (maximizing economic return, minimizing investment cost, conserving water, and water quality), institutional and social site conditions (financial, labor availability, durability, and robustness), and physical site conditions (soil and topography).

19.1 Introduction

The history of irrigation parallels that of agriculture. Irrigation has been practiced for more than 5000 years and was essential to early civilizations that developed in arid and semiarid environments, where irrigation makes the difference between the viability and non-viability of agriculture. Also in Mediterranean or sub-humid environments, where rainfall is limited or non-uniformly distributed, irrigation is responsible for an important part of the crop production. An estimated 17% of global cultivated land is irrigated and produces about 40% of the world's food.

Luciano Mateos died in December 2022 before publication of this work was completed.

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The twentieth century experienced a dramatic expansion of world irrigation. The area equipped for irrigation worldwide is 308 million ha of which 83% were irrigated around the year 2005. These figures represent about a sevenfold increase from the beginning of the twentieth century. Sixty-two percent of the area equipped for irrigation uses surface water, while 38% uses groundwater, and only 0.1% uses nonconventional water sources. About 70 % of the irrigation area is in Asia and 17% in America. The largest continuous areas of high irrigation concentration are along the rivers Ganges and Indus; in the Hai He, Huang He, and Yangtze basins in China; along the Nile River in Egypt and Sudan; and in the Mississippi-Missouri river basin in North America. Zones of high irrigation density in Europe are along the Danube and Po rivers. The 3.8 Mha of land irrigated in Spain is concentrated along the main river plains, the Mediterranean coast, and over aquifers in the central plateau.

Agriculture is the largest water-use sector worldwide, accounting for about 70% of water withdrawals from rivers and aquifers and 90% of consumptive water uses. The development of irrigated agriculture has boosted agricultural yields and contributed to price stability, making it possible to feed the world's growing population. The future of agriculture in many countries relies on the possibility of maintaining, improving, and expanding the irrigated area. However, irrigation is facing increasing competition from domestic and industrial sectors as the pressure on water resources increases, to the point that in many regions, it is becoming a threat to the environment. To fully understand some of the irrigation management practices described in Chaps. 20 and 21, it is essential that the reader reviews the main features of the different approaches, methods, and equipment used in irrigated agriculture.

19.2 Classification of Irrigation Systems

The earliest irrigation was by gravity diversion (from natural streams) and from water lifters powered by humans, animals, or the flow of water. On-farm irrigation systems were supplied either directly from the water source or through channels supplying several farms. Water moved by gravity over the soil surface is conducted by the irrigator to the crop plants or spread over level basins limited by small ridges.

Water distribution systems from the source to the farms use gravity or are pressurized with pumps. They can be collective or serve single farms. Pressurized systems use pipes while gravity systems use mainly open channels. The source of supply may be surface water, groundwater, or both (conjunctive use). A variety of surface irrigation methods, sprinkle, and drip/micro-systems are used for the application of water to the fields.

In collective distribution systems, delivery schedules determine when each farmer will receive water and how much, thus affecting on-farm irrigation operations and performance. The delivery schedules may be on-demand, arranged, and fixed rotation. Under on-demand delivery, the user decides when to irrigate, how much water to apply, and for how long. It is typical of modern pressurized systems. Under fixed rotation, flow rate, frequency, and duration are fixed by the water authority or agreed upon within the farmers' community. Under arranged schedules, rate, frequency, and/or duration are arranged between the farmer and the water supply agency.

Irrigation can be applied to the land in several ways. The choice depends upon many factors, including topography, economics, crop type, soil type, water availability, farming practices, and others. The following major categories of on-farm systems cover most of the variation:

- Surface irrigation
- Sprinkler irrigation
- Localized irrigation (drip/micro-irrigation)

A fourth, less common, category is sub-surface irrigation, which consists of maintaining a saturated water table within reach of the crop roots.

Surface irrigation (also referred to as flood irrigation) consists of the application and distribution of water over the field by gravity, wetting the entire soil surface or most of it. The distinguishing feature of this irrigation method is that water moves over the same medium where it infiltrates to fill the crop root zone. The rate of infiltration and its spatial distribution are therefore controlled by the soil characteristics. This feature makes it difficult to apply small depths of water; thus, surface irrigation is typically applied at long (from 1 week to more than 1 month) time intervals. Although the area of surface irrigation is decreasing, it is by far the most common form of irrigation throughout the world, accounting for about 70% of the total irrigated area.

Sprinkler irrigation consists of the application of water similar to how rainfall occurs. Water is distributed across the field through a system of pressurized pipes. It is then sprayed into the air to wet the entire soil surface. The spray heads (sprinklers) break up the water flow into small water drops that fall onto the ground.

Drip/micro-irrigation systems apply water directly where the plant is growing, wetting only a small part of the soil surface and sometimes only part of the root zone. This is why localized irrigation is another term for this method. Water is distributed to the water emission outlets through polyethylene pipes; thus, the irrigation system needs to be pressurized. Water application is generally at a low flow rate, in small amounts, and, frequently, to keep a high water content in the wetted zones. The water may be applied either above or below the soil surface.

Sprinkler and drip/trickle irrigation are expanding, with current areas of about 20% and 5% of the global irrigated area, respectively. The shift from surface to pressurized systems is being faster in countries like Spain, where surface, sprinkler, and localized irrigation systems account now for 31, 22, and 47% of the total irrigated area, respectively.

19.3 Selecting an Irrigation Method

Irrigation system selection depends on multiple physical and socioeconomic factors. It should be carried out by experienced professionals who interact with the farmer or irrigation manager. The factors to be considered are:

(a) *Project goals.* As in most production activities, the main goal is maximum economic return, although, for example, if capital is limited, the goal could be to minimize the initial cost. There may be social and environmental (conserving water and water quality) goals that should also be met.
(b) *Institutional and social site conditions.* The former include legal and political aspects like financial incentives, land use regulations, or water rights that may be of primary importance. Social site conditions include the availability of support for irrigation equipment maintenance and dependable labor availability. For small-holder irrigation in developing countries, additional site conditions to be considered are divisibility (suitability of an irrigation method for a wide variety of field sizes and configurations), skills and effort required for operation and maintenance, and ruggedness (durability, robustness).
(c) *Physical site conditions.* These conditions may refer to the water supply and quality, the land features (soil and topography), the cropping system, the climate, and the energy availability.
  - Water. Source, quantity, quality, reliability, and delivery schedule for the water supply may make some irrigation methods more preferable or impose constraints on the selection of some of them.
  - Topography and field configuration. Field slope, topographic irregularity, field shape, and physical obstructions may preclude the selection of some irrigation methods.
  - Soil characteristics. Soil texture, depth, heterogeneity, infiltration characteristics, erodibility, salinity, drainability, and the presence of a shallow water table must all be considered when selecting an irrigation method.
  - Crops and cultural practices. Crop height, germination, root and foliage diseases, and cultural practices (plant spacing, soil tillage and cultivation, application of fertilizer and pesticides, crop rotation)
  - Climate. Precipitation quantity and distribution will determine whether full or supplemental irrigation is required (Chap. 22), making one or other irrigation method more adequate and economically feasible. Wind is an important factor when considering sprinkler irrigation. Irrigation can be used to modify crop climatic conditions like regulation of temperature, frost prevention, and regulation of humidity, but not all methods offer the same possibilities.
  - Energy availability and reliability. If pumping is required, the energy source must be dependable.

19.4 Design and Management of Irrigation Systems

19.4.1 Surface Irrigation

The surface irrigation process is described in four phases (Fig. 19.1), although not always all of them take place. The water that is applied to one end of the field (the high edge or point if the field is not leveled) advances over the soil until it spreads across the entire surface or flow paths (furrows). This is the advance phase. Then, if the field is open at its tail end, the water starts to run off, whereas if it is surrounded by a dike or ridge, the water begins to pond. The interval between the end of the advance phase and the inflow cutoff time is the wetting phase. After water application is stopped, the water on the surface begins to decline, infiltrating into the soil and draining from the surface if there is an open field end. Two phases are distinguished during the drainage period: the depletion phase (or vertical recession) and the recession phase (horizontal recession). The depletion phase runs from cutoff to the appearance of the first bare soil under the water; the recession phase begins then and ends when the surface is completely drained.

The infiltration opportunity time is the difference between the recession and advance times; thus, it can be calculated from the advance and recession trajectories easily (Fig. 19.1). The infiltration rate initially decreases rapidly with time to reach later a constant rate. Therefore, the variation of infiltrated water across the field is less than the variation of opportunity time.

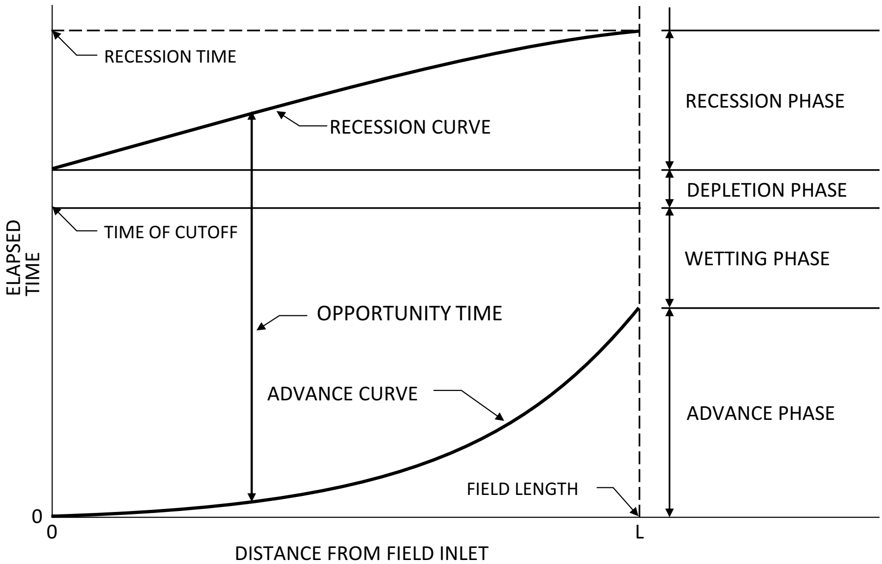

Fig. 19.1 Advance and recession trajectories of the water front in surface irrigation, indicating (on the right) the phases of an irrigation event

Furrow irrigation is the most common surface irrigation method. Furrows are small channels formed in the soil using a ridger plow. This method avoids flooding the entire field surface; water infiltrates through the wetted perimeter. Furrows may be level, nearly along a contour line with a small slope, or down the slope of the field. The flow into each furrow is independently controlled, using siphons, gated pipes, or perforated pipes. Furrow irrigation can therefore be used with a large range of stream sizes by adjusting the number of furrows irrigated at the same time. The furrow length and inflow rate should be regulated so that water will flow to the end of the furrow rapidly, but without erosion. This will ensure good infiltration uniformity, although the tail flow may be too high and thus runoff excessive. Infiltration uniformity and application efficiency can be improved simultaneously by using a high initial inflow rate until the advance phase is completed and cutting back the inflow afterward. Another way of improving infiltration uniformity is using surge flow: instead of applying a continuous stream of water, the flow is intermittently applied through on-off cycles. By surging the water, some soil surface sealing occurs, thus reducing infiltration and speeding advance during subsequent surges over previously wetted portions.

Border irrigation requires the construction of small earthen dikes (borders) separating evenly graded basins or strips typically 5–15 m wide. Water is released onto the border strips through an outlet located near the center of its top. The slope across the width of the strips is leveled to zero slope; thus, the water moves along the longitudinal gentle slope of the strip. The entire surface of the strips is flooded. A variation of border systems is level basins, which are perfectly flat and surrounded by check banks, meaning that all the water applied to a level basin infiltrates into the soil and there is no runoff. Borders can then be unnecessary.

19.4.2 Sprinkler Irrigation

All pressurized irrigation systems should apply water at a rate below the infiltration rate of the soil, thus avoiding runoff. Thus, here, the irrigation system controls the rate of water infiltration while in surface irrigation the soil itself controls the infiltration rate during irrigation. With sprinkler irrigation, water is distributed across the field through a pressurized pipe and sprinkled over the soil using nozzles. Sprinkler devices for agricultural use generally fall into two broad categories: rotating head sprinklers and spray sprinklers. Rotating head sprinklers move themselves in a circle driven by different mechanisms. In the case of impact sprinklers, this mechanism is an impact arm. The sprinkler head pivots on a bearing as the impact arm repeatedly hits the water jet pushed by a spring. When the arm hits the jet, water scatters watering the area around the sprinkler. Impact sprinklers can be designed to rotate in a full or partial circle. They can have one or two nozzles and many sizes, allowing flow from 2 to 280 L min^{-1}, a throw radius from 7 to 30 m, and operating pressures between 140 and 690 kPa.

Spray and spinner sprinklers operate typically at a pressure of less than 200 kPa. The water jet from a nozzle impinges on a plate that deflects the water in all directions. The discharge plate can be smooth or serrated and can be flat, concave, or convex, producing different water distribution patterns. Water leaves a smooth plate in small droplets; serrated plates create tiny streamlets with larger droplet sizes. The typical radius of throw of spray sprinklers is in the range of 2.5–5 m.

Rotating spray plate sprinklers, commonly referred to as rotators, have features of both impact and spray sprinklers. The water discharging from the nozzle impinges onto a circular plate that rotates without the need for an impact arm. The shape and configuration of the plate determine the multiple trajectories of the water and its distribution pattern. The radius of throw can be up to 15 m. Rotators typically operate at a lower pressure than impact sprinklers (100–345 kPa) and can accommodate lower flow rates without compromising performance.

These sprinkler devices are spaced to give a relatively uniform application of water over the field being irrigated using a series of sets or a continuous move system. There are several types of sprinkler systems. The most common are described below.

Hand-move portable systems consist of one or more pipelines (laterals) with sprinklers mounted on risers connected to the laterals at regular distances. The height of the risers adapts to the crop height. When the desired amount of water has been applied to the area covered by the set of laterals, the pipelines are dissembled and carried to the next position. This operation is repeated until the watering of the entire field. Distribution uniformity may be improved by using alternate sets: on every other irrigation cycle, the pipelines are placed in intermediate positions. Most hand-move portable systems use rotating impact sprinklers, but rotating spray plate sprinklers are also used. This system adapts to all topographies, soils, and crops, although moving the laterals is hard in tall crops such as maize. Variations of hand-move portable systems are wheel line and side-move lateral systems. In the former system, the lateral line is mounted on wheels with the pipe acting as an axis driven by an engine that moves the whole lateral from one position to another. In side-move systems, the lateral is supported by a frame on which the wheels are mounted.

Stationary or solid-set systems are similar to portable systems except that both the main line and the laterals remain in place permanently (if the main and laterals are buried) or during the growing season. Rotating spray plate sprinklers are becoming the most commonly used sprinkler type for stationary systems. Stationary systems adapt well to crops that require frequent applications of water, to facilitate germination and for frost protection. Compared to portable systems, solid-set systems have a high initial investment but require little operation labor.

A center pivot system consists of a single lateral supported by wheeled towers that are self-propelled, typically with electric motors, so that the whole lateral rotates around the pivot point in the center of the irrigated area. Water is supplied also at the pivot point. For long center pivot laterals (e.g., 400 m), the period of rotation may vary between 12 and 120 h, although 12-hour-to-3-day cycles are most common, applying between 10 and 25 mm per cycle. Since the outer lateral segments irrigate an annulus of greater area than the inner segments, application intensity must increase from the pivot point to the lateral distal end to apply uniform water depth. This may generate runoff and erosion in some soils if the system is not designed and managed properly. The sprinklers used in center pivots may be of any kind, but the trend is toward low-pressure sprinklers. Centre pivot systems adapt to most field crops and topographies. They may be unsuitable for small fields or field shapes where circular geometries do not fit well. Moreover, the fields must be free of obstacles. Several solutions have been developed to overcome obstacles, and the installation of end guns (large sprinklers at the end of the lateral) and corner systems (an additional arm that swings out on the corners and tucks back in on the edges) allows irrigating part of the corners of squared fields that would not be irrigated with the conventional center pivot. Centre pivots can be used for site-specific variable rate irrigation, by using solenoid valves that regulate the application rate of each sprinkler.

Linear move systems are similar to center pivots except that they do not rotate but translate (move laterally). Water is supplied to the moving lateral using a flexible hose or from an open ditch parallel to the translation direction. Contrary to center pivots, this system adapts well to rectangular fields and applies the water with uniform intensity across the field. All types of sprinklers can be used in linear move systems. However, the tendency is to use drop tubes, installed at short distances along the lateral and low-elevation spray application (LESA) or low-energy precision application (LEPA). LESA systems use sprayers located near the top of the crop canopy, while LEPA systems use low-pressure nozzles located very close to the soil surface. The soil is furrowed, and the furrows are blocked at regularly spaced intervals to prevent runoff and infiltration non-uniformity.

19.4.3 Drip/Micro-irrigation

Drip/micro-irrigation systems are designed to localize the water only to parts of the soil surface and apply it frequently. The water emitters may be microtubes, orifices, nozzles, or perforated pipes. Applications may be from daily to several times per week, but sometimes (on sandy soils), daily needs are applied in several pulses throughout the day. The systems may be located on or under the soil surface and are permanent (solid set). Subsurface drip irrigation (SDI) is relatively new. The laterals are installed typically at 0.3–0.6 m below the soil surface. This system allows easier traffic and soil cultivation, reduced weed germination, and minimal soil evaporation but may have the problems of root intrusion into the emitters and impaired detection of system failures.

Many types of emitters are capable of supplying water directly to the crop root zone. Drip irrigation generally refers to the use of emission devices from which water drips onto the soil: drip tape or on- and in-line emitters (small plastic devices inserted in or embedded in the lateral), while micro-irrigation refers to the use of micro-sprayers or micro-sprinklers. Micro-sprayers and micro-sprinklers are connected to the lateral using spaghetti hoses. The flow rate of these emitters is very small. Drippers range from 0.5 to 8 L/h and micro-sprayers or micro-sprinklers from 20 to 80 L/h.

Drip/micro-irrigation is primarily used for wide-spaced or high-value crops such as fruits, fresh vegetables, and greenhouse crops. The drip/micro-systems differ for permanent crops, non-permanent crops, and greenhouse crops.

Permanent crops include all kinds of fruit tree orchards and vineyards. Drip/micro-systems for permanent crops may use drippers, micro-sprayers, or micro-sprinklers as emission devices. For instance, sandy soils or shallow-rooted trees are more effectively irrigated with micro-sprinklers/sprayers, whereas closely spaced trees (hedgerows) are better suited for drip lines. Sometimes, tree branches interfere with micro-sprinklers/sprayers, and sometimes wetting only a small part of the soil prevents diseases. In those two cases, drippers are also preferable. However, micro-sprayers and micro-sprinklers can provide some frost protection. Drip and micro-sprinkler systems for permanent crops typically have one lateral per tree row if the rows are closely spaced or two if they are spaced more than that—let's say 5 m. The number of emitters per tree depends on the soil type, plant spacing, and type of emitter. The idea is to have sufficient root zone wetted volume, which depends on annual rainfall, canopy cover, species, and soil type. Drip irrigation is also used for non-permanent crops, particularly for row crops such as vegetable crops and also for some field crops (e.g., cotton, tomatoes). After harvest, the irrigation system is removed to allow land preparation. Drip systems for row crops mainly use in-line drippers or drip tape. Usually, there is one drip line per row, but sometimes, two are necessary, or one every second row is sufficient to provide water to each plant root zone, depending on the soil's physical properties. Drip tapes last for one or two seasons. Drip lines last longer (7–15 crop seasons) and, if buried (SDI), can remain in the field permanently. High-frequency irrigation for greenhouses may use all kinds of emitters, depending on the crop and soil substratum.

Drip/micro-systems require clean water to avoid emitter clogging. Filters are therefore essential components of drip/micro-systems, and water filtration accounts for a great part of the maintenance and operation efforts. Fertigation and chemigation (the application of fertilizers and pesticides through the irrigation systems) are relatively easy and common with drip/micro-systems, as well as automation of the operation (initiation and termination of irrigation in the different system irrigation units).

Drip/micro-systems allow uniform and efficient application of water. They adapt very well to all kinds of topographies, field sizes, shapes, and crops and are very easy to operate. They are more and more used in large-scale commercial farming and smallholder farming both in developed and developing countries.

19.5 Drainage

Drainage is necessary to evacuate the excess of irrigation or rainfall water and to wash the excess of salts. This will ensure adequate aeration of the crop root zone and prevent the harmful effect of salt accumulation. Where natural drainage is insufficient, surface and/or subsurface drainage must be facilitated artificially.

Surface drainage to remove excess water from the soil surface is expedited by excavating shallow open ditches. The dimensions and density of the drainage ditches are calculated based on the expected intensity and duration of storms, soil type, and crop.

Subsurface drainage is used to control the groundwater table and to remove salts for leaching. Many irrigation projects require subsurface drains, which may be deep ditches or buried perforated pipes. Open ditches have advantages for removing large volumes of water. They may also serve as collectors of subsurface drains. The main disadvantages of open drainage ditches are that they occupy land that might otherwise be cropped, obstruct farming practices, and tend to have high maintenance costs. Clay tile drains have been widely used for subsurface drainage. The tiles are usually 30–60 cm in length and 10–25 cm in diameter. Corrugated plastic tubing is increasingly being used. Perforated pipelines are generally available at 8–30 cm diameters. Tile and plastic drains are normally installed with a surrounding envelope (synthetic fabrics, sand and gravel, or other porous filter material) that permits water to pass from the soil into the drain without significant passage of soil particles.

The soil hydraulic conductivity is a measure of its drainability; it is therefore a basic criterion for the design of drainage systems. Proper spacing of drains is complex; thus, it is best determined from field experience obtained under conditions similar to those of the area to be drained. However, several equations have been developed for estimating the appropriate spacing of subsurface drains if available field experience is not applicable. These methods consider factors such as hydraulic conductivity, rooting depth, depth of drain, rainfall, irrigation practices, water quality, and soil salinity.

Pumped wells may serve to both lower the groundwater table and, where groundwater is of good quality for irrigation, to supply water that supplements the main source of irrigation supply. This is called conjunctive use.

19.6 Water Reuse

When applying irrigation water to a field, some water losses (surface drainage and deep percolation) are unavoidable in most situations. These losses return to the hydrological system where the irrigated field is located, so they are called return flows. In many cases, the return flows can be reused downstream, for irrigation or other purposes. Therefore, the reuse of return flows tends to reduce the global benefit of improving on-field efficiency. Reuse can take place within the field (conjunctive use mentioned above), in the farm (e.g., by recycling runoff), in the irrigation district, or at watershed levels. The reuse of treated urban wastewater is one example of the latter, although in this case, the origin of the return flow is not from agriculture.

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Irrigation Scheduling Using Water Balance

20

Francisco J. Villalobos, Luciano Mateos, and Elias Fereres

Abstract

The simplest and most robust method for irrigation scheduling, i.e., deciding the dates and amounts of irrigation, is based on water balance. Soil water deficit (depth of water required to bring the soil to field capacity) is calculated using *ET* and rainfall data, and rules are defined for calculating the dates and depths of irrigation. Rules are based on the critical *SWD*, the amount of water that the crop can extract in the rooting depth before water stress occurs. The critical *SWD* is the product of root depth, soil available water, and allowable depletion. The latter depends on evaporative demand when we want to prevent reductions in expansive growth. Otherwise, most crops can use around 70% of stored soil water before stomatal closure occurs. In arid areas, we can calculate mean irrigation calendars for planning purposes. Irrigation scheduling of high-frequency irrigation systems is very simple as it focuses only on irrigating with an amount equal to actual crop *ET* since the last irrigation while ignoring water storage in the soil.

20.1 Introduction

Irrigation scheduling is a process by which one determines when to irrigate and how much water to apply by calculating the dates and depths of irrigation. Measurements of plant (leaf water potential, canopy temperature) or soil water status (water

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content, water potential) may be used for scheduling irrigations, but here we will only deal with the simplest, albeit powerful method, the water balance approach. It involves the determination of all the inputs and outputs of water from the field, and it is based on maintaining adequate soil water content in terms of crop performance. To use this method, it is especially important to know exactly crop *ET*.

Given the technical difficulties in measuring the water balance components in practice, this method is applied based on estimates of some of the water balance components. It is therefore highly desirable, when possible, to take measurements (neutron probe, gravimetric sampling) that allow us to check the accuracy of estimated values.

This chapter first presents the foundations and applications of the water balance method. Then the information required for applying the method and the rules for determining the dates and amounts of irrigation are presented.

20.2 The Water Balance Equation for Irrigation Scheduling

The water balance equation allows calculating the decrease in soil water content as the difference between outputs and inputs of water to the field. Therefore, soil water deficit (*SWD*) for day t is calculated as:

$$SWD_t = SWD_{t-1} + ET - I_e - P_e \qquad (20.1)$$

where P_e is effective rainfall and I_e is effective irrigation. In both cases, the term effective means after discounting losses due to runoff or deep percolation. Soil water deficit was defined in Chap. 8 as the amount of water required to bring the soil to the upper limit (field capacity). Note that instead of considering the amount of water in the soil, we use a deficit of water that increases from zero when the soil is at field capacity.

Once you have a method to estimate *SWD*, you must establish rules of decision to determine the date and the depth of irrigation. The decision rule to adopt depends on numerous factors such as the crop, the soil, the climate, and the irrigation system.

The critical *SWD* that should not be exceeded is calculated as:

$$SWD_c = Z_R \cdot PAW \cdot AD \qquad (20.2)$$

where Z_R is effective rooting depth (m); *PAW* is plant available water (mm/m), which is the difference between field capacity and permanent wilting point; and *AD* is the allowable depletion (fraction). Commonly found *PAW* values for sandy, loam, and clay soils are around 100, 150, and 200 mm/m, respectively. An average *PAW* value of 120 mm/m has been found for a wide range of light- to medium-textured soils and may be used in the absence of local information.

20.3 Effective Rooting Depth

In the context of irrigation scheduling, effective rooting depth (Z_R) is the soil depth where roots can extract most of the soil water and is equivalent to the soil water reservoir that is being managed by the irrigator. This depth may be considered constant for perennials (alfalfa, fruit trees). In annual crops, Z_R increases from a minimum to a maximum value ($Z_{R\max}$) that depends on the crop and the soil (Table 20.1). The variation of Z_R for annual crops can be calculated as follows:

$$Z_R = Z_{R\min} + \left(Z_{R\max} - Z_{R\min}\right) R_f \tag{20.3}$$

where $Z_{R\min}$ is the value of root depth at planting, which is equal to the sowing depth. The maximum value of root depth for annual crops occurs around or after flowering. The factor R_f describes the rate of growth of the rooting depth during the cycle and may be calculated as a function of time (t; Eq. 20.4a) or as a function of thermal time (TT; Eq. 20.4b) from sowing:

$$R_f = \frac{t}{t_{s-m}} \tag{20.4a}$$

Table 20.1 Maximum effective root depth under no soil restrictions and factor for calculating allowable depletion (F_{AD}) for important agricultural species

Crop	Max. root depth (m)	F_{AD}
Alfalfa (hay)	1.0–2.0	0.09
Apple	1.0–2.0	0.10
Barley	1.0–1.5	0.09
Bean (Phaseolus) (dry seed)	0.6–0.9	0.11
Coffee	0.9–1.5	0.12
Cotton	1.0–1.7	0.07
Grapes (wine)	1.0–2.0	0.11
Lettuce	0.3–0.5	0.14
Maize (grain)	1.0–1.7	0.09
Millet	1.0–2.0	0.09
Olives	1.2–1.7	0.07
Orange	1.0–1.5	0.10
Palm trees	0.7–1.1	0.07
Peach	1.0–2.0	0.10
Peas (dry harvest)	0.6–1.0	0.12
Potato	0.4–0.6	0.13
Rapeseed, Canola	1.0–1.5	0.08
Rice	0.5–1.0	0.16
Sorghum (grain)	1.0–2.0	0.09
Soybeans	0.6–1.3	0.10
Sugar Beet	0.7–1.2	0.09
Sugar Cane (virgin)	1.2–2.0	0.07
Sunflower	0.8–1.5	0.11
Tea	0.9–1.5	0.12
Tomato	0.7–1.5	0.12
Winter wheat	1.5–1.8	0.09

The wide interval in root depth shown reflects the sensitivity of root distribution to irrigation management. For information on more species, see Appendix 10.3

$$R_f = \frac{TT}{TT_{s-m}} \tag{20.4b}$$

where $t_{s\text{-}m}$ and $TT_{s\text{-}m}$ are the time and thermal time from sowing to maximum rooting depth, respectively. The primary factor determining maximum rooting depth is the soil, particularly the soil depth and its mechanical resistance to root penetration. Therefore, for any given crop, the maximum rooting depth depends on soil characteristics, and that explains the wide variation in the maximum effective root depth of each species presented in Table 20.1. For instance, Table 20.1 shows that in the case of sunflowers, the maximum root depth varies from 1 to 2.5 m. In some extremely open, deep soils, it has been found that water extraction by sunflower crops occurs down to 3 m and more. Irrigation management affects the distribution of the root system; frequent irrigation promotes root growth in the surface layers, while long irrigation intervals favor more root growth in the deeper layers. Because mechanical resistance increases exponentially as the soil dries, root growth occurs very slowly or does not occur at all in dry soil. This is the reason why it is advisable to start the growing season with a fully charged soil profile (zero water deficit in the anticipated root zone). In that case, if irrigation is delayed, root growth will occur at progressively deeper moist layers because water uptake dries progressively the soil layers above, and that limits new root growth. The distribution of roots is therefore the result of the dynamics of root water uptake and of the application of water, which determine where the conditions are favorable for new root expansion. This has led to the (wrong) popular belief that roots seek out water. What roots do is proliferate where soil environmental conditions are good in terms of water, nutrient content and temperature. Thus, irrigation management affects the distribution of the root system but not its depth. Frequent irrigation favors high rooting density in the surface layers, while infrequent irrigation or rainfed conditions generate root systems with less density near the surface and much more in the deep layers. If such deep soil layers are dry, very little root growth will occur there.

20.4 Allowable Depletion

Plants can extract soil water down to the permanent wilting point, but crop performance is affected before that. The allowable depletion is the fraction of plant available water that can be extracted by the crop without negative effects on yield but could also be determined as the *PAW* fraction above which a certain process such as transpiration, assimilation, or growth proceeds unaffected. Therefore, the *AD* may depend on the process considered and on evaporative demand, as plant water status is affected by soil water potential and transpiration rate (Chap. 14). Growth rates may be affected after only 10–20% of available water has been used, while transpiration is usually affected after much higher *PAW* values (60–70%). The evapotranspiration of field crops, according to Ritchie, is reduced after 2/3 of the available water has been extracted. This is a simple rule valid when expansive growth is not critical for yield (full cover situations, harvest value dependent on dry matter). On the contrary, when growing horticultural crops, we are concerned with the size of the harvestable organ (root, bulb, leaves), so water deficits should be avoided, and a low *AD* should be adopted. The same would happen when we deal with field crops during vegetative growth. In those cases, evaporative demand should be taken also into account, with *AD* decreasing as ET_0 increases:

$$AD = 1 - F_{AD} ET_0 \tag{20.5}$$

where F_{AD} is a sensitivity factor shown in Table 20.1 for the main agricultural species (for a more complete list, see Appendix 10.3). If Eq. 20.5 yields a value of *AD* below 0.2, we adopt $AD = 0.2$.

Example 20.1
The soil in our farm is of sandy loam texture and 1 m depth. We want to irrigate maize (after full canopy cover) and onion and need to know the critical soil water deficit for irrigation management.

The values of maximum *ET* expected are 5 mm/day (onion) and 8 mm/day (maize). According to the soil type, we can adopt a value of potential available water of 120 mm/m.

According to Appendix 10.3, the maximum root depth of onion is between 0.5 and 0.8 m. We take the mean value (0.65 m). The value of F_{AD} is 0.14 (Appendix 10.3), so using Eq. 20.5, we get:

$$AD = 1 - F_{AD} ET_0 = 1 - 0.14 \cdot 5 = 0.3$$

Now we calculate the critical soil water deficit as:

$$SWD_c = Z_R \;\; PAW\; AD = 0.65\,\text{m} \times 120\,\text{mm}/\text{m} \times 0.3 = 23.4\,\text{mm}$$

The maximum root depth of maize is between 1.0 and 2 m, which in any case is greater than the actual soil depth (1 m), so we adopt 1 m as the maximum root depth. As we have reached full canopy cover, we are not concerned about expansion and adopt $AD = 0.7$. The critical soil water deficit will be:

$$SWD_c = Z_R\; PAW\; AD = 1.0\,\text{m} \times 120\,\text{mm}/\text{m} \times 0.70 = 84\,\text{mm}$$

20.5 Criteria for Irrigation Scheduling

The basic rule for irrigation scheduling is to irrigate just before the soil water deficit reaches the critical *SWD* defined in Eq. 20.2, applying a dose equal to *SWD*. This rule implies no water deficit with a minimum number of irrigations. However, the characteristics of the irrigation system may impose restrictions on the dates and depths of irrigation.

Irrigation scheduling by water balance is equivalent to operating with a credit card with a maximum credit (*PAW*) and a critical credit (critical *SWD*), above which interest rates increase (crop yields decrease). We may deposit money whenever we want (irrigate), and some friends may unexpectedly deposit money as a gift (rain). We spend money every day (*ET*); thus, the deficit in the account increases. If we want to avoid high interest rates and minimize the number of deposits (as they imply a cost, the labor involved in applying irrigation), we should go to the bank just before the deficit reaches the critical value and deposit an amount of money equal to the deficit. This would be the basic rule. If we go sooner to the bank, then the number of deposits would increase. If we go later, we will exceed the critical credit, and the interest rate will increase.

20.5.1 Restrictions to the Dates of Irrigation

Some irrigation schemes, typically those with surface irrigation, are organized according to a rotation, and farmers receive water at stated intervals (e.g., weekly), so the possible dates of irrigation are fixed, and the farmer decides the irrigation amount. Pressurized irrigation systems may work on demand, so the farmer chooses the date and the amount. However, even in this case, dates may be restricted by holidays or other operations on the farm that are incompatible with irrigation (e.g., application of pesticides) or require labor or equipment necessary for irrigation.

20.5.2 Restrictions to the Irrigation Depth

The type of irrigation system and its design may impose restrictions on irrigation depths. Surface irrigation systems are designed for applying a rather large depth (over 50–60 mm) and become highly inefficient when smaller depths are applied, except in smallholder irrigation systems of very small plots. Irrigation machines (center pivot, lateral move, siderolls) move within a given range of speeds that determine the irrigation depths that they can apply. Hand-move sprinkler systems have to be organized taking into account the time required for displacing the lateral, which usually leads to an optimum irrigation depth (or duration).

20.5.3 Decisions on Irrigation Dates and Depths

The basic rule for deciding when to irrigate is to do it just before the soil water deficit reaches the critical *SWD*, that is, calculated according to the soil and the crop. If we irrigate sooner than that, we will increase the number of irrigations and thus the cost, but we will be on the safe side in terms of water deficit and would be able to cope with possible failures of the irrigation system. If we irrigate later, and thus *SWD* exceeds the critical value, water stress will occur, and it may have a negative effect. This would be the case of deficit irrigation when the water supply is not enough to meet the crop water requirement. In the case of rotation of water supply, on any date when water is available, we should irrigate if we expect the critical *SWD* to be exceeded before the next date with water supply.

Example 20.2
We are irrigating corn during summer with a mean daily *ET* = 8 mm/day. Water is available every 10 days (July1, July 11, July 21, etc.), and the critical *SWD* is 120 mm. On July 1, the *SWD* is 20 mm. Should we irrigate? The answer is no. We can wait until July 11 as *SWD* will be $20 + 10 \times 8 = 100$ mm. We should irrigate on that date (July 11) as *SWD* would exceed the critical value soon after that, so waiting until July 21 should be discarded.

Once the irrigation date is decided, the basic rule is to refill the soil, i.e., bring the soil to zero *SWD*; therefore, the irrigation depth should be equal to *SWD* at the date of irrigation. However, the irrigation depth could be larger than that (excess irrigation) when salt leaching is required. On the contrary, the depth could be smaller, thus leaving some soil water holding capacity unfilled, which may store rainfall in the days after irrigating. This strategy may improve rainfall use at the expense of increasing the number of irrigations.

Example 20.3
Different strategies for date and depth of irrigation are applied to corn planted in March in Cordoba (Spain). The critical *SWD* is 94. Figure 20.1 shows the basic strategy (irrigated when *SWD* reaches the critical value) and apply a

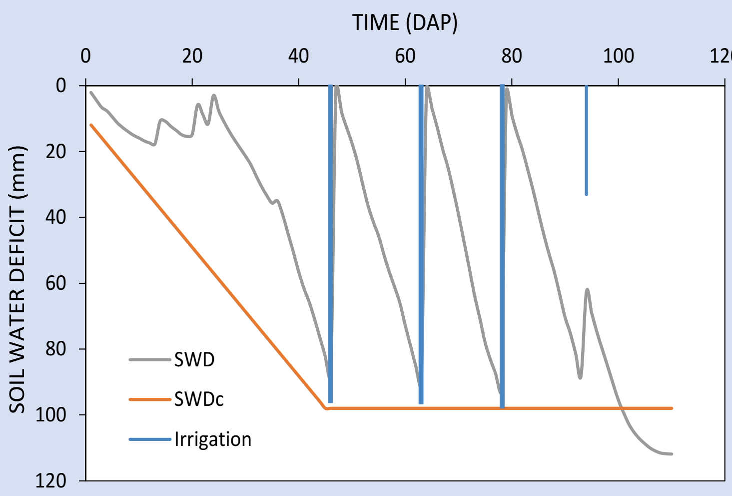

Fig. 20.1 Irrigation schedule of grain sorghum maize planted April 15 in Hinojosa (Spain). The curves of soil water deficit and critical water deficit are shown. The strategy followed is to irrigate when *SWD* equals the critical *SWD* and apply a depth equal to *SWD*

(continued)

Example 20.3 (continued)
dose equal to *SWD*. In this case, we apply three irrigations. In Fig. 20.2, a more conservative strategy is followed: irrigate before *SWD* reaches the critical value. The number of irrigations would be 4. If we adopt a strategy designed to take advantage of rainfall (do not bring the soil to zero deficit), the number of irrigations is also 4 (Fig. 20.3). In Fig. 20.4, we assume a rotational

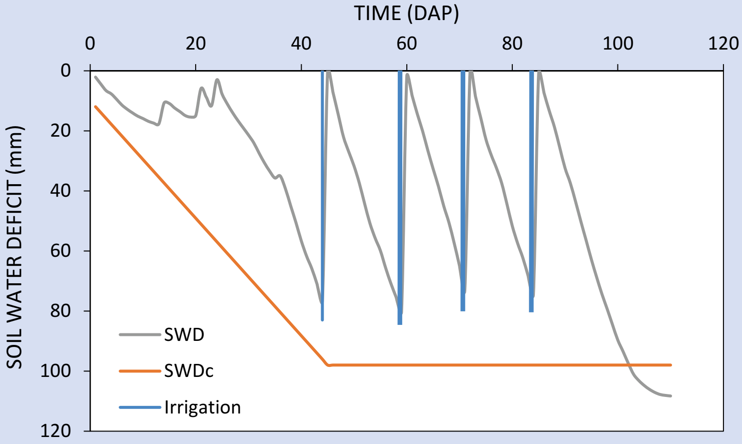

Fig. 20.2 Irrigation schedule of grain sorghum maize planted on April 15 in Hinojosa (Spain). The curves of soil water deficit and critical water deficit are shown. The strategy followed is to irrigate when *SWD* equals the critical *SWD* minus 20 mm and apply a depth equal to *SWD*

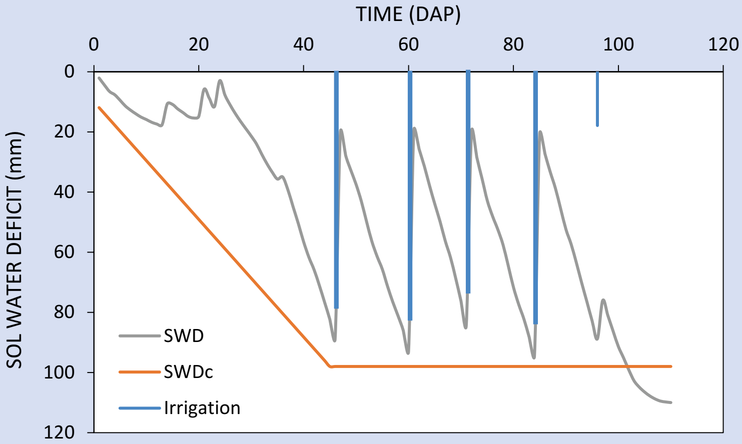

Fig. 20.3 Irrigation schedule of grain sorghum maize planted on April 15 in Hinojosa (Spain). The curves of soil water deficit and critical water deficit are shown. The strategy followed is to irrigate when *SWD* equals the critical *SWD* and apply a depth equal to *SWD* minus 20 mm

(continued)

Example 20.3 (continued)

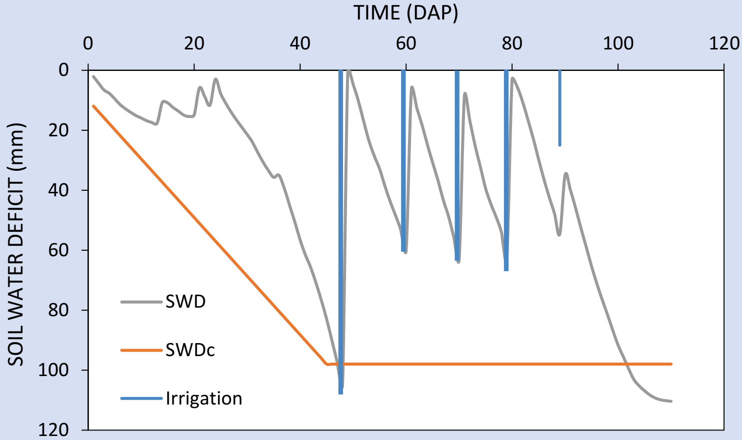

Fig. 20.4 Irrigation schedule of grain sorghum maize planted on April 15 in Hinojosa (Spain). The curves of soil water deficit and critical water deficit are shown. Here a fixed rotation water delivery is assumed, and water is available at 10-day intervals. The strategy followed is to irrigate when the expected *SWD* 10 days later will exceed the critical *SWD* and apply a depth equal to *SWD*

water supply of 10 days. The number of irrigations would be 5. Note that the farmer does not need to irrigate every 10 days but only on those days when he cannot wait until the next possible date for irrigation.

The rules about irrigation depths have to be corrected near the end of the crop cycle to leave the soil as dry as possible to allow rainfall storage during fallow and to prevent excessive deep percolation and, thus, nitrate leaching. To achieve such an objective, the soil water deficit at harvest should approach 80–90% of available water in the profile. This can be achieved by solving the water balance equation from the date of the last irrigation until harvest, which allows calculating the depth for the last irrigation as:

$$I = SWD_{t_L} - SWD_{t_H} + \sum_{t_H}^{t_L} ET_i \tag{20.6}$$

where t_L and t_H refer to the dates of the last irrigation and harvest, respectively.

Example 20.4
We are irrigating a crop whenever *SWD* reaches a critical value of 96 mm, which results from a soil depth of 1 m, *PAW* 160 mm/m, and *AD* 0.6. We need to irrigate on September 1 and want to end the irrigation season on October 1, after using 90% of the *PAW*. Therefore, the final *SWD* should be 144 mm. The average *ET* during September is 3 mm/day. Applying Eq. 20.5, we calculate the irrigation depth as:

$$I = SWD_{t_L} - SWD_{t_H} + \sum_{t_H}^{t_L} ET_i = 96 - 144 + 30 \times 3 = 42\,\text{mm}$$

Note that by applying the correction, we could save 54 mm of irrigation water.

20.6 Irrigation Schedules

The dates and depths of irrigation have to be decided in real time according to the specific weather of each year by updating the soil water deficit day after day according to crop *ET* and rainfall. In arid areas where rainfall is negligible during the irrigation season, an average irrigation calendar may be defined a priori using mean *ET* values. This approach was originally developed in California by E. Fereres. It allows better allocation of labor and irrigation equipment as the dates and depths of irrigation for each crop in the farm are calculated at the start of the season.

When irrigation systems are permanent (micro-irrigation or solid-set sprinkler systems) and there is no labor cost associated with applying irrigation, timing is unimportant, and irrigation is applied as frequently as desired. Thus, when using the water balance under high-frequency irrigation (e.g., drip), we may ignore, in principle, the soil water storage, so that the scheduling strategy is to simply replenish the *ET* accumulated since the last irrigation. As explained in Example 20.4, some irrigation water may also be saved at the end of the season under high-frequency irrigation by safely using some of the stored soil water.

Example 20.5

We are scheduling the irrigation of a tomato crop with a crop coefficient of 1.2 and a drip irrigation system with emitters of 2 L/h spaced 1 × 0.75 m. We will calculate the operation time of the system if yesterday's ET_0 was 7 mm/day

The previous day's *ET* was:

$$K_c\,ET_0 = 1.2 \times 7\,\text{mm}\,\text{day}^{-1} = 8.4\,\text{mm}\,\text{day}^{-1}$$

Each hour of operation of the irrigation system is equivalent to an applied depth:

$$2\,\text{L}/\text{h}/\left(0.75\,\text{m}^2\right) = 2.67\,\text{mm}\,\text{h}^{-1}$$

Therefore, the operation time should be:

$$8.4/2.67 = 3.15\,\text{h}\,\text{day}^{-1}$$

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Irrigation Scheduling Using Plant- and Soil-Based Methods

21

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Abstract

Over the last decades, many novel approaches to irrigation scheduling based on the use of sensors and new technologies have been proposed. These methods are based on the measurement of variables related to the plant or soil water status. Plant-based methods evaluate physical variables associated with plant response to water deficit and help in defining when irrigation is needed. However, the practical application is hindered by the sensitivity of water stress indicators to atmospheric demand and the low sensitivity to mild water deficits, so they are useless for preventing reductions in expansive growth. Soil-based methods include techniques measuring the water content or water potential of the soil, and they may provide indication on both when to irrigate and how much water to apply. Their main limitation lays on how to cope with the large spatial variability in soil water content.

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21.1 Introduction

Albeit powerful, the water balance approach for irrigation scheduling relies on estimates of the water balance components, adding uncertainty to its outputs and leading to errors that are cumulative over time. Supplementary measurements of water status are then highly recommended as they may allow the user to detect deviations in the water balance estimates and/or facilitate decision-making. In the last decades, the development of new sensors, monitoring techniques, and data transfer methods are providing new avenues for a robust characterization of the plant and soil water status. Some of these new technologies offer interesting opportunities in the context of irrigation scheduling, as an alternative or as a complement to the water balance approach. This chapter reviews the basis, the relative merits, and the main issues of the most important methods for irrigation scheduling based on plant or soil measurements.

21.2 Plant-Based Methods

This group includes non-automated, traditional methods based on manual records or observations of plant water status and gas exchange and automated instrumentation where the measured variable is recorded continuously. A priori, plant-based measurements of water status should be ideal for irrigation scheduling purposes since they are more directly related to crop performance than soil moisture. However, they show several limitations and drawbacks that hinder their suitability in practice. First, they can be helpful for defining *when* irrigation is required but provide no indication on *how much* water should be applied (except partially for methods estimating transpiration). Second, plant-based indicators of water status reflect the balance between plant water supply factors (depth and root density, soil water content) and plant water demand factors (leaf area, water vapor deficit by the atmosphere), which challenges the definition of universal thresholds for triggering irrigation. This picture is further complicated because these plant indicators are often sensitive to the developmental stage, nutritional status, and other features. Therefore, the detection of water stress often requires additional measurements in well-irrigated plants acting as controls. As a final remark, most of the plant-based methods proposed for irrigation scheduling require purchasing sophisticated and expensive equipment and/or rely on labor-intensive measurements, so they have been so far mostly restricted to research studies.

21.2.1 Water Potential

Leaf water potential (Ψ_l) is a direct indicator of plant water status and probably one of the most widespread since it can be easily measured with Scholander pressure chambers. This technique is based on the application of pressure on the limb of a leaf, which is placed into a chamber that encloses it completely, with the exception of the petiole. Pressure is increased until the appearance of a drop on the sectioned petiole. At this time, the pressure applied is approximately equal to the additive inverse of leaf water potential. Measurements in more than eight to ten leaves are usually needed to characterize each plot. The operation of pressure chambers is slow, labor consuming, and, therefore, expensive. Consequently, it is only affordable for big farming companies growing high-value crops.

Typically, leaf water potential changes along the day following a curve with a maximum before dawn and a minimum sometime after midday, as shown in Fig. 21.1. However, some atmospheric conditions (e.g., passing clouds) can modify this pattern, to some extent. On sunny summer days, leaf water potential often varies little during the central hours of the day, which is the usual measurement time using pressure chambers. In the case of fruit trees, a widespread technique is that of measuring the water potential on leaves that have been covered for 15–20 min with aluminum foil, to force stomatal closure and stop transpiration. This time is considered enough for the leaf water potential to equilibrate with that at its insertion with the stem. The so-called stem water potential is always less negative than when measured in the illuminated leaves and presents the advantage of reducing the variability of the records associated to differences in stomatal opening among leaves.

In Chap. 14 we explored the relation between transpiration, water potential, and plant resistance. According to Eq. 14.2, leaf water potential values are affected by changes in transpiration rates or in the plant resistances to water at a given level of soil moisture. As a result, the use of absolute thresholds of water potential in irrigation scheduling can induce errors under conditions different from those where the thresholds were defined. Leaf water potential is not only determined by soil water availability, but a product of the interactions of the different elements that compose the soil-plant-atmosphere continuum. Thus, this indicator is sensitive to evaporative demand and to some crop characteristics like the root/leaf area ratio. This explains

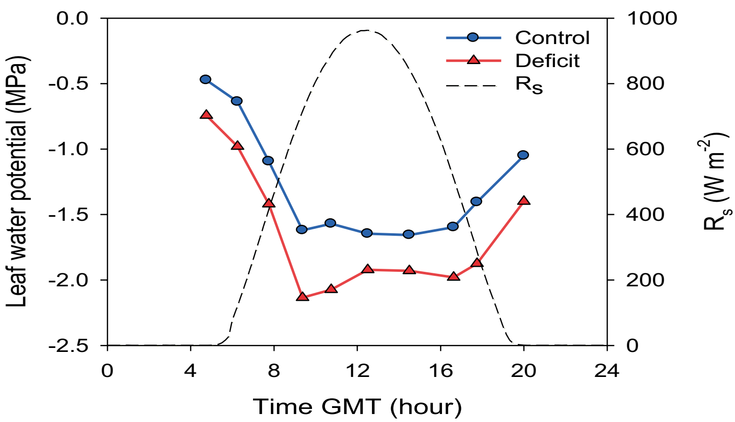

Fig. 21.1 Time course of leaf water potential under well-watered (control) and deficit irrigated (deficit) conditions in an olive orchard (Córdoba, Spain) on July 30, 2013. Water potential was measured with a Scholander pressure chamber. The dashed line represents solar radiation (R_s)

why very different water potentials are often measured for different crops under ample water supply. For example, with the soil close to field capacity, midday leaf water potential usually ranges between −1.0 and −1.2 MPa in cotton and between −0.5 and −0.7 MPa in tomato. The same variability can be observed at different crop development stages. For instance, in well-irrigated maize midday water potential can range from −0.5 MPa before the rapid growth of the stem to −1.1 MPa when maximum plant height is achieved.

A large body of literature has focused on the definition of water potential thresholds for triggering irrigation although they have been successfully applied only in a few crops like cotton. Typical threshold of leaf water potential for stomatal closure is often between −1.0 and −1.5 MPa for different species. In general, expansive growth will be reduced before these thresholds are reached, so they are not practical under partial cover or when maximum expansion is desired (e.g., horticultural crops). In those cases, a more conservative threshold would be required. On the other hand, the use of water potential thresholds is particularly challenging for crops/cultivars with isohydric behavior (see Sect. 14.4.2). In these genotypes, stomata tend to close for preventing the decrease in leaf water potential; this implies that under water deficit, transpiration is reduced to maintain a high leaf water potential, i.e., leaf water potential is barely sensitive to soil moisture variations.

Leaf water potential may help in deciding when to irrigate, but not on how much water to apply. As a result, the measurement of leaf water potential is often more useful as a diagnostic technique to assess the existence of water stress when irrigation is scheduled using other methods (e.g., water balance).

Although leaf water potential measurements are usually performed around midday for irrigation scheduling purposes, the use of pressure chambers before dawn also provides valuable information. Transpiration may be negligible during the night, which allows plant tissues to rehydrate, eventually equilibrating their water potential with that in the root zone. As a result, the so-called pre-dawn water potential is often used as a surrogate of the soil water potential (see Eq. 14.2). However, nighttime transpiration could be significant on nights with high vapor pressure deficit (VPD), preventing plants from fully equilibrating with the soil.

Lately, a new type of microtensiometer has been developed for the measurement of water potential in woody species. It is based on a microelectromechanical pressure sensor and a nanoporous membrane that hydraulically connects the xylem with the sensor. The device is small enough to be embedded in woody stems, allowing the continuous monitoring of water potential under field conditions. The suitability for continuous monitoring and automation makes this technology particularly promising, although it still requires further testing for its direct application to irrigation scheduling.

21.2.2 Leaf Turgor Pressure

This indicator represents the pressure exerted by the protoplasm on the walls of leaf cells. Tissue dehydration results in a loss of turgor that eventually leads to wilting symptoms. Magnetic leaf patch-clamp pressure probes can be used for measuring leaf turgor. These devices consist of two magnetic patches that are mounted in the adaxial and abaxial sides of a leaf, in tight contact with its surface. A pressure-sensing chip measures the attenuation of the applied external pressure, which is related to leaf turgor.

These sensors are suitable for automatic and continuous recording under field conditions. Apparently, the probes work satisfactorily only for well-hydrated leaves, which explains the scarce adoption of the technique.

21.2.3 Canopy Temperature

The development of infrared radiation sensors has enabled the remote measurement of canopy temperature. The temperature of the crop surface is related to the degree of water stress: as crop transpiration is reduced by water stress, the excess energy not spent in latent heat flux causes the heating of leaves, whose temperature increases. However, climatic factors (especially those affecting the energy balance) modify the relationship between temperature and stress, so they must be considered. Canopy temperature is otherwise a late indicator of water stress, in the sense that it reflects changes in stomatal conductance, which occur much later than the reduction in expansive growth.

Among the various methods based on canopy temperature proposed for irrigation scheduling, the most successful is the Crop Water Stress Index (*CWSI*), which is defined as:

$$CWSI = \frac{\left(T_c - T_a\right) - \left(T_c - T_a\right)_{\min}}{\left(T_c - T_a\right)_{\max} - \left(T_c - T_a\right)_{\min}} \tag{21.1}$$

where T_c and T_a are canopy and air temperature, respectively. Subindexes max and min indicate the maximum and minimum possible values. The minimum corresponds to a crop with no water stress and the maximum to a crop with maximum stress (non-transpiring). If $CWSI = 0$, then there is no water stress, while if $CWSI = 1$, the degree of stress is the maximum possible. Besides, this index is theoretically related to the rate of transpiration by the following expression:

$$CWSI = 1 - E_p / E_{p\max} \tag{21.2}$$

where E_p and $E_{p\max}$ are actual and maximum transpiration rates, respectively.

The *CWSI* enables us to decide when to irrigate but not the amount to be applied, as with most plant-based methods. In general, the value of *CWSI* indicating that irrigation is needed is around 0.25. In principle, the method applies only to full cover crops. In heterogeneous canopies with partial cover, the temperature of the soil surface (which depends largely on the water content of the upper soil layer) can potentially affect measurements of canopy temperature, if soil is present in the field of view of the sensor. However, modelling approaches have been developed for correcting the effect of soil temperature on the *CWSI*.

The calculation of *CWSI* requires knowing $(T_c-T_a)_{\min}$ and $(T_c-T_a)_{\max}$. Using the equations for sensible and latent heat flux (Chap. 5), we may compute the difference in temperature between the canopy and the air above as:

$$T_c - T_a = \frac{1}{\Delta + \gamma\left(1 + {r_c}/{r_a}\right)}\left[\frac{\gamma\left(1+{r_c}/{r_a}\right)(R_n - G)r_a}{\rho C_p} - VPD\right] \tag{21.3}$$

where R_n is net radiation, G is sensible heat flux, ρ is air density, C_p is air-specific heat, γ is the psychrometric constant, Δ is the slope of the saturation vapor pressure as a function of temperature, and r_c and r_a are canopy and aerodynamic resistance, respectively. Equation 21.3 may serve to calculate $(T_c-T_a)_{\min}$ that decreases linearly as *VPD* increases (Fig. 21.2), a relationship called *base line*:

$$(T_c - T_a)_{\min} = a_b - b_b\, VPD \tag{21.4}$$

where a_b and b_b are the intercept and slope of the linear regression of $(T_c-T_a)_{\min}$ and *VPD*. The same coefficients allow deducing the upper limit of dT as:

$$(T_c - T_a)_{\max} = a_b / (1 - b_b\Delta) \tag{21.5}$$

From Eq. 21.3, for conditions of maximum and zero evaporation, the coefficients of the base line may be calculated as:

$$a_b = \frac{\gamma^*}{\Delta + \gamma^*}\frac{(R_n - G)r_a}{\rho C_p} \tag{21.6}$$

$$b_b = \frac{1}{\Delta + \gamma^*} \tag{21.7}$$

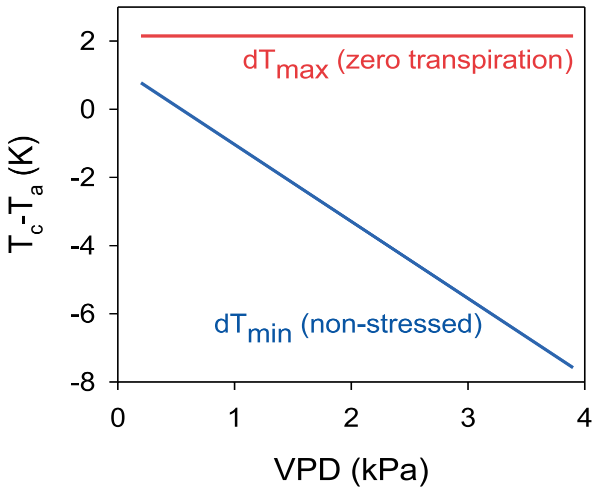

Fig. 21.2 Temperature difference between the canopy (T_c) and the air (T_a) for zero ($dT_{\max}$) and maximum transpiration ($dT_{\min}$, base line) for cotton in Córdoba

where:

$$\gamma^* = \gamma\left(1 + r_c / r_a\right) \tag{21.8}$$

Differences in temperature between the canopy and the air are higher for smooth uncoupled canopies (e.g., short grass) than for rough coupled vegetation (e.g., tree orchards), as demonstrated in Example 21.1. Another relevant observation is that the cooling effect of transpiration is proportional to *VPD*, as implicitly assumed in Eq. 21.3. This agrees with the fact that *CWSI* is of little use in humid areas or cloudy days (low *VPD*), where the signal-to-noise ratio is smaller.

Example 21.1

We will calculate the base line and the increase in temperature for zero transpiration when air temperature is 25 °C, net radiation is 600 W m^{-2}, and soil heat flux is 100 W m^{-2} in the following cases:

(a) Crop of height 1 m, $r_a = 20$ s m^{-1}, $r_c = 50$ s m^{-1}
(b) Forest of height 10 m, $r_a = 5$ s m^{-1}, $r_c = 150$ s m^{-1}

The slope of the saturation vapor pressure with respect to temperature will be:

$$\Delta = \frac{4098\, e_s}{\left(237.3 + T_a\right)^2} = \frac{4098 \times 3.167}{\left(237.3 + 25\right)^2} = 0.189\,\mathrm{kPa\,K^{-1}}$$

(a) Crop

$$\gamma^* = \gamma\left(1 + r_c / r_a\right) = 0.067\left(1 + 50/20\right) = 0.2345\,\mathrm{kPa\,K^{-1}}$$

$$a_b = \frac{0.2345}{0.189 + 0.2345}\frac{\left(600 - 100\right)20}{1200} = 4.61\,\mathrm{K}$$

$$b_b = \frac{1}{0.189 + 0.2345} = 2.36\,K\,\mathrm{kPa^{-1}}$$

$$\left(T_c - T_a\right)_{\max} = 4.61/\left(1 - 2.36 \times 0.189\right) = 8.3\,\mathrm{K}$$

(continued)

Example 21.1 (continued)

(b) Forest

$$\gamma^* = 0.067(1 + 150/5) = 2.077\,\text{kPa K}^{-1}$$

$$a_b = \frac{2.077}{0.189 + 2.077}\frac{(600 - 100)5}{1200} = 1.9\,\text{K}$$

$$b_b = \frac{1}{0.189 + 2.077} = 0.44\,\text{K kPa}^{-1}$$

$$(T_c - T_a)_{\max} = 1.9/(1 - 0.44 \times 0.189) = 2.1\,\text{K}$$

Example 21.2

Dr. F. Orgaz found the following base line for cotton in Córdoba:

$$(T_c - T_a)_{\min} = 1.23 - 2.26\,VPD$$

We will calculate the *CWSI* for conditions of *VPD*= 3 kPa, (T_c–T_a) = −3 °C, and air temperature of 25 °C.

$$(T_c - T_a)_{\min} = 1.23 - 2.26 \times 3 = -5.5°\text{C}$$

$$e_s = 0.6108\exp\left[(17.27 \times 25)/(237.3 + 25)\right] = 3.168\,\text{kPa}$$

$$\Delta = (4098 \times 3.168)/(237.3 + 25)^2 = 0.189\,\text{kPa K}^{-1}$$

$$(T_c - T_a)_{\max} = 1.23/(1 - 2.26 \times 0.189) = 2.15°\text{C}$$

$$CWSI = \frac{-3 - (-5.5)}{2.15 - (-5.5)} = 0.33$$

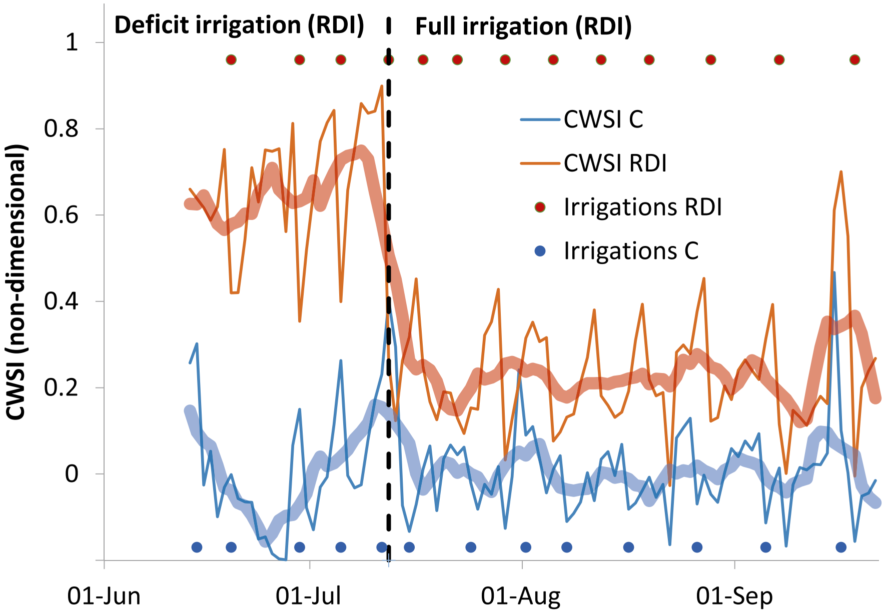

Fig. 21.3 Time course of *CWSI* for pistachio in Madera County, CA, in 2006 for two irrigation treatments. The vertical black line (dashed) marks the end of the period when irrigation was reduced for the RDI (regulated deficit irrigation) treatment. (Adapted from Testi et al. (2008). Irrig Sci 26:395–405)

Canopy temperature measurements may be taken with a handheld infrared thermometer (often similar to a handgun) that must be aimed with the sun at the back, forming an angle of about 30° with the horizontal to view only vegetation and not the soil surface. The *VPD* can be measured with humidity sensors or from readings of dry and wet bulb temperatures. Temperature and humidity should be measured at 0.5–1 m above the crop surface, avoiding the edges of the plot.

Canopy temperature can be monitored remotely with infrared sensors or thermal cameras mounted on proximal or airborne platforms. This enables the characterization of the spatial variability of crop water status, which can be used to plan subsequent sampling, to adjust the amount of water to apply in specific irrigation sectors, or to diagnose problems with the irrigation system in specific plots (see Chap. 39). An example of the use of *CWSI* for pistachio in California is presented in Fig. 21.3.

21.2.4 Expansion Rate

The expansion rates of leaves, stems, or fruits are sensitive even to mild water deficit. They can be measured using high-resolution displacement sensors (see Sect. 21.2.5) or, in the case of leaves, by measuring changes in leaf dimensions, which is labor intensive. Expansion rates are reduced long before photosynthesis is affected, so they may be used as an early indicator of water stress, if a well-watered control is available as control. This technique is not suitable when expansive growth stops, as is the case with determinate species (e.g., sunflower, corn, wheat) during the reproductive growth phase.

The use of expansion rate as an indicator of water deficit is also complicated by the effect of evaporative demand. Figure 14.6 (Chap. 14) shows leaf expansion rates measured in Córdoba (Spain) for sunflower in spring and summer, with low and high evaporative demand, respectively. In the summer, leaf expansion rates start to decrease with a lower depletion of soil water, i.e., expansion if more sensitive to soil water when ET_0 is high. To some extent, the effect of soil water availability can be improved by normalization, dividing the expansion rates by ET_0 or *VPD*. Using control unstressed plants as a reference is a possible solution.

21.2.5 Stem Diameter Variations

When transpiration begins in the early morning, part of the water stored in plant tissues is lost until root water uptake equals transpiration (Fig. 14.1, Chap. 14). This leads to a contraction of plant tissues, including stems. This is reversed when transpiration decreases in the evening, which allows plant tissues to rehydrate and increase in volume. Daily fluctuations of stem diameter can be measured with high-resolution sensors (linear variable displacement transducers, *LVDT*) providing information on plant water status. On the one hand, the magnitude of the stem contraction (maximum daily shrinkage, *MDS*) increases with water stress, but only in some cases (Fig. 21.4), limiting the adoption of this technique. However, these sensors provide continuous records of stem diameter and thus of stem growth rates, which are an early indicator of stress. Unfortunately, the definition of thresholds for daily growth rates is often complicated as they are affected by some plant characteristics or developmental stages. For instance, stem growth is heavily depressed in years of high fruit load in tree crops, even if they are well irrigated.

21.2.6 Stomatal Conductance

Leaf stomatal conductance can be measured with porometers. It is a relatively late indicator of water stress, so it is more suitable after full cover is achieved, when expansive growth is less important for yield formation. Stomatal conductance is strongly affected by environmental conditions (e.g., radiation, temperature, humidity) and highly variable among leaves, which limits its use in irrigation scheduling. The measurements should be compared with records taken from well-watered control plants (Fig. 21.5).

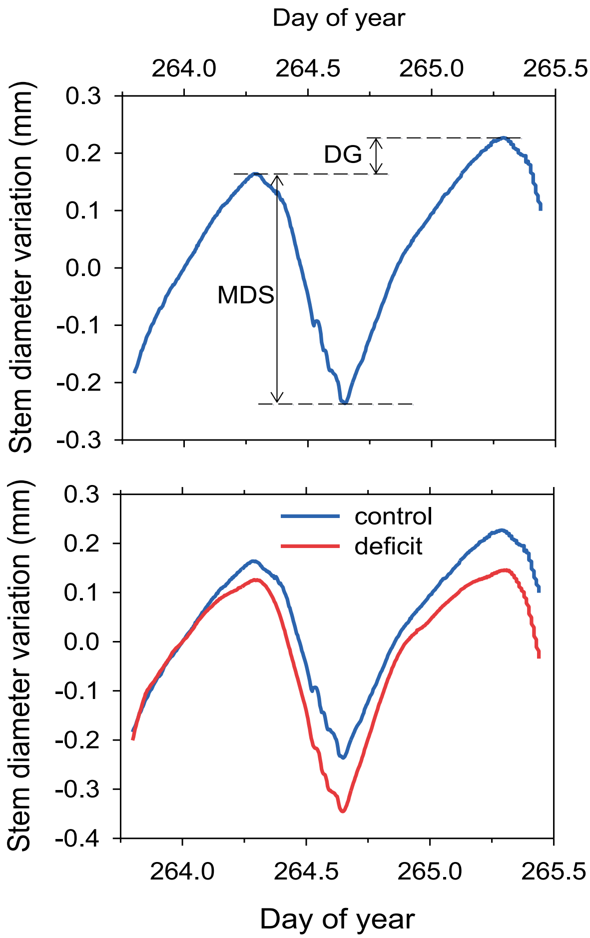

Fig. 21.4 Stem diameter variation-derived indexes (upper panel) and differences in the time course of this variable between well-watered (control) and deficit irrigated (deficit) trees (lower panel) in La Harina farm, Córdoba, Spain. Records were taken during September 20–22, 2013, with *LVDT* sensors installed in the trunk. *DG* daily growth, *MDS* maximum daily shrinkage

21.2.7 Sap Flow

Several methods are available to determine water flow through stems, a surrogate of transpiration, by using heat as a tracer.

(a) Heat balance methods solve the heat balance for a stem segment during continuous application of heat. The amount of heat taken up by the sap stream is computed and used to calculate sap flow rate. The heat is applied with a flexible gauge wrapped around the stem or using stainless steel electrode plates inserted into the wood.

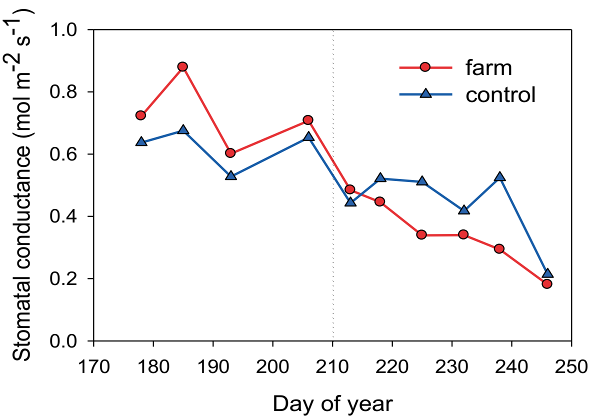

Fig. 21.5 Time course of maximum stomatal conductance measured in peach trees during the morning in La Veguilla farm, Córdoba, Spain, during the summer of 2008. Some trees had double water supply to ensure maximum transpiration (control) after DOY 210 (indicated with a dashed line) as compared to the farm schedule (farm). This is reflected in higher stomatal conductance after that date. (Adapted from Testi et al. (2022). Irrig Sci 40:407–422)

(b) The thermal dissipation method is based on the continuous or transient application of heat through a cylindrical probe of ≤2 mm diameter that is inserted radially into the stem. A second probe installed some millimeters below the heater records temperature changes in the xylem, so the temperature difference between the probes is related to variations in sap flow rates. Despite being an empirical method, it is one of the most widespread because of the simplicity of the sensors, which makes them more affordable.
(c) Heat pulse techniques include several approaches based on the application of short heat pulses at regular intervals using thin linear heater probes inserted in the stem. Xylem temperature is measured before and after the heat pulse at specific down- and upstream locations with respect to the heater using probes of similar dimensions. Temperature responses to heat pulse emission are used to derive sap velocity.

Each sap flow method presents specific features that make them more or less appropriate under some conditions. For instance, some are useless for determining high sap flow rates, while others work fine only above a threshold of sap velocity. Similarly, some devices are only suitable for specific ranges of stem diameter. In any case, sap flow measurements today are only suitable for woody species.

Sap flow can be used as a surrogate of transpiration although the former should theoretically lag the latter on an hourly basis (see Fig. 14.1, Chap. 14). As transpiration is one of the major components of crop evapotranspiration, sap flow measurements could be very useful in irrigation scheduling when combined with the water balance method, particularly when soil evaporation can be independently measured or estimated. In any case, due to the spatial variability of sap velocity in the xylem,

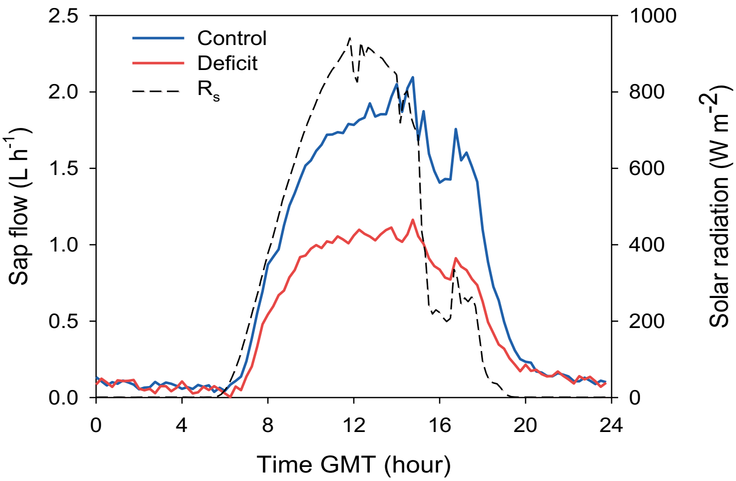

Fig. 21.6 Time course of sap flow of olive trees under well-watered (control) and deficit irrigated (deficit) conditions in La Harina farm, Córdoba, Spain, on August 22, 2013. Sap flow was measured with the compensated heat pulse technique. The dashed line represents solar radiation (R_s)

calibration of sap flow records is a prerequisite when accurate absolute estimates of transpiration are sought, irrespective of the method.

Variations in sap flow rates may serve as an indicator of water status. In this regard, relative reductions in sap flow should theoretically match those of photosynthesis but will occur later than those in the growth rate. In addition, transpiration and hence sap flow are highly influenced by evaporative demand and atmospheric conditions in general, which precludes the establishment of "safety thresholds." Concurrent measurements of sap flow on well-watered control plants are then required for determining when the rate recorded under conventional irrigation management is reduced below its maximum (non-stressed) value. Alternatively, estimates of unlimited transpiration using crop simulation models (see Chap. 40) may serve as the reference to detect changes in water status. Figure 21.6 shows the diurnal curves of sap flow of olive trees under ample water supply and deficit irrigation. In both cases, the sap flow curve is delayed from that of solar radiation.

21.2.8 Water Content of Plant Tissues

Gravimetrical determinations represent the simplest alternative for measuring the water content of specific plant organs, avoiding the need for sophisticated instrumentation. In leaves, relative water content (*RWC*) is estimated as:

$$RWC = (FW - DW)/(SW - DW) \tag{21.9}$$

where *FW* is the fresh weight of the leaf sample, *DW* is its oven-dry weight, and *SW* stands for the maximum (saturated) weight, which is obtained after soaking the

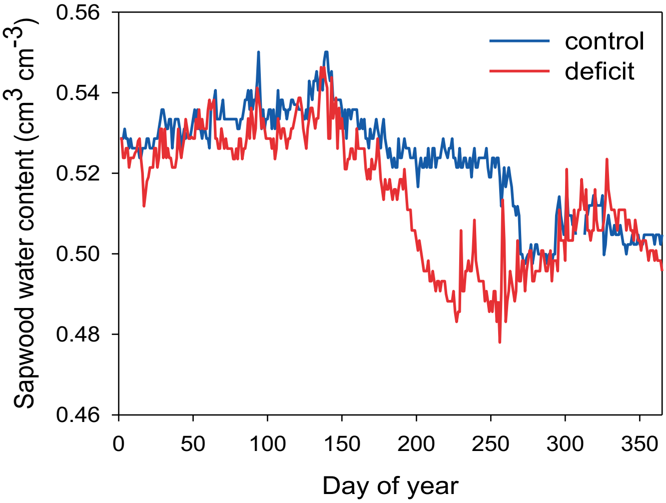

Fig. 21.7 Time course of sapwood water content in olive trees under full or deficit irrigation. (Adapted from Lopez-Bernal et al. (2012). Tree Physiol 32:1420–1429)

leaves in water for several hours. This method is prone to error, partly because *FW* should be measured immediately after excising the leaves. Furthermore, determinations are time consuming, so they are of little help for irrigation scheduling. Indeed, water potential is considered a more rigorous and applicable measure of water status.

In tree species, sapwood water content also reflects plant water status. In most cases, the change in water content is too small to be useful for irrigation scheduling, but long-term variations respond to water supply as shown in Fig. 21.7 for olive trees. Apart from destructive gravimetrical determinations, water content can be indirectly estimated from the thermal properties, electrical resistance, and dielectric constant of sapwood, which are only used in research.

21.2.9 Qualitative Evaluation of Plant Water Status

The use of visible symptoms of water stress to decide the date of irrigation is a rapid method that requires no equipment. Indeed, many farmers still rely on crop appearance to decide when to irrigate. Their success depends largely on their experience. The main drawbacks of this method are as follows:

(a) It is difficult to establish general criteria. Each species may show characteristic symptoms, which can vary even for different cultivars. Some of the more typical are leaf curling (grasses), changes in leaf orientation (sorghum, beans), reduced plant size, temporary wilting (sugar beet), leaf shedding (almond), stiffness and dark color of stems (cotton), and darker color of young leaves (beans).

(b) The visible symptoms usually appear when the plant water stress has been suffered for some time, which in many cases implies that a fraction of the attainable yield has been already lost at the time of symptom appearance. Visible symptoms are, therefore, late indicators of water stress.

21.3 Soil-Based Methods

In this section, we review the main approaches for determining the water potential or water content of the soil. The techniques differ in their principles, the need for sophisticated instrumentation, labor requirements, and cost, among others. For some, readily automated commercial devices are available.

The main advantage of soil measurements of water status is that, unlike plant-based methods, they provide useful information for deciding both the time and dose of irrigation (except for tensiometers). On the contrary, the often-large spatial variability in soil water status poses a major challenge for these methods, since they are mostly based on point measurements and so only representative of a very small soil volume. Therefore, many sensors or extensive monitoring programs would be required (often expensive) if a robust estimate of the average water status of the plot is needed. Finally, measurements should be performed in positions within the soil volume where most root water uptake takes place, which depends on crop and irrigation system characteristics. In localized irrigation systems—where soil water content varies drastically within decimeters—finding representative positions for the measurement points is even more challenging.

21.3.1 Gravimetric Sampling of Soil Moisture

This is a direct method for measuring soil water content. It is often used to calibrate indirect methods (e.g., neutron probe). The method involves taking soil samples (using an auger or a sampling tube), weighing (to determine the fresh mass), drying in an oven (at 105 °C), and weighing again (dry mass). Alternatively, soil samples can be dried in a microwave oven.

The main drawbacks of this simple method are the destructiveness (the measurement cannot be repeated at the same point) and the high demand for labor. Since the spatial variability of soil water content is often significant, a high number of samples must be collected. This may be impractical in the context of irrigation scheduling.

This method poses problems in stony soils due to the difficulty in sampling. In soils with high organic matter, mass losses may occur by oxidation and/or burning, so drying should be performed at 50–70 °C. Another possible source of error is the loss of moisture from the sample before drying, which must be avoided by using suitable containers (cans, bags, etc.). Finally, the gravimetric method requires knowing the soil bulk density (which is often highly variable in space) to convert soil water content from mass to volume fractions.

21.3.2 Neutron Probe

This is an indirect method for measuring soil water content. It has been used extensively in research and applied to irrigation scheduling in some countries (e.g., Australia). A neutron probe is composed of a radioactive source (typically Americium-241/Beryllium) that emits high-energy neutrons, a slow neutron detector, and an amplifier/output unit. The emitter and the detector are located together in a cylindrical piece that is lowered into the soil through an access tube. The access tube may be of steel, aluminum, or PVC. The high-energy neutrons (fast neutrons) collide mostly with hydrogen atoms, becoming slow neutrons. The higher the water content of soil, the greater the number of collisions, and the greater the number of slow neutrons originated, which is measured with the detector.

Contrary to other methods, where water content or potential is estimated for a discrete point, the estimates by neutron probes integrate the water status of a given volume of soil. The radius of influence is inversely proportional to the water content of the soil. For example, in a medium texture soil, the radius can vary from about 0.5 m at the lower limit of soil water content to about 0.2 m when the soil is saturated.

The main drawbacks of the neutron probe are its high cost and the need for qualified personnel, but, more importantly, using radioactive equipment implies that its use must abide by the safety regulations in place. Moreover, measurements cannot be automated, so the temporal resolution is low, and the installation of the access tubes may be difficult in compacted or stony soils. Its main advantages are the high speed of measurement and the high reliability of the records when the probes are properly calibrated. Under these conditions, the neutron probe may be useful for deciding the timing and dose of irrigation.

21.3.3 Measurements of the Dielectric Constant of the Soil

TDR (time domain reflectometry), *FDR* (frequency domain reflectometry), and capacitive techniques are based on estimates of the soil dielectric constant, which mainly depends on its water content. This is because there is a sharp contrast between the dielectric constant of pure water (80) and that of dry soils (~2–5). The first commercial applications of these techniques date back to the 1980s.

A *TDR* system consists of an oscilloscope connected to two metal rods that are inserted parallel into the soil. When an electric potential difference is applied to one end of the rods, the energy is transmitted along the rod until its end, where it is reflected back toward the oscilloscope, where potential is continuously recorded. The transmission speed of the wave on the return trip depends on the dielectric constant of the medium (soil surrounding the rods), so it is possible to deduce the dielectric constant from the transit time of the wave through the rods.

TDR shows several advantages over other measurements of soil water status. First, the relationship between water content and dielectric constant is barely affected by soil type. This is important because it implies that the technique is theoretically independent of soil texture. However, special soil types like those of volcanic origin may require specific calibrations. On the other hand, *TDR* measurements have high temporal resolution and may be automated for long-term in situ monitoring. The main disadvantages of these devices include their high cost and the difficulty of installation of the rods within the soil. The contact between the sensors and the soil must be very close, because air has a very low dielectric constant that can distort the measurements; this generates errors in expansive soils, which fracture and tend to retract from the rods when drying. Finally, in saline or very wet soils or when the guides are very long, the signal attenuation can be excessive, so the reflected signal may be insufficient to be detected, and the measurement can fail.

Capacitance and *FDR* sensors determine the soil dielectric constant by measuring the time required to charge a capacitor (formed by two electrodes) using the soil as the capacitor. Both techniques are soil specific and hence may require calibration, but the cost of the devices is generally lower than that of *TDR* probe.

21.3.4 Tensiometers

Tensiometers measure the soil matric potential, which may be used to decide when to irrigate. The matric potential is negative (zero corresponds to free water), so it is convenient to express it as soil water tension, which is the opposite of the soil matric potential (i.e., its absolute value).

A classic tensiometer is a cylindrical tube with its upper part connected to a vacuum gauge and its bottom to a porous ceramic capsule. The capsule acts as a membrane permeable to water and solutes. This capsule is saturated with water and placed in contact with the soil at the measurement depth. If it is in contact with an unsaturated soil, the lower soil water potential will cause a suction of the water in the body of the tensiometer, which is detected by the vacuum gauge. As the soil dries, the gauge reading increases (the water leaves the tensiometer through the capsule). If the soil is wetted, the water reenters the capsule, which causes a reduction in the gauge reading.

The maximum tension that can be measured with a tensiometer is theoretically 1 atm (100 kPa), although most tensiometers allow readings only between 0 and 80 kPa. The soil water tension for a soil at field capacity is between 10 and 30 kPa. In sandy and coarse texture soils, the threshold tension for irrigating can be within the 0–80 kPa interval. By contrast, in clay soils much of water content usable by plants can be out of the tensiometer range. When the tension exceeds 100 kPa, the pores of the ceramic capsule lose water, causing air entry that breaks the continuity of the water column, so the manometer displays a zero reading. As they work better with high values of soil water content, tensiometers are more suitable for irrigation scheduling in high-frequency irrigation systems. As a result, they have been more commonly used in perennial crops.

21.3.5 Equitensiometers

Equitensiometers allow an indirect determination of soil water potential. They are based on measuring the electrical resistance between two electrodes embedded in a porous material (gypsum, fiberglass, or nylon matrixes) buried in the soil. Water and solutes are exchanged between the sensor and the soil, eventually reaching an equilibrium in matric water potential. The lower the soil matric potential, the higher the resistance measured between the electrodes of the block; this relationship has to be calibrated in the laboratory. The measurement interval in which electrical resistance measurements are more accurate is for tensions above 10–30 kPa, depending on sensor material. Consequently, these instruments are more suitable for operation in medium or heavy textured soils. In gypsum-based sensors, the gypsum slowly dissolves which limits their service life to a few years (at best). The addition of gypsum to the soil during sensor installation can be useful for extending their life. As a final remark, they should not be used in saline soils, as the salt content affects the electrical resistance.

21.3.6 Basic Criteria for Sensor Deployment

The optimum number and placement of devices for monitoring soil water status in the context of irrigation scheduling depend on several factors related to the crop, soil characteristics, and the irrigation system. When the majority of the roots are located near the surface (lettuce, potato, etc.), a single measurement point may provide enough information to track the system dynamics, while larger rooting depths require deploying several devices. Sensor placement depends on the spatial distribution of the roots. In furrow irrigated annual crops, devices should be located in the plant rows. In drip irrigation systems, they should be installed within the drip-wetted area but apart from the emitter. In the case of fruit tree orchards, they should be placed within the wetted area near the tree.

When analyzing sensor outputs, the trends and the velocity of record variations provide indication on whether enough water is being applied to meet the demand, which can be used to automate the operation of the irrigation system. This is illustrated in the following examples for partial and full cover drip irrigation systems:

- Partial cover irrigation (Fig. 21.8, left): Sensors may be distributed in two dimensions. We can place one sensor at 10–20 cm from the emitter (sensor 1) that will act as a control and another in the wet bulb edge (sensor 2). It may be desirable to place another at a depth somewhat greater than that of the wet bulb. Any increase in the water content/potential in sensor 2 may indicate an excess of irrigation.
- Full cover irrigation (Fig. 21.8, right): Sensors should be placed at different depths. A sensor installed at a depth slightly greater than that reached by the wet bulb will show over-irrigation by increases in its measurements of water content/potential.

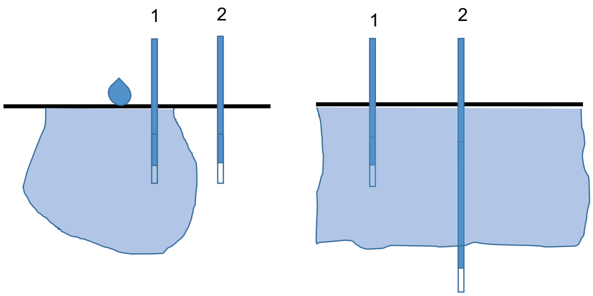

Fig. 21.8 Control of irrigation doses with pairs of sensors. In the case of drip irrigation with isolated wet bulbs (left), excess irrigation would be detected by the increase in water content or potential in sensor 2. For full coverage systems (right), the role of sensor 2 would be similar

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Deficit Irrigation

22

Elias Fereres and Francisco J. Villalobos

Abstract

When the level of irrigation supply is less than crop *ET*, deficit irrigation (DI) programs are needed to optimize the use of the limited water. In annual crops where yield and transpiration are linearly related, DI aims at achieving maximum profits by minimizing application losses and maximizing the use of stored soil water and seasonal rainfall. Crops that respond positively to mild water deficits are good candidates for DI programs that decrease irrigation water use while maintaining yield. DI programs for fruit trees and vines aim at inducing water deficits when they are least harmful to yields, including high evaporative demand periods. Achieving optimal use of limited water is accomplished by solving an optimization problem using knowledge of water availability and cost and net farm profits.

22.1 Introduction

For many decades, the paradigm of irrigation development was to supply crops with sufficient water to meet their full water requirements. This approach was chosen because the large investments associated with irrigation networks, from dams to on-farm equipment, were best justified if farmers would achieve maximum yields, normally associated with maximum transpiration. Intensification of irrigation has been generalized worldwide in most of the irrigated lands. However, there were irrigation development situations where, to reach a maximum number of farmers, the irrigation supply was less than that needed to meet the full crop demands. In other cases,

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the system capacity was inadvertently designed to supply less than required. Sometimes, different crops or more intensive rotations were introduced, exceeding the capacity of the original system. More recently, water allocation to irrigation has been challenged by other sectors of society, so the supply has been reduced below the original allotment. Furthermore, periodic droughts cause water scarcity situations aggravated by excessive water use, so the irrigation water supply becomes more unreliable. Under water scarcity, irrigation has less priority than other sectors such as urban use or minimum environmental flows. Under all these conditions, farmers do not have sufficient irrigation water to meet the full crop water requirements, so crop transpiration will be reduced below its maximum potential. Normally, the decrease in transpiration results in a reduction in crop production of variable magnitude depending on many factors (Chap. 14). Deficit irrigation (DI) is thus defined as an irrigation management practice where insufficient water is applied so crop transpiration stays below its maximum unstressed value. This chapter discusses how to manage DI to minimize yield reductions and maximize farmers' productivity and profits in situations of water scarcity.

22.2 The Yield Response Function to Water

DI forces farmers to solve an optimization problem: given a restricted level of supply, what is the optimum irrigation program to maximize their goals? Normally, farmers seek maximum revenue or net income from their operations, which is not necessarily equivalent to achieving maximum production. The basic information needed to optimize the use of a limited water supply through DI is the relationship between water applied and yield. If the yield and irrigation water ($Y{-}I$) relationship is known for a specific situation at the field scale, the manager can determine the optimum amount of I to reach maximum net profits. This will be the level of I above which, the value of the additional crop produced would be less than the cost of one additional water unit. Given the close, linear relationship between transpiration and biomass production discussed in Chap. 14, and because of the conservative nature of the harvest index (HI) of many crops, the relationship between transpiration and crop yield is linear for the major crops over a wide range of transpiration, starting with the maximum yield at the maximum, unstressed transpiration value. However, the relation between yield and irrigation water ($Y{-}I$) is not linear, and is primarily affected by the uniformity of distribution of irrigation water over the field.

To better understand the $Y{-}I$ relationships at the field scale, Fig. 22.1 shows the variation in irrigation depth in different parts of the field, going from the areas that receive more water than the required depth to the areas that receive less water than required. Such spatial differences are caused by variations within the irrigation system that deliver different amounts in different parts of the field due to manufacturer and pressure variations, wind effects, and other factors that cause a lack of uniformity in water distribution. The shape and slope of the line that describes the actual water distribution in the field (Fig. 22.1) represents the distribution uniformity,

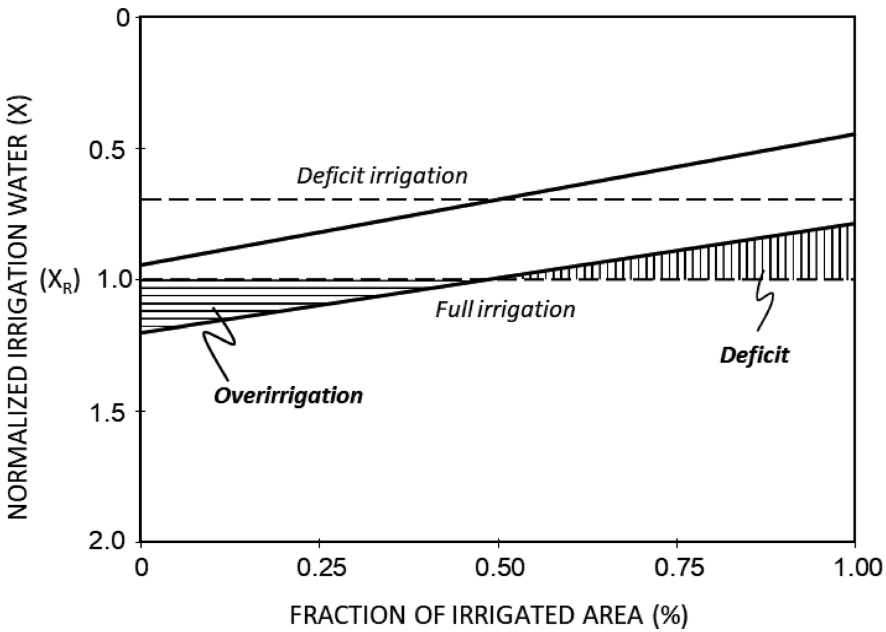

Fig. 22.1 Relations between normalized irrigation water and the fraction of the irrigated area that receives at least that amount. X_R indicates the level of water required as shown by the horizontal dashed line at 1.0, and another dashed line at 0.7 indicates a level of DI that is 30% less than X_R. The actual water distribution across the field is shown by the solid lines for full and deficit irrigation, going from the areas that receive the most water to the areas that receive the least

which is always less than 100% (horizontal lines). When this line has a high slope, we have a low uniformity, so some areas receive much more water than others. In the case of DI, where water applied is less than that required (see Fig. 22.1), some areas within the field will receive much less than required, so local yields could be seriously diminished by severe water stress. On the other hand, deep percolation losses under DI are greatly reduced as most or all the limited irrigation water remains accessible to the root system, leading to a high efficiency of water use.

To supply sufficient water to all the areas in a field, additional water must be applied to arrive at the required depth in the areas that receive the least water. Figure 22.2 represents a generic yield response function with two levels of irrigation uniformity, high and low. The linear function between yield and *ET* is also shown. As irrigation increases, more irrigation water is not used in *ET* and is lost as runoff or deep percolation. If irrigation uniformity is high, losses would be small and maximum yields will be achieved with little excess water (Fig. 22.2). However, if uniformity is low, irrigation application has to increase to meet the needs of the areas that receive the least water, while others will be getting an excess. In the case of Fig. 22.2, water application under low irrigation uniformity must double the required amount to achieve maximum yields.

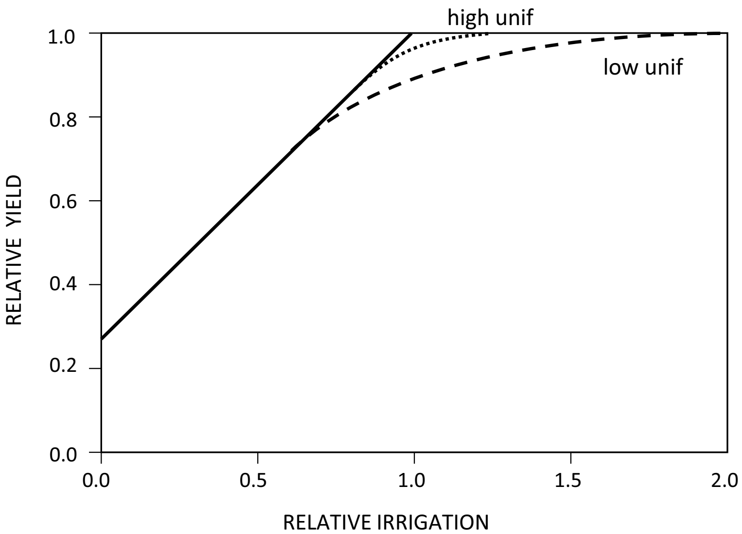

Fig. 22.2 Generic relations between relative irrigation and relative yield under two levels of uniformity. The solid line is the linear relationship between relative yield and relative *ET*

The *Y*−*I* function for a given crop and field needed to quantify I_{opt} requires knowledge of the relation between *Y* and *ET* and the actual irrigation uniformity (Chap. 23).

22.3 Deficit Irrigation in Annual Crops

To define the *Y*−*I* function, the relations between yield and transpiration (E_p) must be known. While the $B-E_p$ relationship is unique for a given crop and is only affected by the environment in which the crop is grown, the $Y-E_p$ relationship of a crop can vary depending on the timing and intensity of the E_p deficits. This is because of the differential sensitivity to water stress of the different crop developmental stages. Water deficits imposed at sensitive stages affect disproportionally more the harvest index (*HI*) than biomass production, while the *HI* does not vary from the unstressed value if water deficits during the sensitive stages are avoided or are not severe enough. As a general rule, when transpiration deficits are imposed progressively and are moderate, *HI* is not affected, and the reduction in *Y* is proportional to the reduction in *B*. Figure 22.3 shows the typical *Y* responses of an annual crop as *ET* is decreased by water deficits. The thick line represents the response to uniform, progressive water deficits, and the two steeper lines represent the responses when water deficits are more severe and/or occur at the most sensitive stages of crop development. In most annual crops, the most sensitive stages are those at which yield-determining processes (such as flowering, fruit set, and fruit growth) occur. For instance, in the case of grain crops, the reproductive stages are more sensitive

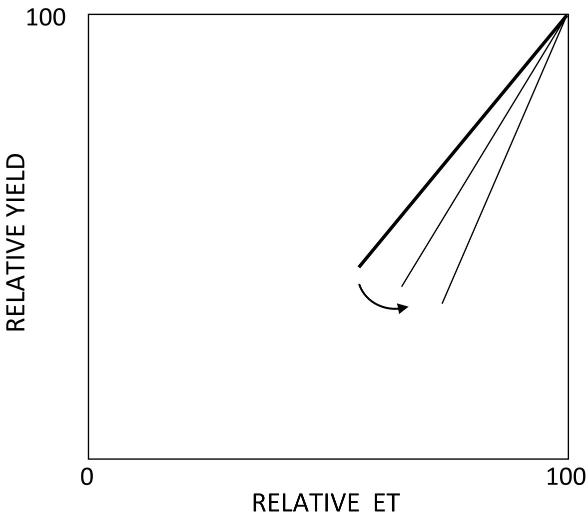

Fig. 22.3 Relations between relative crop yield and relative *ET* influenced by the severity of water deficits during sensitive developmental stages. The arrow indicates the response trend as water deficits are applied at the most sensitive stages and with increased severity

than the vegetative phase. By contrast, most horticultural herbaceous crops are not amenable to DI because generally they are harvested for fresh weight and size, which are very sensitive to water deficits. The following is a discussion of how DI can be designed for the major crops.

22.3.1 Maize

The most sensitive period to water deficits is flowering, from tasseling to silking. Severe water deficits during that period delay or prevent silk emergence, impairing pollination and resulting in very low grain numbers. Following in sensitivity is the early grain filling period where severe stress results in grain abortion. Late grain filling is less sensitive, and the least sensitive is the vegetative phase, as leaf growth recovers after the release of temporary water deficits. Note that during the vegetative phase, the goal is to develop a canopy that intercepts maximum radiation; thus irreversible reductions in canopy expansion caused by severe deficits also limit yield substantially. In general, maize is not a crop adapted to DI, as any reduction in E_p harms Y. Mild E_p deficits of around 10% or less, during the mid to late vegetative phase, have the least impact on production and may be a viable DI strategy in case of water scarcity.

22.3.2 Wheat

As in other winter cereals, flowering is the most sensitive period to water deficits, in particular the pollination to grain set period. However, the stages of development before and after pollination are also quite sensitive. In the pre-flowering phase, when the number of florets in the spikes is being determined, water deficits may cause a reduction in grain numbers. After pollination, the abortion of grains also reduces grain numbers under water stress. Grain filling in its early stages is also quite sensitive to water deficits, which harms grain weight. During the early vegetative phase, wheat is quite tolerant to water deficits, but at the tillering stage, water deficits may reduce tiller numbers. Winter cereals have compensatory mechanisms, and a reduction in grain numbers may be partially compensated by increased grain weight if conditions during grain filling are favorable. Thus, deficit irrigation of wheat is a viable strategy if deficits are restricted to the early vegetative and late reproductive stages, with mild to moderate reductions in transpiration. There are situations, however, where farmers have limited access to irrigation water, sufficient to apply one irrigation only. In that case, depending on rainfall probability and soil water storage, the most profitable time to supplement rainfall would be around flowering. In shallow soils and very low post-flowering rainfall probabilities, it should be delayed as much as possible to avoid severe stress during grain filling, while in the opposite case, the single irrigation would be most profitable at the pre-flowering stage to maximize the number of grains which could then be filled based on stored soil water.

22.3.3 Rice

Rice is generally grown under flooded conditions; thus it is not subjected to soil water deficits. However, newer rice-growing methods are based on wetting and drying of the soil. Rice has a small, shallow root system and is extremely sensitive to water deficits. The few (2–3) days around pollination time are the most sensitive to water deficits and can cause almost complete crop failure. It is not a crop suitable for deficit irrigation, so water supply must be concentrated on an area that permits meeting its full water requirements.

22.3.4 Soybean

Although it is an indeterminate-type plant, the flowering of most modern varieties is determinate, normally occurring during a 2–3-week period. Water deficits during flowering and fruit set are most detrimental to yield. The next, most sensitive period is seed filling, when water deficits cause premature leaf senescence and reduce seed filling. Water stress during the vegetative period affects canopy cover and hence radiation interception. When it occurs during the late part of that period, it is less detrimental, if it is not severe enough to cause premature, irreversible leaf senescence. Soybean is mostly produced under rainfed conditions; thus the likelihood of using deficit irrigation is small; nevertheless, in terms of relative sensitivity, soybean is quite sensitive to water deficits, about the same as maize; thus the DI strategy should be quite conservative, aiming at producing at least 80–90% of full yields with limited irrigation.

22.3.5 Potato

It is very sensitive to water deficits and thus a candidate for DI strategies that only induce mild water stress. The most sensitive stage for yield is the time during stolon formation and tuber initiation. Irreversible effects on canopy expansion should be avoided during early canopy development. The period of tuber growth is less sensitive, but yields are also affected, in particular if canopy senescence is hastened by water deficits. The relative sensitivity to water stress varies somewhat among the wide range of existing cultivars.

22.3.6 Sorghum

It is tolerant to water deficits and is a good substitute for maize when water shortages force DI. Mild to moderate water deficits have little or no impact on yields because of the increase in harvest index. The most favorable DI strategy is to sustain the level of water deficit throughout the season, for example, applying 75% of full *ET* needs, aiming to reach harvest time with the root zone profile exhausted of available water. Severe stress that reduces *ET* below 50–60% of the maximum causes a decrease in *HI* and is detrimental to yield. Thus, DI strategies in sorghum should keep *ET* above 60% of the maximum. The optimal economic level would be 70–80% of maximum *ET* depending on water availability and irrigation costs.

22.3.7 Tomato

Like many other vegetable crops, tomato is not amenable to deficit irrigation as yields are reduced with reductions in *ET*. However, in processing tomatoes, mild deficits reducing *ET* by less than 10% during ripening do not affect yield and increase dry matter content. Stress imposed during other developmental stages reduces canopy growth, fruiting, and yields.

22.3.8 Sugarcane

It is very sensitive to water deficits during the period of stalk growth, early in the crop cycle. The least sensitive period is maturation where mild to moderate deficits lead to increased sucrose accumulation in the stalk and reduction in harvest fresh weight (and harvest costs). Therefore, DI should aim at imposing some *ET* deficits during the maturation period with reductions of *ET* of no more than 10–15% of the seasonal value. On the other hand, water supply should not limit canopy growth until the crop reaches full cover.

22.3.9 Cotton

It is a good candidate for DI where the season length is limited by low temperatures at the beginning and end of the season. Water deficits during the late vegetative growth period hasten flowering and boll formation, and during the maturation phase, they enhance boll opening and synchrony for effective mechanical harvest. Moderate water deficits during those two phases result in an increase in *HI* and a reduction in season length that better fits some environments. Again, as in sorghum, severe water stress is detrimental to net profits and reduces *HI*; thus DI should keep *ET* above 60–70% of the maximum. The most sensitive period where water deficits should be avoided is during fruit set to prevent fruit abortion.

22.3.10 Sunflower

It is a drought-avoiding species with a high growth rate during the vegetative phase but low biomass accumulation during the reproductive stage when it accumulates high-energy fats and proteins. The period from the end of flowering to early fruit set is the most sensitive to water deficits, followed by early seed filling, late seed filling, early vegetative, and late vegetative. This is because sunflower has a strong compensatory growth capacity following the release of water deficits during the vegetative phase. DI strategies should aim at imposing moderate deficits during the vegetative phase, well after crop establishment but ending it before leaf growth is completed. Such a period is not very long relative to the crop cycle; thus, *ET* reductions should not exceed 10–20% of seasonal *ET* for optimum irrigated production.

22.4 Deficit Irrigation of Fruit Trees and Vines

The most powerful measure to respond to water scarcity in annual crops is to adjust the planted area to the available supply, planning a mild to moderate reduction in *ET* (10–15%). This is not possible in permanent crops where the irrigated area cannot be reduced and the investment and maintenance costs are substantial, so sustaining the plantations is a primary objective. Occasionally, farmers may take advantage of drought years to replace old orchards with new ones of different species or cultivars. With such exception, to cope with a reduction in water supply, some form of DI is required to minimize the impact of water deficits. This is particularly important in permanent crops because water deficits also affect subsequent years' production. Furthermore, there is a need to avoid the possibility of tree death with the negative economic consequences due to the multi-year investment losses if the plantation is lost.

The responses of fruit trees and vines to water deficits are much more complex and less understood than in annual crops. The yield-determining processes are also more complex and commonly, yields oscillate with time even under optimal growing conditions. This feature is called *alternate bearing* (Chap. 13), which varies in importance among the different fruit tree species and cultivars. Water deficits in the current season affect yields of the subsequent season(s), depending on its timing and severity. Knowledge of the sensitivity of the different processes to water deficits is required to allocate water to avoid harming the current and/or subsequent years' yields.

One important benefit of DI in fruit trees and vines is related to the enhancement of fruit quality features caused by moderate water deficits. The most important case is that of wine grapes. Plants grown under moderate water deficits, applied both early during berry growth and late after the berries changed color, promote the synthesis of several biochemical compounds that are essential wine quality components. High-quality wines are produced mostly in rainfed environments or under substantial DI programs, while wines obtained from grapes grown under unlimited supply are seldom of good quality for winemaking. Other fruits benefit from an increase in the sugar content or other positive changes in composition induced by DI. With the exception of wine grapes, quality features have no effect on fruit prices received by farmers. Fruit size, which is appreciated in many markets, is reduced by DI, which makes it not viable, as in the case of apples.

Experiments with peach and pear trees demonstrated that irrigation may be restricted in periods when yields are insensitive to water stress and water can be saved with minimal or no yield loss, sometimes producing more net profits than under full irrigation. Imposing water stress on tree crops and vines at certain developmental stages considered the least sensitive to water deficits has been called regulated deficit irrigation (RDI), a term now used for any DI approach followed in trees. However, there is another DI approach, applying a fraction of the *ET* throughout the irrigation season. This sustained or continuous DI (*CDI*) strategy generates a stress pattern different than that of *RDI*, at least in temperate environments, where ET_0 varies widely during the growing season. The usual stress pattern in *CDI* starts early in the season when a fraction of *ET* is applied, but trees extract additional water from the wet soil with the consequence that water deficits seldom develop. Depending on the magnitude of the deficit and the water storage capacity of the root zone, water deficits will increase in magnitude in *CDI* as the season progresses, reaching the highest level when ET_0 is highest close or near the end of the season, in the absence of rainfall. This has the advantage of decreasing tree *ET* at a time of high evaporative demand, resulting in increased water use efficiency (Chap. 14).

22.4.1 Regulated Deficit Irrigation

The physiological basis of *RDI*, i.e., imposing water stress at specific developmental stages, resides in the differential sensitivity of vegetative growth and photosynthesis to water stress (Chap. 14). Expansive growth is more sensitive to water deficits than carbon assimilation; thus mild to moderate water stress slows down or stops leaf and stem growth before it impacts photosynthesis. During fruit growth of some tree species, there are periods when vegetative growth takes place and fruit growth slows down almost to a stop. In those periods, water stress reduces growth in general, but fruit growth can fully recover upon release of stress, while vegetative growth has been curtailed. The result is less vegetative growth (and less pruning costs) while fruit size is unaffected. There are some species where moderate water deficits change the partitioning of assimilates in favor of the fruits with beneficial effects on yield and fruit quality. In deciduous trees, the period after fruit harvest is another insensitive period where water deficits may be applied without affecting yield, provided that next year's bud development processes have been completed.

The yield response to *ET* deficits generated by *RDI* strategies may be generalized as shown in Fig. 22.4. Three different response regions may be defined:

A: Small reductions in *ET* applied during insensitive periods do not reduce yields.

B: As *ET* deficits increase, yield decreases with a gentle slope.

C: Same as C but with a much steeper slope. Water deficits during the more sensitive periods can reduce yields dramatically (dashed line in Fig. 22.4).

The width of Region A depends on the species:

- Non-existing: very sensitive species such as avocado, walnut, and apple
- 5–15% *ET* reduction: citrus (depending on species and cultivars), pears, almonds, etc.
- 10–20% *ET* reduction: peach, plum, apricot, pistachio, etc.
- 20–30% *ET* reduction: olive

Region B also varies in magnitude with species and cultivars following the differential sensitivities indicated for Region A. The mild slope indicates that the water savings must be compared against yield losses to find an optimum net income under DI. On the contrary, the steep slopes of Region C suggest that *ET* deficits of such magnitude will have detrimental effects on net income and should be avoided at all costs. There are extreme drought situations, however, where the water supply is so

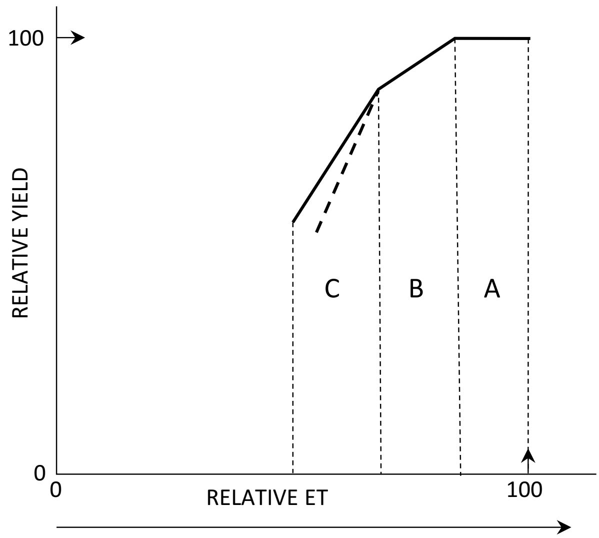

Fig. 22.4 Generalized yield responses to *ET* deficits induced by *RDI* strategies in fruit trees expressed in relative terms

limited that tree survival is at risk. The limited information available suggests that severe pruning is not recommended as a measure to reduce *ET* and that a supply equivalent to 25–35% of unstressed *ET* is the minimum needed to prevent extensive tree death.

22.5 Deficit Irrigation at Farm Level

Water restrictions at the farm level force managers to make strategic decisions before planting. They must decide what crops to grow and how to allocate different water amounts to each crop to make the best use of the limited supply available. Different crops need different irrigation amounts with different timing. Economic issues (markets and subsidies) are critical in determining the farm's net profits once the total supply available is known. The goal would be to optimize the use of land and irrigation water given the supply restrictions, which is achieved with economic optimization models. These models provide optimal cropping patterns and irrigation amounts for each crop that maximize the objective function that is normally the total farm income. Once the model is built, it can be used to explore different scenarios of varying crop and water prices and other factors, such as the impact of changing subsidies on the strategic decisions of farmers. One complicating factor at the farm level is the uncertainty of water restrictions. Too often, water authorities delay the announcement of the restriction to farmers after some of the best options for using the limited water (e.g., early planting) are no longer viable. In the event of a drought, farmers must be proactive in securing their water supplies and maintain open communication with the water authority to make the best use of the limited water under uncertainty.

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Optimizing Irrigation

23

Francisco J. Villalobos and Luciano Mateos

Abstract

The main irrigation performance indicators are distribution uniformity, adequacy, application efficiency, and irrigation efficiency. They evaluate different aspects of the irrigation process and have to be used jointly for a comprehensive assessment. A simple model combining the spatial distribution of irrigation with the biomass-transpiration relationship allows the calculation of optimum irrigation amounts. For cheap water, optimum irrigation will seek maximum yield and will depend only on uniformity and the irrigation requirement. As water prices increase, economic factors play a key role in the calculation of optimum irrigation. Irrigation uniformity has a large impact on the spatial variation of N uptake and losses. Conventional N fertilizer applications will lead to higher N losses than fertigation, which can be quantified. The key parameters in the design and management of irrigation systems are the seasonal irrigation requirement and the peak irrigation system capacity. In locations with dry summers, the variability of the seasonal irrigation requirement depends only on rainfall variations, and the variability of peak irrigation is negligible. The dose of irrigation events can be calculated following similar rules for all irrigation methods.

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23.1 Introduction

The final purpose of an irrigation system is to supply water to meet the crop evapotranspiration (*ET*) and, thus, allow stomatal opening for photosynthesis' supply of CO_2 while keeping the plants at an adequate temperature. Other uses of irrigation (frost protection, solarization, fertilizer and pesticide application, soil conditioning for sowing or harvest) may also be important in agricultural practice. On the other hand, irrigation interacts with other farm operations reducing the time available or even the possible dates of irrigation. The key parameters in the design and management of irrigation systems are the peak irrigation system capacity and the seasonal irrigation requirement. Both depend mostly on crop *ET*, which in turn will be affected partly by the irrigation system. The crop and the soil will also affect the optimum irrigation interval and, thus, the irrigation depth per event. Each irrigation method will also have specific parameters that will require optimization like application rate in pressurized systems.

23.2 Irrigation Uniformity and Efficiency

The analysis starts by determining how applied irrigation varies in space. Figure 23.1 shows an example of the measured distribution of applied irrigation in a field. The lack of uniformity implies the existence of areas with excess and areas with deficit irrigation. The intersection of the curve and the horizontal line of the target (required)

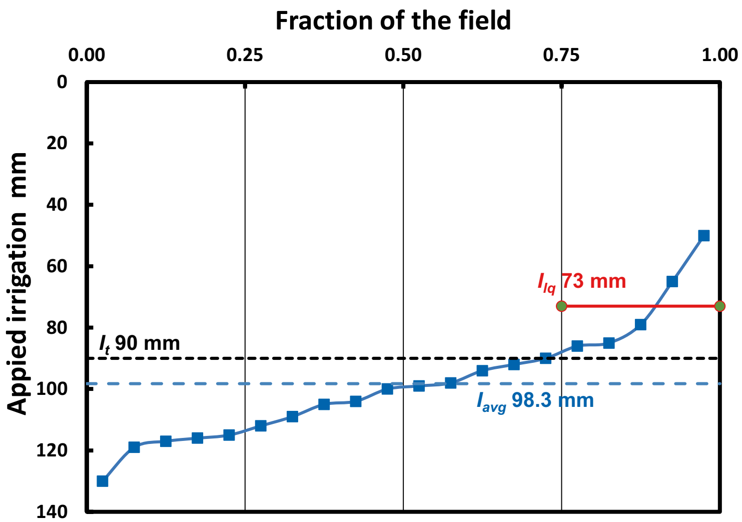

Fig. 23.1 Distribution of applied depth across the field. The distribution is sorted from larger to smaller depth and plotted versus the fraction of the area. Horizontal lines represent the average applied depth (I_{avg}), the target depth (I_t), and the average depth of the low quarter (I_{lq})

depth shows the fraction of the field adequately irrigated, i.e., where ET is not limited by water stress.

The distribution of applied water with localized irrigation is measured by collecting the volume of water discharged by a sample of emitters. In sprinkler irrigation, applied water is collected in a grid of catch cans. In furrow irrigation, the applied water is measured at the furrow inlet and infiltrated water is estimated from the measured infiltration time.

Several performance indexes have been proposed to benchmark irrigation systems for their design and management.

The low quarter distribution uniformity, DU_{lq}, describes the level of irrigation uniformity:

$$DU_{lq} = \frac{I_{lq}}{I_{\text{avg}}} \times 100 \tag{23.1}$$

where I_{lq} is the mean application in the 25% lowest depths and I_{avg} is the average depth.

In general, the target depth should be equal to the irrigation required ($I_t = I_{\text{req}}$). To quantify how irrigation meets the target depth, we use irrigation adequacy, *AD*, the fraction of the field that receives at least the required (target) depth (I_t). It may be approximated using the low quarter adequacy, AD_{lq}, as:

$$AD_{lq} = \frac{I_{lq}}{I_t} \times 100 \tag{23.2}$$

If $AD_{lq} = 1.0$, only 12.5% of the field will be under-irrigated. The target depth may be the soil water deficit, *SWD* (Chap. 20). If salt leaching is required, then I_t should be greater than the *SWD* at the time of irrigation (Chap. 24).

Application efficiency, *AE*, is the ratio of target and average applied depth, i.e., evaluates how irrigation applied meets the target irrigation depth. Therefore:

$$AE = \frac{I_t}{I_{\text{avg}}} \times 100 = \frac{DU_{lq}}{\text{AD}_{lq}} \times 100 \tag{23.3}$$

This equation shows that *AE* will increase as uniformity increases but may be achieved also by reducing irrigation (with lower *AD*). Note that for a given uniformity, high *AD* requires reducing the *AE*.

Another interesting, albeit harder to measure, indicator is irrigation efficiency, *IE*, the ratio of irrigation water beneficially used by the crop to the amount of water that leaves the boundaries (applied—Δ water stored in soil) of the system:

$$IE = \frac{\text{Irrig.water beneficially used}}{I_{\text{avg}} - \Delta\,\text{soil water}} \times 100 \tag{23.4}$$

The equation may be applied to the soil root depth of a field, a farm, an irrigation scheme, or a whole watershed. The water beneficially used is mostly *ET* but also includes salt leaching requirements and water used for preparing the seedbed, crop establishment, and harvest preparation. Non-beneficial uses include deep percolation above leaching requirements, surface runoff, weed transpiration and evaporation from reservoirs, sprinklers, and wetted soil.

IE is estimated using water balance models. If the water beneficially used equals the target depth, then *AE* is an estimate of the maximum *IE*, i.e., *IE* is lower than *AE*. Furthermore, the difference between *AE* and *IE* may be large, for instance, when irrigation is applied at the end of the growing season unless the applied depth is corrected (see Chap. 20).

23.3 Quantitative Optimization of Irrigation at the Field Level

We start with the assumption that biomass production is proportional to transpiration and that the harvest index does not change with the level of water stress (Chap. 14). This is valid for mild to moderate stress. Therefore, yield will be proportional to transpiration in any location of the irrigated field. We also assume that evaporation from the soil surface (E_s) is equal in all points of the field and that excess irrigation has no penalty on yield (but see Sect. 23.4).

We assume that applied irrigation follows a uniform (i.e., rectangular) distribution. Therefore applied irrigation (I) will lie between a minimum and a maximum:

$$I_{\mathrm{min}} = I_{\mathrm{avg}} \frac{4\,DU_{lq} - 1}{3} \tag{23.5}$$

$$I_{\mathrm{max}} = I_{\mathrm{avg}} \frac{7 - 4\,DU_{lq}}{3} \tag{23.6}$$

where I_{avg} is the average irrigation applied and DU_{lq} is the low quarter uniformity coefficient (Sect. 23.2). The irrigation crop water requirement was defined in Chap. 10 as:

$$I_{req} = ET^{*} - P_e - SWE \tag{23.7}$$

where ET^{*} is unstressed (i.e., maximum) seasonal crop *ET*, P_e is effective precipitation, and *SWE* is soil water extracted from the soil between planting and harvest.

We have three possible situations:

(a) $I_{\mathrm{max}} < I_{\mathrm{req}}$: The whole field is under-irrigated. In this case, yield will be proportional to transpiration and thus to the irrigation applied in each point of the field.
(b) $I_{\mathrm{min}} > I_{\mathrm{req}}$: The whole field is over-irrigated, so yield will be Y_x (maximum yield).

(c) $I_{\min} < I_{\text{req}} < I_{\max}$: Parts of the field are over-irrigated, and parts are under-irrigated, so the former will reach Y_x, while the latter will produce a yield in proportion to irrigation received in that location.

To calculate the average yield (Y_{avg}) in the whole field, we calculate the integral of yield using applied irrigation (I) as the variable of integration. For instance, for the third case, we calculate:

$$Y_{\text{avg}} = \frac{1}{I_{\max} - I_{\min}} \left[\int_{I_{\min}}^{I_{\text{req}}} Y_x \frac{ET^* - E_s - I_{req} + I}{ET^* - E_s} dI + \int_{I_{\text{req}}}^{I_{\max}} Y_x dI \right] \tag{23.8}$$

After integration, we get the relationship between average yield (kg/ha) and average applied irrigation (I_{avg}, mm):

$$Y_{\text{avg}} = \frac{3Y_x}{8(1 - DU_{lq})E_{px}} \left(\frac{7 - 4DU_{lq}}{3} E_{px} - \frac{4DU_{lq} - 1}{3} E_{p0} - \frac{I_{\text{req}}^2}{2I_{\text{avg}}} - \frac{(4DU_{lq} - 1)^2}{18} I_{\text{avg}} \right) \tag{23.9}$$

Note that $ET^*–E_s$ is unstressed (maximum) transpiration (E_{px}) and $SWE+P_e–E_s$ is transpiration for zero irrigation (E_{p0}).

For the first case ($I_{\max} < I_{\text{req}}$):

$$Y_{\text{avg}} = \frac{Y_x}{ET^* - E_s} \left(SWE + P_e - E_s + I_{\text{avg}} \right) = Y_x \frac{E_{p0} + I_{\text{avg}}}{E_{px}} \tag{23.10}$$

And for the second case, ($I_{\min} > I_{\text{req}}$), $Y_{\text{avg}} = Y_x$.

The equations above are also helpful to calculate ET as a function of irrigation applied, as we have stated that yield is proportional to transpiration. Therefore actual ET will be:

$$ET = E_s + \frac{3}{8\left(1 - DU_{lq}\right)} \left(\frac{\left(7 - 4DU_{lq}\right)}{3} E_{px} - \frac{\left(4DU_{lq} - 1\right)}{3} E_{p0} - \frac{I_{\text{req}}{}^2}{2I_{\text{avg}}} - \frac{\left(4DU_{lq} - 1\right)^2}{18} I_{\text{avg}} \right) \tag{23.11}$$

which is valid when $I_{\min} < I_{\text{req}} < I_{\max}$. If $I_{\max} < I_{\text{req}}$, then ET is $SWE+P_e+I_{\text{avg}}$. The difference I_{avg}-ET will be the average deep percolation (DP) in the field.

The model illustrates several points:

(a) To achieve maximum yield, it is necessary to apply $3\ I_{\text{req}}/(4\ DU_{lq}-1)$. For instance, with $DU_{lq} = 0.75$, the gross irrigation should be 150% of the irrigation requirement.

(b) If we improve irrigation uniformity and apply the same total irrigation, the ET will increase (Eq. 23.11). This is part of the so-called rebound effect of modernization of irrigation schemes, which may lead to increased water use, thus limiting the generation of water savings.

(c) The maximum profit per unit area is achieved with less water than that required for maximum yield. The optimum value will depend on the price of harvest (P_H, €/kg) and the cost of irrigation water (Q_I, €/m^3):

$$I_{\text{opt}} = \frac{3\,I_{\text{req}}}{\sqrt{48\,F\left(1-DU_{lq}\right)+\left(4\,DU_{lq}-1\right)^2}} \tag{23.12}$$

where F is a dimensionless parameter equal to the virtual cost of maximum transpiration divided by the income obtained with the maximum yield:

$$F = \frac{10\,Q_I\,E_{px}}{P_H\,Y_x} \tag{23.13}$$

Note that P_H should be corrected to discount variable costs.

This equation indicates that the optimum irrigation amount is related to the irrigation system (DU_{lq}), to the crop species and location (ratio E_{px}/Y_x), and to external economic factors (ratio Q_I/P_H). The ratio E_{px}/Y_x is proportional to Vapor Pressure Deficit (VPD) and larger for C3 than for C4 species (Chap. 14). Therefore, the optimum irrigation of a given crop should decrease as we move to a drier environment.

Example 23.1
We are growing maize with maximum yield of 16,000 kg/ha and seasonal ET of 750 mm with E_s = 150 mm. P_e and SWE are 150 and 100 mm, respectively. The irrigation system is sprinkler with DU_{lq} = 0.75. The price of maize is 0.3 €/kg. If the water price is 0.05 €/m^3, then F = 300/4800 = 0.0625, so the optimum irrigation will be 688 mm. In this case yield would be 15,950 kg/ha (from Eq. 23.9). With water price of 0.15 €/m^3, we should apply 600 mm to get a final yield of 15,667 kg/ha.

As F gets very small, the optimum irrigation will only depend on DU_{lq}, i.e., with free water we will try to reach maximum yield by applying an irrigation amount inversely proportional to DU_{lq} (Fig. 23.2).

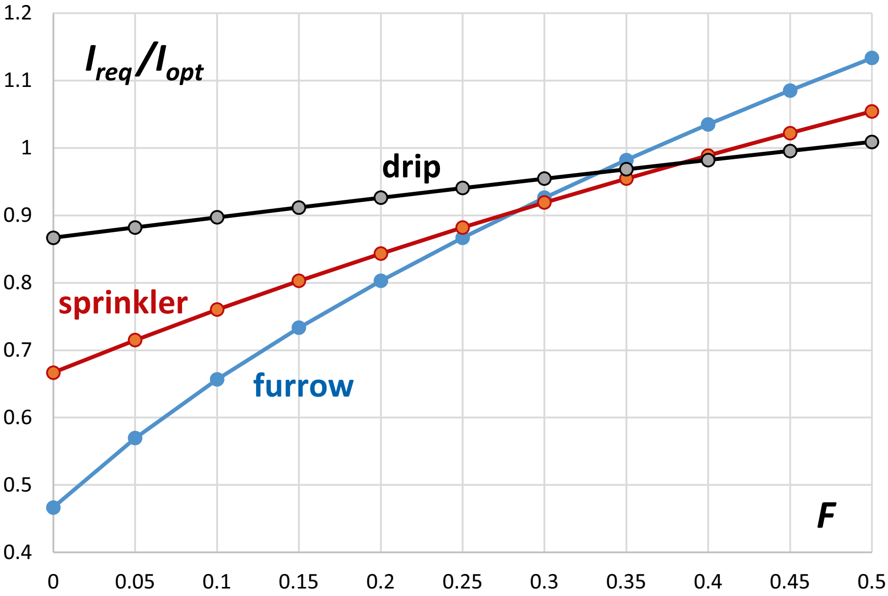

Fig. 23.2 Relationship between the ratio optimum/required irrigation and the *F* factor (virtual cost of maximum transpiration/income with maximum yield). We have assumed DU_{lq} of 0.60 for furrow (blue), 0.75 for sprinkler (red), and 0.90 for drip (grey) irrigation

23.4 Irrigation Uniformity and Efficient Use of N

When N fertilizer is applied with irrigation water (fertigation; Chap. 29), the amount of N will vary spatially in proportion to applied irrigation. Crop yield will then be proportional to water applied according to the equations presented in 23.3. N loss may be estimated as the product of deep percolation (*DP*) and the average N concentration of irrigation water. This is a conservative estimate as the N concentration of drainage water will exceed that of irrigation water. To achieve maximum yield, we would need an excess N proportional to DP/I_{avg}.

On the other hand, with conventional fertilization, N is managed independently of irrigation and we have a more complex situation (Fig. 23.3). There will be:

– Areas under-irrigated: Water will limit yield, so we will have an excess N that may be leached after the growing season.
– Areas over-irrigated: N is limiting yield. N losses during the growing season will be proportional to the water excess.

Therefore, spatially uniform (conventional) application of N leads to higher N losses and lower yield than using fertigation. The main difference in N loss should occur after the growing season in under-irrigated areas.

One consequence of this analysis is that conventional (uniform) N application limits yield in proportion to irrigation applied. To achieve maximum yield, we

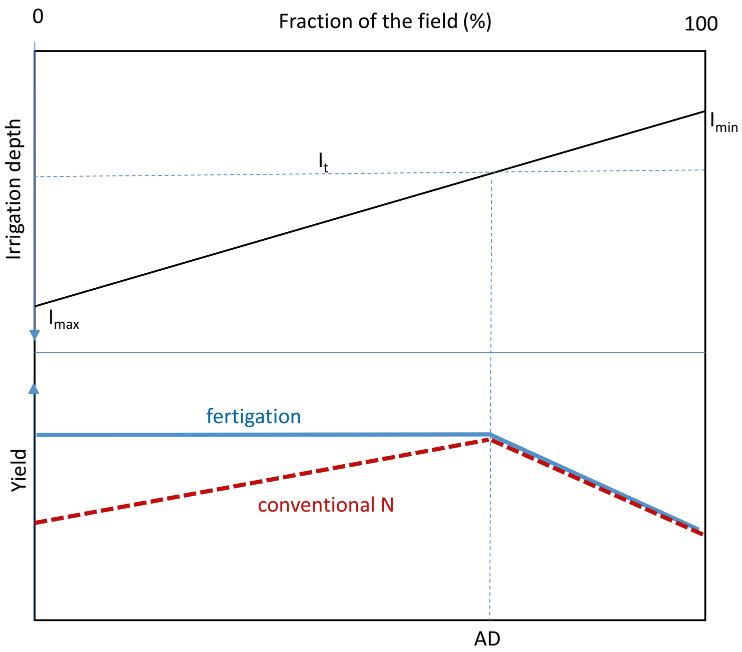

Fig. 23.3 Spatial variation of applied irrigation and yield assuming either that N is applied by fertigation or uniformly to the whole field. *AD:* irrigation adequacy

should add an excess N to ensure enough N supply in the area of maximum irrigation, i.e., the excess N would be equal to N leaching with I_{max}. If the N fertilizer required for maximum yield is N_f, the amount of fertilizer to apply is:

$$N_f' = N_f \frac{I_{\max}}{I_{\mathrm{req}}} \tag{23.14}$$

In addition to drainage losses during the season, the under-irrigated areas of the field (to the right of *AD* in Fig. 23.3) will have more residual N left at the end of the season which could be lost in the fallow period depending on management and rainfall. The N loss would vary from zero (at point *AD* in Fig. 23.3) to a maximum at the point of minimum yield.

Example 23.2
In Example 23.1 we evaluated the optimum irrigation for maize when low quarter $DU = 0.75$. If the water price is 0.05 €/m^3, the optimum average irrigation is 688 mm, while the irrigation requirement is 500 mm. If the total N fertilizer required is 270 kg N/ha:

(continued)

Example 23.2 (continued)

(a) With fertigation, we could apply a concentration of 270 kg N/5000 m^3 = 0.054 kg N/m^3. In points of the field receiving more water than I_{req}, we reach maximum yield and have excess N.
In points receiving less than I_{req}, water is the limiting factor. The average N lost with drainage would be total drainage (1880 m^3/ha) times the concentration (0.054 kg N/m^3), 101.5 kg N/ha. Total applied N should be 270 + 101.5 = 371.5 kg N/ha.

(b) With conventional fertilization, assuming that N loss is proportional to drainage, we will have maximum N loss where maximum irrigation is applied (915 mm). At that point, drainage is 415 mm (45% of irrigation applied), so we can estimate N loss as 45% of N applied. Then, 55% of N applied will be available. To avoid N deficiency, we should apply 270/.55 = 494 kg N/ha. If we applied only 371.5 kg N/ha, then yields would decrease as I increases (N would be more limiting). The same result would be achieved using Eq. 23.14.

23.5 Peak and Seasonal Irrigation Demand

Planning of irrigated areas or the design of an irrigation system should consider two main parameters for the farm, the maximum system capacity (Q_{max} in L/s/ha) and the seasonal irrigation (I_{sum}, m^3/ha). The first determines the required pumping capacity and the second the storage or allocation needed. The cost of irrigation systems and reservoirs will be proportional to both parameters, so they need to be optimized.

The main driver of peak and seasonal irrigation is ET. There is still some confusion regarding the effect of the ground cover and irrigation system on ET. For trees, it is common to use a factor to reduce the crop coefficient as a function of the ground cover. However, that requires a standard definition of the crop coefficient. Crop coefficients should include the effect of intercepted radiation, so the values shown in Appendix C in Chap 10 require no further adjustments.

The effect of the irrigation system on ET depends on four factors, namely, plant wetting (or not), fraction of ground cover, fraction of soil wetted, and frequency of irrigation. Some authors use the maximum of ground cover and fraction of wet soil to establish a minimum value of crop coefficient. This approach is partly right although it ignores the frequency of irrigation. On the other hand, intercepted radiation depends not only on the ground cover but also on crop height, leaf area density, solar angle, and crop row orientation. Therefore, corrections of K_c based on ground cover should be taken with caution and superseded by intercepted radiation.

Example 23.3
In hedgerow tree orchards, the fraction of intercepted radiation (Q) is proportional to tree volume per unit surface area (Chap. 3, Sect. 3.8). With a distance between rows of 4 m, trees of height 3.5 m and width 1 m (25% ground cover) will intercept the same as trees with height 3.0 m and width 1.2 m (30% GC). The crop coefficient scales up with the fraction of intercepted radiation (Chap. 10), so both orchards would have the same K_c despite the difference in GC.

23.5.1 Seasonal Irrigation

The maximum seasonal irrigation could be calculated to satisfy the needs of the most demanding crop every year. This is rarely the case as the planning is often based on satisfying a probability level (e.g., 80%) for a given crop rotation. There are several factors to consider in determining the average and minimum irrigation amounts:

– Calculations should be performed using crop simulation or water balance models. For instance, *CropET* (**https://www.uco.es/fitotecnia/cropET.html**) allows the integration of salinity, uniformity, and economic factors in the calculation of irrigation requirements. The results of the model can be used to calculate the statistics of the seasonal irrigation requirement, like those shown in Table 23.1. In that case, maize *ET* is higher in the drier location, but the coefficient of variation of ET is similar in Calipatria and McArthur. However, the crop water requirement is more variable in the wet location due to variability in rainfall.
– Crop rotations are usually preferred to monocultures (Chap. 36). When winter crops are included, the overall farm water demand will decrease strongly. However, designing for the average rotation limits the flexibility of the system.
– If permanent crops like fruit trees or vineyards are considered, we should ensure that enough water is available every year at least for tree survival. Unfortunately, mortality due to water stress is highly dependent on acclimation, so it is not easy to determine a minimum allocation for keeping the trees alive.
– Some crops satisfy specific demands of the industry (e.g., processed tomato, tobacco) or the fresh market (vegetables) that require security in the product supply and, therefore, require a guaranteed supply of irrigation water.
– Socioeconomic aspects may be critical for water allocation. Small amounts of water may be highly efficient in producing winter horticultural crops, while large amounts of irrigation water may be spent in subsidized summer crops. The optimal allocation will depend on the scale: a single farmer will try to get the maximum profit from the farm, while a community (e.g., region) may try to improve its gross product, employment, or environmental conditions.

Table 23.1 Seasonal *ET*, rain, and irrigation requirement for maize sown in 1 April in two locations of California with low (Calipatria) and high seasonal rainfall (McArthur)

	ET	Rain	I_{req}	*ET*	Rain	I_{req}
	Average mm			CV %		
Calipatria	981	17	864	7	102	8
McArthur	788	124	580	9	77	18

Average values and coefficients of variation have been calculated using *CropET* for the crop's growing season in 32 years. Both locations have dry summers

23.5.2 Maximum System Capacity

The maximum crop demand changes from year to year as *ET* and rainfall change. Interannual variability in maximum ET increases from dry to wet summer areas. As rainfall and *ET* may be inversely related because of cloudiness, we should directly analyze the distribution of *ET-P*. The two locations analyzed in Table 23.1 have median irrigation requirements in July of 46 and 63 mm/week for McArthur (wet) and Calipatria (dry), respectively, with similar CVs, below 8.5%. Therefore, the variability of peak *ET* is low in locations with dry summers. Furthermore, in those places, summer crops will also show a low variability in seasonal *ET* as summer *ET* will be its main contributor (Table 23.1).

When applied irrigation cannot meet the maximum crop demand, a water deficit occurs. The impact will be proportional to the time integral of the water deficit and will depend strongly on the phenological phase (Chaps. 14 and 22). Nevertheless, a high probability level (e.g., 80%) will ensure that even when the irrigation requirement exceeds the irrigation capacity, the water deficit will not be severe. Example 23.4 shows the case of cotton irrigation in Riverside. The probability of not meeting the *ET* demand is reduced as we increase $Q_{\max}$. If we adopt $Q_{\max}$ of 50 mm/week, which is the average *ET* in July, we will have water stress in 58% of the years, reaching a maximum soil water deficit of 99 mm. If we take a value of 55 mm/week (80% probability level), some water stress will occur in 24% of years only, with a maximum *SWD* of 93 mm.

Example 23.4
We irrigate cotton on a 1-m-depth soil of medium texture in Riverside, California. Using a simple water balance, we can deduce the *SWD* for different values of $Q_{\max}$ and evaluate the probability of exceeding a given *SWD* (80 mm)

	$Q_{\max}$ (mm/week)				
	45	50	55	60	65
% years with water stress	94	58	24	6	0
Average *SWD* (mm) in years with stress	92	89	84	83	–
Maximum deficit (mm)	101	99	93	84	75

23.6 Irrigation Duration and Interval

We may write a general equation for the depth of irrigation in a single event:

$$I_{avg} = Z\, f_w\, PAW\, AD = IR \cdot WI = \frac{T_I\, q}{A} \tag{23.15}$$

where:

Z: rooting depth (m)
f_w: fraction of soil area wetted by irrigation
PAW: plant available water (mm/m)
AD: allowable depletion
IR: gross daily irrigation requirement (mm/day)
WI: interval between irrigations (days)
T_I: irrigation duration (hours)
q: discharge of emitter (sprinkler or dripper) or flow into irrigation unit (e.g., furrow, basin) (L/hour)
A: area covered by one emitter or irrigation unit (m^2)

For the design of irrigation systems, we may first consider the worst conditions, i.e., maximum *ET* period that will correspond to the minimum irrigation interval.

$$WI_{min} = \frac{Z\, f_w\, PAW\, AD}{IR_{max}} \tag{23.16}$$

Then we should consider how to adapt to periods with lower ET either by reducing the depth of irrigation per event or by increasing the irrigation interval. Surface irrigation systems are especially inflexible for that purpose. In drip irrigation and full-coverage sprinklers, the easiest way of adapting irrigation to lower demand is by reducing the duration of irrigation events while keeping the interval. In hand-move sprinkler systems, we should increase the irrigation interval, as costs are proportional to the number of irrigations. For surface irrigation, we will try to keep the same irrigation duration and use the dates that generate less water deficit.

Example 23.5
We want to irrigate cotton spaced 1 m with a peak net daily irrigation requirement of 8 mm/day on a sandy loam soil of 1 m depth and saturated hydraulic conductivity of 25 mm/h. The plot has a length of 150 m.

We choose $PAW = 120$ mm/m and $AD = 0.7$.

Alternative 1. Hand-move sprinkler irrigation with 12 × 12 m spacing, 1 h required to move the lateral. Application efficiency 80%. Therefore, the gross daily irrigation requirement will be 10 mm/day. With full cover irrigation $f_w = 1$.

(continued)

Example 23.5 (continued)

The minimum irrigation interval would be:

$$\frac{Z\,f_w\,PAW\,AD}{IR} = \frac{84}{10} \cong 8\,\text{days}$$

To irrigate every 8 days, we should apply a gross depth of 80 mm per event. Each sprinkler irrigates 12 × 12 = 144 m^2, so:

$$80 = \frac{T_I\,q}{144}$$

Now, depending on the availability of labor during the day and of additional irrigation equipment (pipes, sprinklers), we will decide the best combination of sprinkler discharge and irrigation duration. For instance, to maximize the time of operation, we could set irrigations of 11 h with 0.29 L/s discharge sprinklers. This option gives around 7 mm/h of application rate, which is well below the maximum infiltration rate of the soil.

Alternative 2. Furrows 1 m wide and 150 m long. Application efficiency 65%. We have water in the canal only 1 day per week (this is a typical rotational distribution of water among the farms in an irrigation scheme).

We cannot adopt an irrigation interval of 14 days in the period of maximum *ET* (14 × 8 = 112 mm exceeds the critical soil water deficit, 84 mm). Therefore, we have to adopt *WI* = 7 days and the amount of irrigation to apply is:

$$\frac{8 \times 7}{0.65} = 86\,\text{mm}$$

$$86 = \frac{T_I\,q}{150}$$

With a slope of 0.5%, the maximum stream size is 1.2 L/s. Taking 1 L/s (3600 L/h), irrigation would take 3.58 h.

Alternative 3. Drip irrigation in every other row (f_w = 0.5). Application efficiency 90%. The gross daily irrigation requirement will be 8.9 mm/day.

The maximum irrigation interval would be:

$$\frac{Z\,f_w\,PAW\,AD}{IR} = \frac{42}{8.9} \cong 4.7\,\text{days}$$

To irrigate every 4 days, we should apply a gross depth of 35.6 mm per event. In this case, we will use drip tape or a drip line with emitters close enough to form a wet strip of 1 m. Each meter of line covers 2 m^2 of soil, so it has to provide 71.2 L in each event. Drip tape with emitters at 0.15 m intervals with a flow rate of 2.8 L/h would take 3.8 h. High discharge rates are beneficial to avoid clogging but may require larger pipes.

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Control of Salinity

24

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Abstract

Salinity threatens the sustainability of many agricultural systems, especially irrigated areas in arid and semiarid zones. Salt concentration in the soil is measured as electric conductivity (*EC*) of the saturated extract (EC_e). Besides the possible specific toxicity, the main effect of salts is the reduction of soil osmotic potential causing an effect similar to that of water deficit. The expected yield under saline conditions can be calculated with a simple model whose parameters are the threshold EC_e and the yield loss per unit increase in EC_e. The salt balance equation may be used to deduce soil salinity as a function of the *EC* of the irrigation water and the leaching fraction (*LF*). The required LF is calculated as a function of the irrigation frequency, the *EC* of the irrigation water and the desired EC_e. The presence of Na deteriorates soil structure, but the effect depends on other factors, especially the salinity of irrigation water.

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24.1 Introduction

According to FAO, around 20% of irrigated land occupies salt-affected soils, while salts affect less than 3% of dryland agricultural area. Salt-affected land is mainly located in irrigated arid and semiarid areas. Preventing the buildup of salts in soils and waters with adequate management is crucial for avoiding land degradation and thus for ensuring the sustainability of agriculture. In the case of irrigated areas, sustainability relies on maintaining an appropriate salt balance in the soil, which depends on the salt concentration of irrigation water and the soil water balance.

The primary source of salts is the weathering of minerals, but this source hardly causes soil salinization of agricultural soils. Soil salinization results from the external supply of salts in irrigation water. In rainfed agriculture, it is related to secondary salinization phenomena, usually caused by the upward movement of water and salts from the subsoil caused by changes in hydrology. Therefore, the salt and water balances are tightly coupled. The salt concentration in the soil solution is greater than that of the water that infiltrates. This difference is the result of soil evaporation not carrying salts while root water uptake only does so very selectively. Therefore, salinity is a real threat in agricultural areas of arid or semiarid regions due to the high ET rates and the scarcity of water needed for leaching the salts out of the root zone.

The contribution of salts from rainwater is insignificant. Irrigation water is often the cause of salinization, as all irrigation waters contain salts in varying concentrations. On the other hand, excess irrigation causes percolation that leaches salts that may eventually reach the sea. The sea can also be the direct source of salinization like in coastal areas when winds carry salts in aerosols. Soils originating from marine sediments can be saline, or marine intrusions can cause salinization of groundwater origin, i.e., by upward movement of water from a saline water table. In addition to the natural sources of salt, excessive application of fertilizers can also contribute to salinization.

24.2 Effects of Salinity on Crops

Salinity is quantified as the electrical conductivity of the soil solution (*EC*, dS/m) or by the salt concentration (C_S, g L^{-1}) which is approximately related by $C_S = 0.64\ EC$. The concentration of cations (*CC*, or anions, meq/L) is roughly proportional to the *EC* by $CC \approx 10\ EC$. The osmotic potential (Ψ_o, kPa) may be estimated from the salt concentration as $\Psi_o = -56.25\ C_S$. Table 24.1 shows intervals of salinity in different water types.

The electrical conductivity is commonly measured in a saturated soil extract (EC_e) which is approximately half the value of that at field capacity (EC_{FC}). To simplify the measurement of soil salinity, instead of saturated paste, we may use a mix of 1 part of dry soil and 5 of water ($EC_{1:5}$) and then estimate EC_e taking into account the texture (*c*, percent clay):

Table 24.1 Intervals of salinity in different bodies of water

		EC	Cs	Ψ_o	CC
		dS/m	g/L	kPa	meq/L
Sea	Min	50	32	−1800	500
	Max[a]	60	38.4	−2160	600
River	Min	0.1	0.064	−3.6	1
	Max	1.5	0.96	−54	15
Groundwater	Min	0.1	0.064	−3.6	1
	Max	5	3.2	−180	50

CC cation concentration. [a]Extreme cases like the Dead Sea, with C_S = 342 g/L, are not included in this interval

$$EC_e = EC_{1:5}\left[-210^{-5}c^3 + 0.0029c^2 - 0.2446c + 13.494\right] \tag{24.1}$$

The effects of a high salt concentration in the soil on crop performance are due to (i) the reduction of osmotic potential in the soil solution, which in many aspects mimics that of water deficits, and (ii) the toxicity and nutrition disorders (antagonistic effects) caused by major ions present in salts (Cl, Na, B). The negative effects of salinity on crops depend on the particular species and the developmental stage. An additional problem occurs with sodium accumulation in soil, a problem defined as soil sodicity, which causes degradation of soil structure.

The main difference between soil water deficit and the osmotic effect due to salts is that the former has two effects. The first is to lower the soil water potential, so roots need an even lower potential for absorbing water. The second is the decrease in hydraulic conductivity of dry soil so that even with a lower potential in the roots, water movement to the root surfaces is limited by the low hydraulic conductivity. The effect of salinity corresponds to the first effect but the hydraulic conductivity is not affected.

Example 24.1

A nonsaline soil (called A) at the wilting point has a matric potential of -1500 kPa and soil water potential is −1500 kPa. We have another soil (called B), with the same texture, but saline. Soil B is at field capacity (matric potential 20 kPa) and has EC_e = 8.4 dS/m (so EC_{FC} = 16.8 dS/m). Therefore, soil B has an osmotic potential −1480 kPa and a soil water potential −1500 kPa. Despite having the same soil water potential, transpiration is zero for soil A, while in soil B, it can be significant for several crop species (e.g., rye).

24.2.1 Impacts of Salinity on Crop Productivity

A soil is classified as saline when EC_e exceeds 4 dS/m. This level represents less than 10% of the salinity of seawater (50–60 dS/m) but is sufficient to affect negatively the growth of many crop plants. Increasing the concentration of salts in the soil involves a decrease of osmotic potential, and therefore a decrease in the soil water potential and thus in shoot water potential, which ultimately leads to reduced expansive growth.

There is a wide variability in the sensitivity of crop species and cultivars within a species to salinity. A simple model has been proposed where the sensitivity is quantified by two parameters. The first is a threshold salinity value, EC_{eu} (measured as soil EC_e) above which yield decreases. The second parameter (B_s) is the percent of yield loss per unit increase in EC_e. The relative yield (Y/Y_x) expressed as a fraction of the maximum yield is calculated as:

$$\frac{Y}{Y_x} = 1 - \frac{B_s}{100}\left(EC_e - EC_{eu}\right) \tag{24.2}$$

Maas and Hoffman published in 1977 a review on crop tolerance to salinity, which is partly summarized in Table 24.2. The crops are classified as sensitive, moderately sensitive, moderately tolerant, and tolerant according to the values of the parameters EC_{eu} and B_s (Table 24.3). As shown in Table 24.3, most fruit trees are sensitive, most horticultural crops are moderately sensitive, and most field crops lie between moderately sensitive and moderately tolerant.

The information in Table 24.2 has to be taken with caution since the response of plants varies with development stages and growing conditions (climate, soil management and irrigation, cultivar, etc.). Furthermore, it should be noted that the data in Table 24.2 were determined with surface irrigation following conventional management, including the application of excess water to obtain a steady state and uniform distribution of salts throughout the root zone. However, soil EC_e may vary substantially during the growing season, so the application of Eq. 24.2 is not straightforward, but would represent the response of a given crop to the long-term, uniform application of irrigation water of a given EC.

24.2.2 Specific Toxicity

Toxicity occurs when certain ions are absorbed by the plant and accumulate to concentrations high enough to cause crop damage. Toxicity related to saline conditions is ascribed to ions usually present in soluble salts, mainly Na and Cl, and B, frequently found in saline irrigation waters. The first symptoms are usually marginal leaf burn and interveinal chlorosis. The sensitivity of crops to ion toxicity is quite variable with tree crops being the most sensitive, which may be affected by low ion concentrations (see Table 24.2). Under high evaporative demand, ion accumulation is faster, thus enhancing the toxic effect.

Toxicity can also be due to the direct absorption of Cl or Na through the leaves (e.g., sprinkler irrigation). This may be an important problem in sensitive crops such as citrus.

Table 24.2 Sensitivity of different crop species to salinity

	EC_{eu}	B_s		Na or Cl in water	B in soil	Na in soil (ESP)
Common name	dS/m	dS/m/%	Type	meq/L Na or Cl	mg/L saturated extract	%
Alfalfa (hay)	2	7.3	MS	10.0–20	4.0–6.0	>40
Apple	1	18	S			<15
Barley	6	7.1	T	10.0–20		
Bean (*Phaseolus*) (dry seed)	1	18.9	S			<15
Cotton	7.7	5.2	T	>20	6.0–15.0	>40
Grapes (wine)	1.5	9.5	MS	5–10.0	0.5–0.75	
Lettuce	1.3	13	MS	–	2.0–4.0	15–40
Maize (grain)	1.7	12	MS	10.0–20	2.0–4.0	<15
Millet			MS			
Olive	5.00	7	MT			
Orange	1.3	16	S	<5	0.5–0.75	<15
Palm trees	4	3.6	T			
Peach	1.7	21	S	–	0.5–0.75	<15
Peas (dry harvest)	2.5		MS		1.0–2.0	<15
Potato	1.7	12	MS	5.0–10	1.0–2.0	
Rapeseed, canola	10.5	13.5	T			
Rice	11.4	10.8	MT			15–40
Sorghum (grain)	6.8	16	MT	10.0–20	4.0–6.0	15–40
Soybeans	5	20	MT			
Sugar beet	7	5.9	T	>20	4.0–6.0	>40
Sugarcane (virgin)	1.7	5.9	MS			15–40
Sunflower	5.5	25	MS	>20	0.75–1.0	
Tomato	2.5	9.9	MS	5.0–10	4.0–6.0	15–40
Winter wheat	6	7.1	MT	–	0.75–1.0	15–40

Adapted from Ayers and Westcott (1989)
For the response to total salt concentration, two parameters are shown: EC_{eu} (dS/m) is the value of EC_e below which yield is not affected. B_s (%/(dS/m)) is the slope of the linear relationship between yield (% of maximum) and EC_e. Crops are classified as sensitive (S), moderately sensitive (MS), moderately tolerant, (MT), and tolerant (T). Concerning the foliar damage by sprinkler irrigation, the threshold concentration of Na or Cl is shown (meq/L). The maximum concentration of B (mg/L in soil saturated extract) and Na (ESP, %) in the soil above which toxicity may occur are also shown

Table 24.3 Examples of species in the four groups of response to salinity and typical parameters of the response

	Tolerant	Moderately tolerant	Moderately sensitive	Sensitive
EC_{eu} (dS/m)	6.0–10	3.0–6.0	1.3–3.0	0–1.3
Slope B_s (typical) (%/(dS/m))	12	13	17	30
EC_e for zero yield (dS/m)	<32	<24	<16	<8

(continued)

Table 24.3 (continued)

	Tolerant	Moderately tolerant	Moderately sensitive	Sensitive
Fiber, seed, and sugar crops	Barley	Winter cereals (wheat, oat, rye, triticale)	Sugarcane	Bean
	Cotton	Legumes (cowpea, soybean)	Legumes (faba bean, peanut)	Guayule
	Sugar beet	Sorghum	Summer cereals (maize, rice, millet)	Sesame
		Safflower	Oil crops (castor bean, flax, sunflower)	
Forage crops	Wild rye (some spp.)	Wild rye (some spp.)	Alfalfa	
	Wheatgrass (some spp.)	Wheatgrass (some spp.)	Common vetch	
	Bermuda grass	Barley, wheat	Oats, rye, maize	
		Ryegrass, fescue, Sudan grass	Brome	
		Clover (*Melilotus* spp.)	Clover (*Trifolium* spp.)	
Vegetable crops	Asparagus	Red beet	*Solanaceae* (potato, tomato, pepper, eggplant)	Carrot
		Zucchini squash	*Cucurbitaceae* (cucumber, melon, watermelon, squash)	Onion
			Brassicaceae (cabbage, cauliflower, kale, turnip, broccoli)	Parsnip
			Others (lettuce, spinach, celery, radish, sweet potato)	
Fruits and nuts	Date palm	Olive, fig, pomegranate	Grape	*Citrus* spp. (orange, lemon, tangerine)
		Pineapple		*Prunus* spp. (peach, almond, cherry, etc.)
		Papaya		Berries (*Rubus* spp., *Ribes* spp.)
				Pome fruits (apple, pear)
				Others (strawberry, avocado)
				Tropical fruits (cherimoya, mango, passion fruit)

24.3 Irrigation Systems and Distribution of Salts

Salts accumulate where leaching is limited at a depth that depends on the amount of drainage water. Lack of drainage causes the buildup of a water table near the surface from where water evaporates, bringing salts to the uppermost soil layers and causing salinization. This is shown in Fig. 24.1 where a saline water table at a depth of 100 cm and $EC = 10$ dS/m is the source of water that evaporates, resulting in a high concentration of salts on the surface. Something like this has also occurred under rainfed conditions, for example, in the Murray Basin and other areas in Australia. The substitution of evergreen forests with high ET for crops that use less water has changed the hydrology of basins, leading to the accumulation of excess water in the lowlands, where the water table rose with the consequent soil salinization. The problem is of such magnitude it is estimated that in 50 years it could affect 25% of the cultivated area of Australia unless specific measures are adopted to alleviate the problem.

Figure 24.2 shows a different profile of salt concentration. In this case, the salts were accumulated in the lower layers due to leaching. Heavy rainfall during winter helped in salt leaching and the EC decreased across the soil profile. This would be the typical salinity profile in irrigated semiarid areas without a water table.

Since salts move with water in the soil, the irrigation method affects their distribution of salts. Figure 24.3 distinguishes areas where salts concentrate more or less depending on the irrigation method. Furrow irrigation provides leaching in almost the entire surface of the ground, except in the ridges. Drip irrigation wets only part

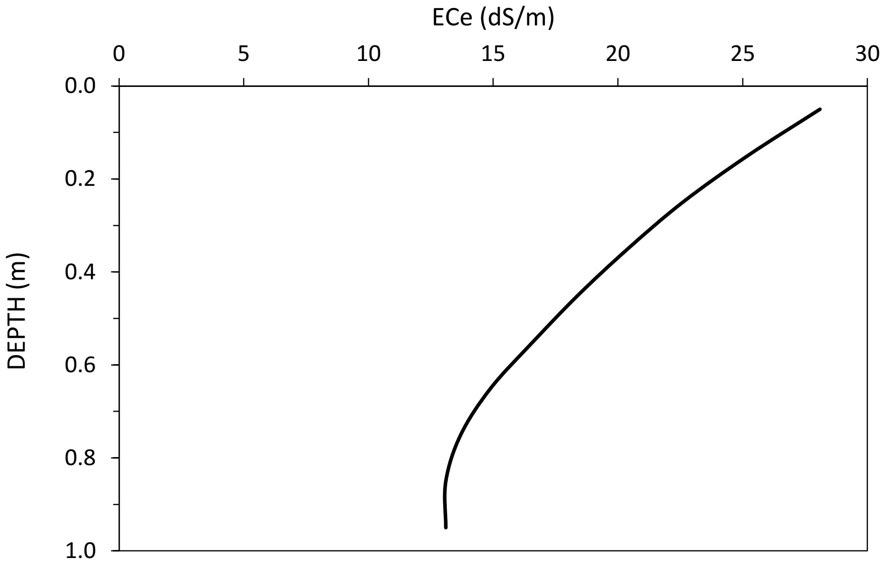

Fig. 24.1 Soil salinity profile above a saline water table ($EC_w = 10$ dS/m) at the end of the growing season of a sorghum crop

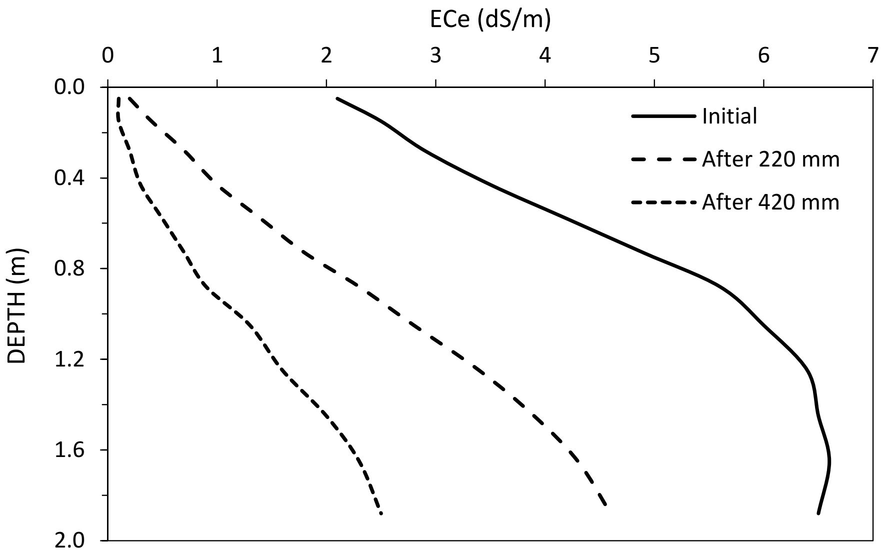

Fig. 24.2 Soil salinity profiles in a sandy loam soil before (initial) and after 220 and 420 mm of rainfall

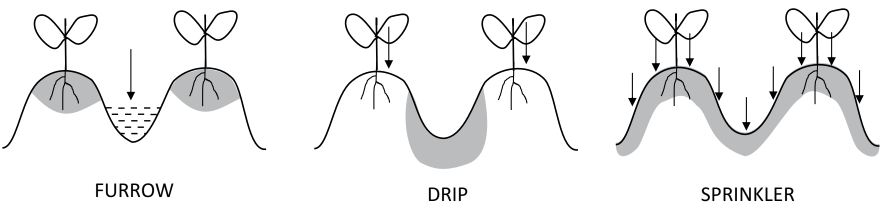

Fig. 24.3 Accumulation of salts from irrigation water for different methods of irrigation. (Adapted from Rhoades and Loveday (1990))

of the ground, so leaching occurs only under the emitters, while the remainder of the surface tends to accumulate salts, particularly at the edges of the wetted zones. Overhead sprinkler or flood irrigation leaches salts evenly throughout the field depending on the uniformity of irrigation.

The *EC* of the soil solution increases as the soil water is depleted, so the osmotic effect of salts depends on the actual soil water content. This is illustrated in Fig. 24.4 where changes in *EC* of the soil solution are parallel to changes in soil water potential. Irrigation frequency also affects the concentration of the salts. High-frequency irrigation keeps high soil water content and is, therefore, able to maintain a lower salt concentration in soil solution. In addition, a relatively constant high soil water content counteracts the effect of salinity on water potential by preventing low matric potentials in soil. On the contrary, low-frequency irrigation involves drying cycles with very low soil water potential before each irrigation (Fig. 24.4). This is one reason why drip irrigation in cotton with saline water is advantageous compared to traditional furrow irrigation.

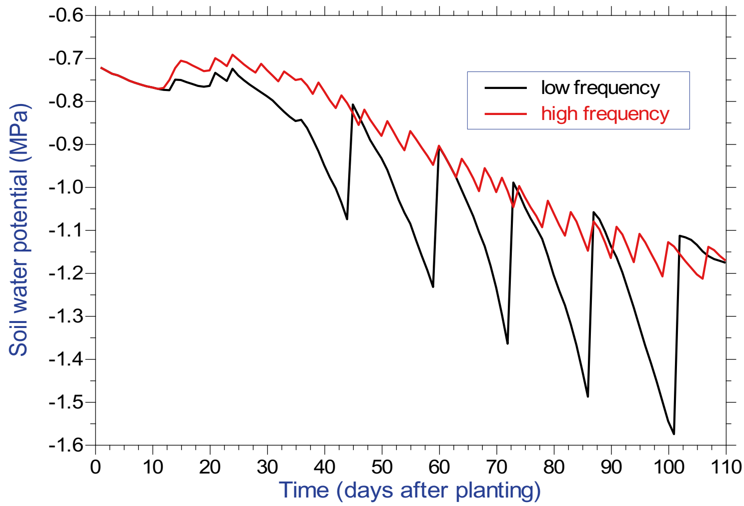

Fig. 24.4 Time course of soil water potential of a sorghum crop irrigated with water of EC_w = 4 dS/m with leaching fraction 0.2 and low or high irrigation frequency

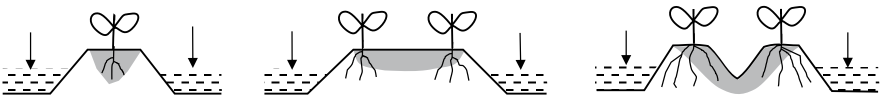

Fig. 24.5 Effects of bed shape and plant distribution on salt accumulation and emergence of furrow irrigated crops. (Adapted from Rhoades and Loveday (1990))

The potentially harmful salts in the soil are those located where root absorption occurs, which must be considered when surveying soil salinity in a field.

Germinating seeds and emerging seedlings are especially sensitive to salinity, so crop establishment is the most critical stage for some species, especially under furrow irrigation. The seedbed configuration, the design of the irrigation system, and the distribution of plants can have a huge impact on crop establishment in saline conditions. Figure 24.5 illustrates various situations for furrow irrigation. Planting on flat ridges with lateral furrow irrigation leads to an accumulation of salts in the center of the ridge. This can be avoided by widening the bed and creating a small furrow in the middle to separate the two central rows. The situation can be further improved if planting is performed on sloping beds with a central furrow that is watered until crop establishment.

In sodic soils (see Sect. 2.4.4), surface crusts develop and prevent seedling emergence. This may be alleviated by sprinkler irrigation (small doses, high frequency) which also would reduce salt concentration close to the seeds. Alternatively, mechanical removal of the crust in the rows could be beneficial although it is feasible only in small plots.

24.4 Salt Balance and Leaching Fraction

To quantify the risk of soil salinization, it is necessary to evaluate its salt balance. This balance implies that the quantity of salts entering the system minus the amount going out equals the increase in the salt content of the soil (ΔS):

$$\Delta S = V_w C_w + V_r C_r + S_s + S_f - \left(V_d C_d + S_p + S_c\right) \tag{24.3}$$

where V and C refer to volume and concentration, respectively, corresponding to the irrigation water (w) , rain (r), and drainage (d). S_s, S_f , S_p, and S_c are the amounts of salts released from the soil (by dissolution or weathering), provided as fertilizer, precipitated and absorbed by the crop, respectively, during the period.

To prevent soil salinization, the amount of salts in the soil should be constant ($\Delta S = 0$). We simplify Eq. 24.3 assuming $S_s + S_f = S_p + S_c$ and neglecting the term related to rainfall, so:

$$V_w C_w = V_d C_d \tag{24.4}$$

The leaching fraction (LF) is defined as the ratio of the drainage volume and the irrigation volume. Using Eq. 24.3, and replacing concentration by electrical conductivity, LF can be expressed as:

$$LF = \frac{V_d}{V_w} = \frac{EC_w}{EC_d} \tag{24.5}$$

Example 24.2
The electrical conductivity of irrigation water is 1 dS/m. Drainage is 25% of applied irrigation ($LF = 0.25$). The EC of the drainage water is obtained by dividing EC_w by 0.25, i.e., $EC_d = 4$ dS/m.

Therefore, by changing the LF, we can control the salt concentration in the soil solution within values above the salt concentration of irrigation water. This is shown in Fig. 24.6 for different LFs. Note that the soil EC increases with increasing depth, taking values at the soil surface similar to 50% of that of the irrigation water (see Sect. 24.5). As LF decreases, this variation with depth is more pronounced.

24.5 Salinity Profiles and Crop Yields

The soil EC profiles are affected by the EC of irrigation water and the LF. This soil EC refers to soil water content at field capacity. To convert to EC_e (which is required to apply Eq. 24.2), we use a factor of 0.5, as EC_e is roughly half of EC at field capacity (EC_{FC}).

We will now show how EC varies with depth in the soil with the following example.

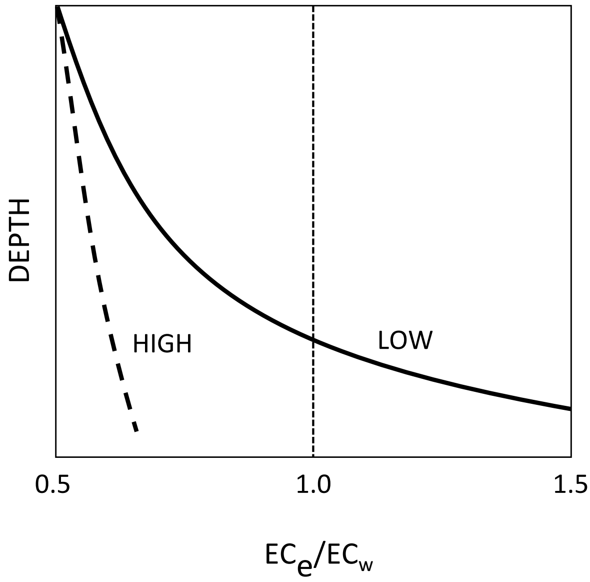

Fig. 24.6 Generic profiles of soil salinity for high or low leaching fraction. Salinity is shown as the ratio of *EC* of the saturation extract and irrigation water EC

Example 24.3

A bean crop (EC_{eu} = 1.0 dS/m, B_s = 19%/dS/m) is irrigated with water of 1.5 dS/m with a leaching fraction of 0.2. We assume a water uptake distribution of the type 40-30-20-10 (the soil is divided into 4 parts of equal depth from where 40, 30, 20, and 10% of the total water extraction occur, respectively).

For every 100 mm applied as irrigation, 80 mm is absorbed by the root system and 20 mm is drained. Applying Eq. 24.5 to each of the four layers in which we have divided the profile, we may deduce the average EC_{FC} for each layer.

In the first layer, the water uptake is 40% of the total (0.4 × 80 mm), so the amount of water draining from this layer is the difference between the water applied (100 mm) and that absorbed, i.e., drainage is 100–32 = 68 mm. Therefore for the first layer, LF and the calculated EC are:

LF0−1 = (100–0.4 · 80)/100 = 68/100 = 1.5/ECFC1; ECFC1 = 2.2

And for the other layers:

LF1−2 = (68–0.3 · 80)/68 = 44/68 = 2.2/ECFC2; ECFC2 = 3.4
LF2−3 = (44–0.2 · 80)/44 = 28/44 = 3.4/ECFC3; ECFC3 = 5.35
LF3–4 = (28–0.1 · 80)/28 = 20/28 = 5.35/ECFC4; ECFC4 = 7.5

(continued)

Example 24.3 (continued)

The values of ECe will be half of those values: 1.1, 1.7, 2.7, 3.75 dS/m.
The arithmetic mean of ECe will be 1.93 dS/m.
The weighted *EC* average, considering water uptake will be:

$$0.4\left(\frac{0.75+1.1}{2}\right)+0.3\left(\frac{1.1+1.7}{2}\right)+0.2\left(\frac{1.7+2.7}{2}\right)+0.1\left(\frac{2.7+3.75}{2}\right)=1.56\,\text{dS/m}$$

If we use the weighted average, recommended for high-frequency irrigation, we would predict a relative yield of 89% of the maximum. Using the arithmetic mean (recommended for low-frequency irrigation), we would predict a relative yield of 82%.

It is possible to deduce analytically the profile of soil *EC*, so the mean value of *EC* may be computed as a function of *EC* of the irrigation water and the *LF* (Fig. 24.7):

(a) The weighted average does not depend on the distribution of root water uptake and may be calculated as:

$$EC_{em1} = -0.5EC_w \frac{\ln(LF)}{1-LF} \tag{24.6}$$

(b) If water uptake decreases linearly with depth like in Example 24.3, then the arithmetic mean will be:

$$EC_{em2} = 0.5EC_w \frac{arc\cos\sqrt{LF}}{\sqrt{LF(1-LF)}} \tag{24.7}$$

where the *arccos* function is given in rad.

A simpler equation may be deduced from the "leaching requirement" equation commonly found in the salinity literature:

$$EC_{em2} = EC_w \frac{1+LF}{5LF} \tag{24.8}$$

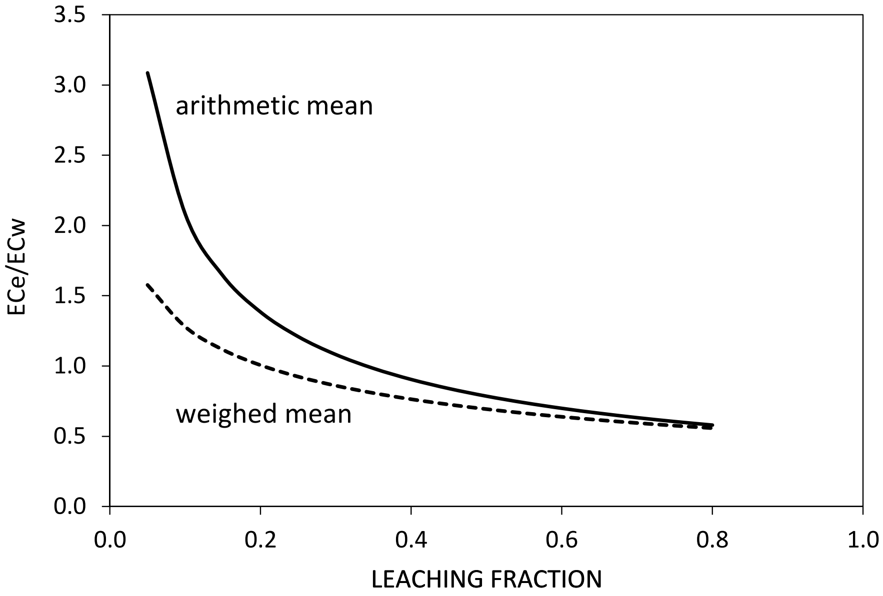

Fig. 24.7 Mean soil salinity (relative to irrigation water *EC*) as a function of the leaching fraction computed as a weighed (of root water uptake) or arithmetic average

Example 24.4
Following Example 24.3 of bean (EC_{eu} = 1.0 dS/m, B_s = 19%/dS/m) irrigated with water of EC_w = 1.5 dS/m and LF = 0.2, we can evaluate the average EC_e using Eqs. 24.6 and 24.8.

Weighted average:

$$EC_{em1} = -0.5 \cdot EC_w \frac{\ln(LF)}{1-LF} = -0.5 \cdot 1.5 \frac{\ln(0.2)}{1-0.2} = 1.51\,\mathrm{dS/m}$$

Relative yield would be:

$$\frac{Y}{Y_x} = 1 - \frac{B_s}{100}\left(EC_e - EC_{eu}\right) = 1 - \frac{19}{100}\left(1.51 - 1\right) = 0.90$$

The result would be very close to that obtained using a numerical approach (Example 24.3).

(continued)

Example 24.4 (continued)

Arithmetic mean:

$$EC_{em2} = EC_w \frac{1+LF}{5LF} = 1.5\frac{1+0.2}{5\cdot 0.2} = 1.8 \text{ dS/m}$$

And the expected yield (as fraction of the maximum) is:

$$\frac{Y}{Y_x} = 1 - \frac{B_s}{100}\left(EC_e - EC_{eu}\right) = 1 - \frac{19}{100}\left(1.8-1\right) = 0.85$$

24.6 Required Leaching Fraction

The required *LF* (LF_r) that is needed to keep a desired EC_e (EC_{em}) will depend on the crop sensitivity (Eq. 24.2) and the *EC* of irrigation water. Then the amount of irrigation to be applied will be:

$$I = \frac{I_{\text{req}}}{1-LF_r} \tag{24.9}$$

where I_{req} is the net irrigation requirement (Chap. 10). The LF_r could be obtained by solving Eqs. 24.6 and 24.7 for *LF* but no analytical solution exists. The following numerical equations may be used:

For low irrigation frequency:

$$LF_r = 0.31\left(\frac{EC_w}{EC_{em}}\right)^{1.7} \tag{24.10}$$

Or, alternatively, the following equation is commonly found in the literature:

$$LF_r = \frac{EC_w}{5EC_{em} - EC_w} \tag{24.11}$$

For high irrigation frequency:

$$LF_r = 0.18\left(\frac{EC_w}{EC_{em}}\right)^{3} \tag{24.12}$$

Example 24.5

A barley crop is irrigated with water of EC_w 5 dS/m. To reach a relative yield of 90% of the maximum, we should keep an average EC_{em} that satisfies the following equation:

$$90 = 100 - 5.0\left(EC_{em} - 8.0\right)$$

Thus EC_{em} = 10 dS/m.

Therefore the LF required for high-frequency irrigation will be:

$$LF_r = 0.18\left(\frac{5}{10}\right)^3 = 0.022$$

And for low frequency:

$$LF_r = 0.31\left(\frac{5}{10}\right)^{1.7} = 0.095$$

Or

$$LF_r = \frac{5}{5 \times 10 - 5} = 0.11$$

Example 24.6

A farm has a limited amount of irrigation water from a canal (EC_w = 0.4 dS/m). It also has a well of unlimited water supply with 2.5 dS/m. We want to grow peppers (EC_{eu} = 1.5, B_s = 14) with a sprinkler irrigation system and LF = 0.2. How can the irrigated area be expanded by using water from the well?

Using water from the canal only:

$$EC_{em} = EC_w \frac{1 + LF}{5LF} = 0.4\frac{1 + 0.2}{5 \times 0.2} = 0.48 \ \text{dS/m}$$

This value is lower than the threshold, EC_{eu} (1.5 dS/m); thus yield would be maximum.

With water from the well:

$$EC_{em} = 2.5\frac{1 + 0.2}{5 \times 0.2} = 3.0 \ \text{dS/m}$$

(continued)

Example 24.6 (continued)

The relative yield would be:

$$\frac{Y}{Y_x} = 1 - \frac{B_s}{100}\left(EC_e - EC_{eu}\right) = 1 - \frac{14}{100}\left(3 - 1.5\right) = 0.79$$

The two types of water could be blended to obtain a given EC_{em}. For instance, if we want to obtain the maximum yield, then the average EC_e should be 1.5 dS/m, which implies the following equation:

$$\left[f\,EC_{\text{well}} + \left(1 - f\right)EC_{\text{canal}}\right]\frac{1 + LF}{5LF} = 1.5$$

where f is the fraction of water taken from the well. In our case we may deduce $f = 0.4$, i.e., by mixing 60% of the water from the canal and 40% from the well, we could achieve maximum yield while increasing the irrigated area by 67%.

We could also change the LF. For instance, by increasing LF up to 0.3, we could use 63% of water from the well, thus increasing further the irrigated area.

24.7 Leaching for Maximum Crop Water Productivity

To maintain crop productivity, we may increase the LF and thus water applied. In other words, irrigation water of poor quality (high EC_w) is equivalent to having a smaller amount of fresh water in terms of crop productivity.

In the previous section, we determined the required LF when the target yield was known. This may lead to unreasonably high values of LF when EC_w and irrigation costs are high. In this case, we may be interested in maximizing the crop water productivity (*CWP*, yield per unit irrigation applied). To do that we may apply Eq. 24.2 for different values of LF until a maximum *CWP* is found. In the case of low irrigation frequency, it is also possible to deduce an analytical solution for optimum LF by maximizing the function:

$$f\left(LF\right) = \left(1 - LF\right)\left\{1 - B'\left[EC_w \frac{1 + LF}{5LF} - EC_{eu}\right]\right\} \tag{24.13}$$

where $B' = B_s/100$. The function is maximized when:

$$LF_{opt} = \sqrt{\frac{0.2B'EC_w}{1 + B'\left(EC_{eu} - 0.2EC_w\right)}} < \frac{1}{5\frac{EC_{eu}}{EC_w} - 1} \tag{24.14}$$

As the inequality indicates, the solution is valid below the value of LF at which maximum yield is achieved.

Example 24.7
We want to irrigate peach (EC_{eu} = 1.7, B_s = 21) with irrigation water of EC_w = 3 dS/m.

Using Eq. 24.1 we deduce LF_{opt} = 0.32. The solution is valid as it is lower than the limit LF to get maximum yield:

$$\frac{1}{5\dfrac{EC_{eu}}{EC_w}-1}=\frac{1}{5\dfrac{1.7}{3}-1}=0.54$$

If we had water with EC_w = 1 dS/m, a value of LF_{opt} = 0.18 would be deduced but now it would exceed the limit value (0.13). Therefore, in this case the optimum LF would be 0.13.

24.8 Leaching Required for Maximum Profit

In the case of low irrigation frequency, it is possible to deduce an analytical solution for the depth of irrigation (I_{opt}) to maximize profit:

$$f(I)=P_H\,Y_x\left\{1-B'\left[EC_w\,\frac{2I-I_{req}}{5\left(I-I_{req}\right)}-EC_{eu}\right]\right\}-Q_I\,I \tag{24.15}$$

where $B' = B_s/100$, P_H is the selling price of harvest (€/kg), Y_x is maximum yield (kg/ha), I is irrigation applied (m^3/ha), Q_I is the price of water (€/m^3), and I_{req} is the net irrigation required (m^3/ha). The profit function is maximized when:

$$I_{opt}=I_{req}+\sqrt{\frac{P_H\cdot Y_x\cdot B'\cdot EC_w\cdot I_{req}}{5\,Q_I}}<\frac{I_{req}\left(5\dfrac{EC_{eu}}{EC_w}-1\right)}{5\dfrac{EC_{eu}}{EC_w}-2} \tag{24.16}$$

As the inequality indicates, the solution is valid below the value of I at which maximum yield is achieved.

Example 24.8

Pepper. EC_{eu} = 1.5 dS/m, B' = 0.14

Y_x = 20,000 kg/ha, P_H = 0.2 €/kg, Q_I = 1 €/m^3, I_{req} = 5000 m^3/ha, EC_w = 1 dS/m

$$\frac{I_{req}\left(5\frac{EC_{eu}}{EC_w}-1\right)}{5\frac{EC_{eu}}{EC_w}-2}=5909\ \mathrm{m}^3/\mathrm{ha}$$

$$I_{opt}=5000+\sqrt{\frac{0.2\cdot 20000\cdot 0.14\cdot 1\cdot 5000}{5\cdot 1}}=5748\ \mathrm{m}^3/\mathrm{ha}$$

24.9 Nonsteady Salinity

The previous analyses are based on a steady-state salt concentration in the soil solution which would be achieved after continuous use of a given irrigation water. However, EC_e may change during the season and from year to year. For instance, in Mediterranean areas, rainfall is concentrated in winter which would provide for salt leaching (at least partially, depending on the amount) and thus to EC_e below the steady-state value. Therefore, the required leaching calculated according to the steady-state solution is an upper limit. The desired leaching would vary depending on the amount of winter leaching, and thus, on the actual EC_e at the start of the irrigation season, which should be measured routinely to keep track of soil salinity trends.

Salinity buildup depends strongly on water EC and drainage dynamics. The first may increase during the irrigation season. The second will depend on the spatial variability of irrigation applied and rainfall during the fallow period. Long-term variations in salinity may occur in association with prolonged droughts that may be alleviated by several rainy seasons.

After applying total irrigation of I in n events, the increase in salt content will be:

$$EC_w\, I - EC_d\left(I - I_{req}\right)\quad \text{if } I > I_{req} \tag{24.17a}$$

$$EC_w\, I \qquad \text{if } I < I_{req} \tag{24.17b}$$

If LF>0, then the soil EC_e will be:

$$EC_e = EC_{ei}\, k^n + \frac{EC_w}{2LF}\left(1-k^n\right) \tag{24.18}$$

where:

$$k = \frac{Z\theta_{FC}}{I/n + Z\theta_i} = \frac{Z\theta_{FC}}{(I - ET)/n + Z\theta_{FC}} \tag{24.19}$$

I: irrigation applied from planting (mm)
ET: total ET from planting (mm)
θ_i: initial soil water content (cm^3 cm^{-3})
θ_{FC}: soil water content at field capacity (cm^3 cm^{-3})
Z: soil depth (mm)

If $LF = 0$:

$$EC_e = EC_{ei} + \frac{I\,EC_w}{2Z\theta_{FC}} \tag{24.20}$$

The average salinity during the irrigation season will be:
If $LF>0$:

$$EC_{eavg} = \frac{1}{2n}\left(EC_{ei} + \left(EC_{ei} - \frac{I\,EC_W}{2(I-ET)}\right)\frac{2k-(1+k)k^n}{1-k} + (2n-1)\frac{I\,EC_W}{2(I-ET)}\right) \tag{24.21}$$

If $LF = 0$:

$$EC_{eavg} = EC_{ei} + \frac{I\,EC_w}{4Z\theta_{UL}} \tag{24.22}$$

Example 24.9
We have sown cotton in a field with EC_e=1 dS/m, depth 1 m, and soil water at field capacity of 0.24 cm^3 cm^{-3}. Seasonal ET is 750 mm. We want to keep the whole field below the threshold EC (7.7 dS/m) on average. The maximum EC in the field will occur at the point where $FL = 0$, i.e., where $I = I_{req}$. At that point

$$EC_{eavg} = EC_{ei} + \frac{I\,EC_w}{4Z\theta_{UL}} = 1 + \frac{750\,EC_w}{960}$$

which should be equal to 7.7, so we deduce EC_w = 8.6 dS/m. This irrigation water would ensure that the average EC in all points of the field is lower than 7.7 dS/m.

24.10 Sodicity and Soil Structure

Sodium-affected soils, referred to as sodic soils, are those with high levels of adsorbed (exchangeable) Na in soil. High exchangeable Na promotes the dispersion of soil colloids and consequently the degradation of soil structure. This degradation involves deterioration in aggregate stability, reduced infiltration due to soil surface sealing, and increased risk of crust formation. Crusting limits crop emergence and increases runoff and, thus, erosion risk. Crusting is the consequence of the breakdown of aggregates and the closing of the pores in the soil surface resulting from rapid soil wetting accompanied by a dispersive effect of the impact of raindrops. In sodic soils, the problem is exacerbated because of the dispersing effect of sodium, which leads to a lack of aggregate stability.

A soil is classified as sodic when the exchangeable sodium percentage (*ESP*) exceeds 15% of the cation exchange capacity. In practice, an indicator used is the sodium adsorption ratio (*SAR*; meq$^{0.5}$/L$^{0.5}$) in the soil saturation extract, which is approximately equal to *ESP*:

$$SAR = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}} \tag{24.23}$$

where all the concentrations are expressed in meq/L.

ESP can be more precisely estimated from *SAR* in the saturation extract following the empirical equation:

$$ESP = \frac{100\left(-0.0126 + 0.01475 \cdot SAR\right)}{1 - 0.0126 + 0.01475 \cdot SAR} \tag{24.24}$$

SAR is an index applied to solutions, including irrigation water. It is also used to assess the effect of the sodium content of the irrigation water on soil structure and hydraulic conductivity due to an excess of sodium in relation to calcium and magnesium. However, this negative effect depends on the *EC* of irrigation water as the dispersing effect of Na is counteracted by the aggregating effect of a high salt concentration in solution (Table 24.4). In addition, Ca concentration in the soil solution changes due to precipitation (as calcium carbonate) or dissolution during or after irrigation. Sodium remains soluble and in equilibrium with exchangeable soil Na at all times, whereas Ca concentration, however, varies until equilibrium. Dissolution is promoted by dilution and by carbon dioxide dissolved in the soil solution. Precipitation may take place when the presence of calcium is accompanied by enough carbonate, bicarbonate, or sulfate to exceed the solubility of calcium carbonate (limestone) or calcium sulfate (gypsum). This is why different corrections of the *SAR* value in irrigation water have to be considered for a more realistic estimation of the potential effects of irrigation water on soil structure and hydraulic conductivity. The most common method is estimating a corrected Ca concentration (Ca_x):

$$Ca_x = \exp\left[0.552 + 0.1637\sqrt{EC_w} - 0.668 \ln\left(\frac{HCO_3 + CO_3}{Ca}\right)\right] \tag{24.25}$$

Table 24.4 Quality criteria for irrigation water

Potential irrigation problem			Units	Degree of restriction on use: None	Slight to moderate	Severe
Salinity reduces crop growth and transpiration						
EC_w			dS/m	<0.7	0.7–3.0	>3.0
Specific ion toxicity *(affects sensitive crops)*						
	Sodium (surface irrigation)		*SAR*	<3	3–9	>9
	Sodium (sprinkler irrigation)		meq/L	<3	>3	
	Chloride (surface irrigation)		meq/L	<4	4–10	>10
	Chloride (sprinkler irrigation)		meq/L	<3	>3	
	Boron		mg/L	<0.7	0.7–3.0	>3.0
Infiltration is reduced						
$\boldsymbol{SAR_x}$	= 0–3	**and** $\boldsymbol{EC_w}$	dS/m	>0.7	0.7–0.2	<0.2
	= 3–6		dS/m	>1.2	1.2–0.3	<0.3
	= 6–12		dS/m	>1.9	1.9–0.5	<0.5
	= 12–20		dS/m	>2.9	2.9–1.3	<1.3
	= 20–40		dS/m	>5.0	5.0–2.9	<2.9
Miscellaneous effects						
	Bicarbonate (whitewash, sprinkler)		meq/L	<1.5	1.5–8.5	>8.5
	pH			**Normal range 6.5–8.4**		

which is used to calculate an adjusted *SAR*, now called adjusted sodium ratio, SAR_x:

$$SAR_x = \frac{Na}{\sqrt{\dfrac{Ca_x + Mg}{2}}} \tag{24.26}$$

Table 24.4 summarizes the main chemical quality criteria of irrigation water.

Example 24.10

The composition of irrigation water with $EC_w = 1.80$ dS/m is as follows:

Ca, 2.32 meq/L; Mg, 1.44 meq/L; Na, 7.73 meq/L; CO_3, 0.42 meq/L; HCO_3, 3.66 meq/L.

(a) Characterize the water quality for irrigation and estimate the relative yield expected if this water is used for drip irrigation of tomatoes with LF = 0.1.
(b) Estimate how much gypsum is required to add 10 meq/L of Ca to irrigation water to improve infiltration. Characterize the quality of the resulting irrigation water and the expected yield. In this case, what should be the leaching fraction to achieve 90% of the potential yield?

(continued)

Example 24.10 (continued)

(a) The ratio (CO_3+HCO_3)/Ca is (0.42+3.66)/2.32 = 2.00.

The adjusted Ca concentration is:

$$Ca_x = \exp\left[0.552 + 0.1637\sqrt{1.8} - 0.668\ln(2.00)\right] = 1.48 \text{ meq / L}$$

And the adjusted *SAR* is:

$$SAR_x = \frac{7.73}{\sqrt{\frac{1.48 + 1.44}{2}}} = 6.39$$

According to Table 24.3, this water would have slight to moderate risk in terms of water availability, slight to moderate risk of reducing infiltration, and slight to moderate toxic effects in sensitive crops to Na.

If LF = 0.1, we can deduce the soil EC from the following equation:

$$LF = 0.18\left(\frac{EC_w}{EC_{em}}\right)^3$$

The expected soil *EC* will be:

$$EC_{em} = EC_w\left(\frac{0.18}{LF_r}\right)^{1/3} = 1.8(0.18 / 0.1)^{1/3} = 2.19 \, \text{dS / m}$$

And the relative tomato yield would be 100% as $EC_{em} < EC_{eu}$:

(b) Gypsum ($SO_4Ca.2H_2O$) molecular weight is 172 g, so its equivalent weight is 86 g. To add 10 meq/L of Ca, we need to add 0.86 g/L of gypsum.

This addition will increase the *EC* of irrigation water by:

$$\Delta EC_w = \frac{0.860 \text{g / l}}{0.64 \, {}^{\text{g}}\!/_{\text{LdS / m}}} = 1.34 \text{ dS / m}$$

Therefore, the *EC* of the new irrigation water will be EC_w = 1.8 + 1.34 = 3.14 dS/m.

The adjusted Ca concentration is:

$$Ca_x = \exp\left[0.552 + 0.1637\sqrt{3.14} - 0.668\ln(0.33)\right] = 4.86 \text{ meq / L}$$

(continued)

Example 24.10 (continued)

And the adjusted sodium adsorption ratio is:

$$SAR_x = \frac{7.73}{\sqrt{\frac{4.86+1.44}{2}}} = 4.36$$

According to Table 24.3, this water would have severe risk in terms of water availability, no risk of reducing infiltration, and slight to moderate toxic effects in sensitive crops to Na.

Now the expected soil EC will be:

$$EC_{em} = EC_w \left(\frac{0.18}{LF_r}\right)^{1/3} = 3.14\left(0.18/0.1\right)^{1/3} = 3.81\,\text{dS/m}$$

The relative tomato yield would be:

$$\frac{Y}{Y_x} = 1 - \frac{B_s}{100}\left(EC_{em} - EC_{eu}\right) = 1 - \frac{9.9}{100}\left(3.81 - 2.5\right) = 0.871$$

If we want to achieve 90% of tomato yield, we need EC_{em} satisfying:

$$0.9 = 1 - 9.8\left(EC_{em} - 2.5\right) \Rightarrow EC_{em} = 3.51\,\text{dS/m}$$

And the required LF will be $LF = 0.18\ (3.14/3.51)^3 = 0.13$.

Appendix (Table 24.5)

Table 24.5 Sensitivity of different species to salinity

	Response to salinity			Toxicity		
	EC_{eu}	B_s	Type	Na or Cl in water	B in soil	Na in soil (ESP)
Common name	dS/m	dS/m/%		meq/L Na or Cl	mg/L saturated extract	%
Cereals						
Barley, grain	8	5	T	10.0–20	0.75–1.0	>40
Maize (grain, sweet)	1.7	12	MS	10.0–20	2.0–4.0	<15
Millet			MS			
Oats	5	20	MT		2.0–4.0	15–40
Rice, paddy	3	12.2	S			15–40
Rye	11.4	10.8	MT			15–40
Sorghum	6.8	16	MT	10.0–20	4.0–6.0	15–40

(continued)

Table 24.5 (continued)

Common name	Response to salinity EC_{eu} dS/m	B_s dS/m/%	Type	Toxicity Na or Cl in water meq/L Na or Cl	B in soil mg/L saturated extract	Na in soil (*ESP*) %
Wheat	6	7.1	MT	–	0.75–1.0	15–40
Wheat, durum	5.9	3.8	T	–	0.75–1.0	15–40
Forages						
Alfalfa	2	7.3	MS	10.0–20	4.0–6.0	>40
Barley, forage	6	7	T	10.0–20		
Barley, hay	6	7.1	T	10.0–20		
Bermuda grass	6.9	6.4	T			>40
Clover (red)	1.5	12	MS			
Clover, berseem	2	10.3	MS			15–40
Clover, white	1.5	12	MS	–	2.0–4.0	15–40
Cowpea (vegetative)	2.5	11	MS			
Fescue	3.9	5.3	MT			15–40
Love grass	2	8.5	MS			
Maize (forage)	1.8	7.4	S	10.0–20		
Meadow foxtail	1.5	9.7	MS			
Orchard grass	1.5	6.2	MS			
Paspalum spp	1.8	9	MS			15–40
Reed canary grass	4.2		MT			
Ryegrass	5.6	7.6	MT			15–40
Sesbania	2.3	7	MS			
Setaria spp	2.4	12.2	MS			
Siratro	2	7.9	MS			
Sudan grass	2.8	4.3	MS			
Townsville stylo	2.4	20.4	MS			
Trefoil, big	3	11.1	MS			
Trefoil, bird's-foot	5	10	MT			
Vetch	3	11	MS		4.0–6.0	15–40
Wheatgrass, crested	3.5	4	MT			>40
Wheatgrass, fairway	7.5	6.9	T			>40
Wheatgrass, tall	7.5	4.2	T			>40
Fruit trees, vines, and shrubs						
Almond	1.5	18	S	<5		<15
Apple	1	18	S			<15
Apricot	1.6	24	S	<5	0.5–0.75	<15
Avocado	1.3	21	S	–	0.5–0.75	<15
Banana			MS			
Blackberry	1.5	22	S		<0.5	<15
Boysenberry	1.5	22	S			<15
Cherry	–	–	S	<5	0.5–0.75	<15
Coconut			MT			
Date palm	4	3.6	T			
Fig	4.2		MT		0.5–0.75	<15
Grape	1.5	9.5	MS	5–10.0	0.5–0.75	
Grapefruit	1.8	16	S	<5	0.5–0.75	<15
Lemon	1	–	S	<5	<0.5	<15
Orange	1.3	16	S	<5	0.5–0.75	<15

(continued)

Table 24.5 (continued)

	Response to salinity			Toxicity		
	EC_{eu}	B_s	Type	Na or Cl in water	B in soil	Na in soil (*ESP*)
Common name	dS/m	dS/m/%		meq/L Na or Cl	mg/L saturated extract	%
Peach	1.7	21	S	–	0.5–0.75	<15
Pear	1		S			<15
Pineapple			MT			
Plum	1.5	18.2	S		0.5–0.75	<15
Pomegranate	4		MT			
Prune	1.5	18	S	<5		<15
Raspberry	1		S			<15
Rosemary	4.5		MT			
Walnut			S		0.5–0.75	<15
Horticultural crops						
Artichokes	6.1	11.5	MT		2.0–4.0	
Asparagus	4.1	2	T		6.0–15.0	
Bean (green)	1	18.9	S			<15
Beet (table)	4	9	MT	>20	4.0–6.0	>40
Broad bean	1.6	9.6	MS			
Broccoli	2.8	9.1	MS			
Brussels sprouts	1.8	9.7	MS			
Cabbage	1.8	9.7	MS	–	2.0–4.0	
Cauliflower	1.8	6.2	MS	>20		
Celery	1.8	6.2	MS		2.0–4.0	
Cucumber	2.5	13	MS	10.0–20	1.0–2.0	
Eggplant	1.1	6.9	MS			
Kale	6.5		T			
Lettuce	1.3	13	MS	–	2.0–4.0	15–40
Melons	2.2	7.3	MS	–	2.0–4.0	
Pea	2.5		MS		1.0–2.0	<15
Pepper	1.5	14	MS	5.0–10	1.0–2.0	
Pumpkin, winter squash	1.2	13	MS			
Radish	1.2–2.0	7.6–13.0	MS		1.0–2.0	15–40
Spinach	2.0–3.2	7.7–16.0	MS			15–40
Squash	2.5		MT		2.0–4.0	
Squash, scallop	3.2	16	MS			
Squash, zucchini	4.7	10	MT			
Strawberry	1	33	S	–	0.75–1.0	
Tomato	2.5	9.9	MS	5.0–10	4.0–6.0	15–40
Watermelon	–	–	MS			
Legumes						
Bean (dry)	1	18.9	S			<15
Chickpea			MS			<15
Cowpea (seed)	4.9	12	MT		0.5–0.75	<15
Dry bean	1	19	S	–	0.75–1.0	
Faba bean	1.6	9.6	MS			
Pea	1.5	14	S		1.0–2.0	<15
Peanut	3.2	29.4	MS	–	0.75–1.0	<15
Soybean	5	20	MT			

(continued)

Table 24.5 (continued)

Common name	Response to salinity			Toxicity		
	EC_{eu}	B_s	Type	Na or Cl in water	B in soil	Na in soil (ESP)
	dS/m	dS/m/%		meq/L Na or Cl	mg/L saturated extract	%
Roots, tubers, and bulbs						
Carrot	1	14	S	–	1.0–2.0	15–40
Onion	1.2	16.1	S	–	0.5–0.75	15–40
Parsnip	–	–	S			
Potato	1.7	12	MS	5.0–10	1.0–2.0	
Sweet potato	1.5	11.1	MS		0.75–1.0	
Turnip	0.9	9	MS		2.0–4.0	
Cassava			MS			
Garlic	3.9	14.3	MS		0.75–1.0	
Sugar, oil, and fiber crops						
Cotton	7.7	5.2	T	>20	6.0–15.0	>40
Castor bean	–	–	MS			
Flax/linseed	1.7	12	MS			
Kenaf	8.1	11.6	T			
Olive	5.00	7	MT			
Rapeseed	10.5	13.5	T			
Safflower	6.5		MS	10.0–20		
Sesame			S	10.0–20	0.75–1.0	
Sugar beet	7	5.9	T	>20	4.0–6.0	>40
Sugarcane	1.7	5.9	MS			15–40
Sunflower	5.5	25	MS	>20	0.75–1.0	

Adapted from Ayers and Westcott (1989)

For the response to total salt concentration, two parameters are shown: EC_{eu} (dS/m) is the value of EC_e below which yield is not affected. B_s (%/(dS/m)) is the slope of the linear relationship between yield (% of maximum) and EC_e. Crops are classified as sensitive (S), moderately sensitive (MS), moderately tolerant, (MT), and tolerant (T). Concerning the foliar damage by sprinkler irrigation, the threshold concentration of Na or Cl is shown (meq/L). The maximum concentration of B (mg/L in soil saturated extract) and Na (*ESP*, %) in the soil above which toxicity may occur are also shown

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Fertilizers

25

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Abstract

This chapter describes the main features of fertilizers, which are the products used to supply nutrients to plants. Currently, these products not only contain nutrients but may also enhance the capacity of plants to absorb nutrients. Traditionally, most mineral fertilizer production was based on nonrenewable and sometimes strategic resources. This can constrain future agricultural sustainability and food security. Thus, special attention is paid nowadays to fertilizer production based on circular economy approaches. Most of the fertilizers used in agriculture are those for supplying primary macronutrients, i.e., N, P, and K. Nitrogen fertilizers are very soluble, and their selection and application should be intended to minimize losses. Phosphorus fertilizers are distinguished mainly by their solubility which determines how and when they can be used. Potassium fertilizers are highly soluble, but losses are not limiting since K is retained in soil. Deficiencies of micronutrients are usually controlled with forms bound to organic compounds (complexes or chelates) which solves immobilization reactions or limitations to be absorbed by plants under certain soil conditions.

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25.1 Introduction

Fertilizers are inorganic or organic products that are used to provide nutrients to plants. Now, the term fertilizer is also used for other products such as microbial inoculants (sometimes referred to as biofertilizers) of physiologically active substances able to increase the capacity of plants to mobilize and absorb nutrients from soils (microbial and nonmicrobial biostimulants). In general, they have to comply with official regulations. For instance, the European Regulation 2019/1009 sets the rules that all EU must follow in their national directives to regulate properties, quality, and traffic of commercial fertilizers. In the USA, fertilizer regulations depend on the states, although some independent associations try to promote uniformity between states in their regulatory guidelines. According to the European regulation, different types of nutrients can be contained in fertilizers:

(a) Primary macronutrients: N, P, and K, which usually must be supplied in large amounts (tens or hundreds of kg per hectare).
(b) Secondary macronutrients: Calcium, magnesium, sodium, and sulfur, also required in high amounts but normally covered by the soil reserve. Sodium is not an "essential nutrient" from a physiological point of view but is required by some species such as C4 plants, and it is defined as a "beneficial nutrient."
(c) Micronutrients: Boron, cobalt, copper, iron, manganese, molybdenum, and zinc are required in small amounts compared with primary and secondary macronutrients; all are "essential nutrients" except cobalt (e.g., beneficial for legumes). The European regulation does not include nickel and chlorine, which are essential but seldom required as fertilizer.

The fertilizer strategy should be designed to achieve the maximum efficiency in the use of nutrients by plants, i.e., most of the supplied nutrients should be taken up by the crop. This means that fertilizer should be applied in chemical forms and with soil conditions that enhance root absorption while minimizing losses by physical processes (e.g., leaching) or chemical reactions in soil. To this end, the *4R approach* has been proposed, which implies that fertilizers should be applied *using the right source, at the right rate, at the right time, and at the right place*.

Fertilizers can be applied before planting (basal or preplant) or after it (top dressing or side-dressing). The application of fertilizer to the soil can be done manually, using machines (fertilizer spreaders) or dissolved in irrigation water (fertigation). Fertilizers can also be applied to vegetative organs (foliar spray), particularly when soil conditions are not favorable for nutrient absorption (e.g., very dry), or to achieve a fast response under deficiency conditions. Fertilizer may be applied on the entire field or just on part of it (localized, preferably close to plants, e.g., subsurface banded application), the latter being preferred for nutrients that can be fixed in the soil, such as P or K, particularly in poor-nutrient soils or soils with a high fixing capacity.

25.2 Fertilizers and Food Security

Increased global use of fertilizers has largely contributed to the increase in food production since the end of the nineteenth century. Figure 25.1 shows the evolution of fertilizer consumption and global wheat yield from 1961 to 2020. Around half of the crop yield may be attributed to fertilizer use (40–60% in the USA and UK), and this contribution is much higher in tropical regions. Table 25.1 shows the variation in inorganic or mineral fertilizer use for the different continents. In Africa, fertilizer rates are much lower than in other continents and this affects agricultural productivity with clear implications on food security. The ratio between nutrients can be quite different depending on continents, not necessarily reflecting different crop requirements but sometimes the accessibility to specific products. Contrasting with the period 2002–2011, there is an overall increasing trend in the use of fertilizers between 2011 and 2020 which likely reflects the need for increasing agricultural production in the world.

The application of fertilizers marked a breaking point in agricultural productivity at the end of the nineteenth century with the appearance of inorganic fertilizers obtained from chemical processes and with a high concentration of soluble nutrients. A relevant innovation was the synthesis of ammonia from atmospheric N_2 (the Haber-Bosch process) at the beginning of the twentieth century which solved the limitation of N supply to crops that constrained agricultural production. These mineral industrial fertilizers are nowadays essential for guaranteeing agricultural sustainability and food security. However, their production is based on nonrenewable resources. Nitrogen fertilizer production relies on high energy consumption (mostly from nonrenewable sources), being a large contributor to greenhouse gas emissions. P and K fertilizers are obtained from mining. The case of P fertilizer is particularly worrying since the production of the raw material (phosphate rock) is expected to peak in the middle of this century and the mines are concentrated in a few countries. The P limited supply and the increased demand will threaten global food security.

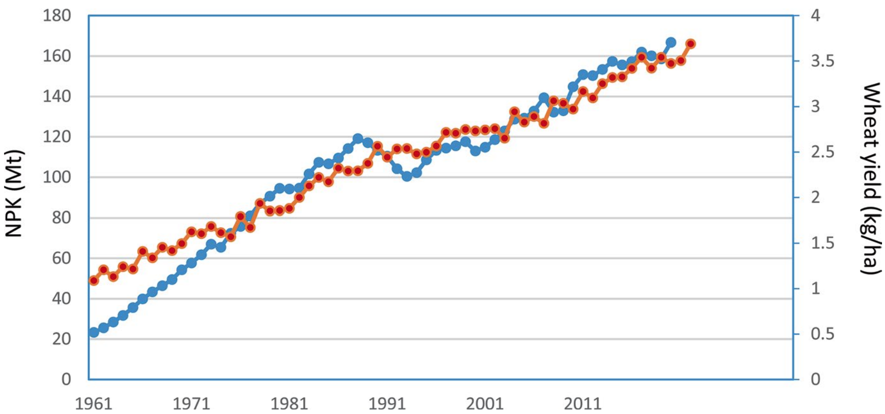

Fig. 25.1 Global use of N, P, and K inorganic fertilizers and average global wheat yield (1961–2020)

Table 25.1 Consumption of mineral fertilizers (Mt) by continents 2011–2020

Mt	Europe			Asia			Africa			America			Oceania		
Year	N	P	K	N	P	K	N	P	K	N	P	K	N	P	K
2011	13.7	1.51	3.35	63.7	11.8	13.5	3.13	0.55	0.43	23.1	4.87	8.92	1.48	0.51	0.25
2012	13.9	1.57	3.35	63.7	11.4	13.2	3.12	0.65	0.45	22.9	4.86	8.79	1.51	0.51	0.26
2013	14.3	1.62	3.48	64.4	11.2	13.3	3.31	0.67	0.48	23.2	5.33	9.74	1.61	0.49	0.27
2014	14.4	1.57	3.49	64.8	11.3	15.8	3.40	0.67	0.53	23.4	5.29	9.94	1.83	0.53	0.32
2015	14.6	1.59	3.40	64.8	11.4	16.1	3.41	0.72	0.55	22.0	4.96	9.38	1.76	0.53	0.32
2016	14.9	1.60	3.43	64.5	11.3	16.1	3.78	0.66	0.57	22.5	4.89	10.01	1.93	0.53	0.33
2017	15.4	1.71	3.61	64.6	11.5	16.9	4.39	0.75	0.75	23.5	5.19	10.73	1.97	0.56	0.36
2018	14.8	1.73	3.73	63.7	10.9	16.4	4.17	0.68	0.77	23.8	5.50	11.09	1.90	0.55	0.38
2019	15.0	1.75	3.63	63.4	10.7	15.3	4.17	0.74	0.80	24.0	5.39	10.89	1.82	0.55	0.38
2020	15.5	1.87	3.88	65.7	11.3	15.7	4.38	0.76	0.82	25.9	6.55	11.73	1.84	0.55	0.36
Area Mha		466			1669			1161			1125		389		
Average kg/ha	33.2	4.0	8.3	39.4	6.8	9.4	3.8	0.7	0.7	23.1	5.8	10.4	4.7	1.4	0.9

Source: FAOSTAT. Average use is calculated for 2020

The so-called P crisis in 2008 was the result of reduced exports of phosphate rock from China, which caused the prices of P fertilizers to triple. The recent discovery of large reserves of phosphate rock in Norway does not significantly change the panorama since new industrial uses will increase the global P demand. Till now, 85% of the phosphate rock was used in fertilizer production. European agriculture is dependent on P imports, so it has been included in the list of critical raw materials in the EU.

25.3 Toward More Sustainable Fertilizer Sources and Use

Apart from being nonrenewable resources, fertilizers are not used efficiently in agriculture and other sectors. The average N fertilizer accumulated in the harvest of cereals is usually less than 40% of the amount applied. There are also relevant losses beyond the farm, so the global efficiency of the N food chain (i.e., fraction of applied N incorporated in human bodies) is only around 10%. In the case of P, it is less than 15% due to soil reactions. Most of P accumulates in grains, but only a small fraction is absorbed during digestion, so most P is excreted and found in wastewater. In Europe, waste P is equivalent to around half of the P fertilizer consumed, so P recycling should be improved. Struvite, obtained from water recycling, may be used as P fertilizer. These types of products are called *bio-based fertilizers*. The use of recycled materials as fertilizers or raw materials for fertilizer production is promoted in the European fertilizer regulation.

25.4 Classification

Fertilizers can be classified according to different criteria:

(a) Depending on their nature: organic and inorganic (also referred to as mineral or chemical). Inorganic fertilizers are those in which nutrients are in the form of minerals obtained by extraction (mining) or by industrial processes. Organic fertilizers are those of animal or plant origin with a minimum declarable content of organic carbon according to legislation. Calcium cyanamide, urea and its condensation and association products, and fertilizers containing chelated or complexed micronutrients can be classified as mineral fertilizers by convention. Chelated and complexed micronutrients refer to a product in which the micronutrient is held by a complexation reaction with organic molecules; in the European regulation, depending on the type of organic molecule, the product is considered "chelate fertilizer" or "complex fertilizer." They both, chelate and complex, should contain a minimum concentration of the micronutrient with a minimum proportion of water-soluble form. In organic farms, only those products from natural sources are allowed (e.g., farm organic residues or Chilean nitrate). Fertilizers can be also defined as organo-mineral when besides nutrients in mineral form they contain a minimum of declarable organic carbon according to legislation.

(b) According to their composition (legislation establishes minimum contents of nutrients):

- Straight fertilizers, which are those with a declarable content of only one macronutrient, or one primary macronutrient (N, P, or K) and one or more secondary macronutrients (such as Ca, Mg, or S).
- Compound fertilizers, which are fertilizers with a declarable content according to the law of more than one primary macronutrient, or more than one secondary macronutrient; they are obtained chemically or by blending or by a combination of both processes. These fertilizers are classified as binary when they have a declarable content of two primary nutrients, or ternary or complete when they have a declarable content of three primary nutrients. These fertilizers are sometimes called "complex." However, this term is frequently applied to compound fertilizers produced by combining ingredients to react chemically leading to a single chemical product with more than one macronutrient, e.g., diammonium phosphate which is a binary fertilizer that contains N and P.

(c) According to their physical presentation, which often determines the conditions of their use and their effectiveness, fertilizers can be classified as:

- Solid fertilizers, with different types of presentation depending on their production, solubility, and method of application:
  - Powder or non-granular, when the product is presented as fine particles usually up to 3 mm diameter. Very few materials are sold now in this form as they present problems in handling (they tend to "cake") and cannot be applied with spreaders. Powder is a usual presentation for sparingly soluble products since low particle size enhances its solubilization.
  - Crystallines, which are usually very soluble fertilizers for preparing fertigation or foliar spray solutions. They are not suitable for application with mechanical spreaders.
  - Granules, designed to improve the uniformity of mechanical distribution. More than 90% of the particles have to present diameters between 1 and 4 mm. The spherical shape is desirable. The distinction between granular and prilled refers to the industrial production method.
  - Pelletized or pelleted: They are granular fertilizers with very uniform sizes of spherical granules which improve the uniformity of distribution.
  - Macrogranules: granules of 1–3 cm to produce a slower release of the nutrients.
- Fluid fertilizers, which can be fertilizers in suspension or solution or both; fertilizers presented only in suspension as dispersed particles are called "suspension fertilizers," while solutions free of solid particles are "solution fertilizers." Pressure solutions are those including anhydrous ammonia in a concentration greater than that that can be maintained in equilibrium with the atmosphere.
- Gaseous fertilizers, with only one fertilizer in this category, anhydrous ammonia, which must be injected into the soil.

25.5 Fertilizer Properties

25.5.1 Physical Properties

The physical properties of fertilizers are not regulated by law but are critical for correct handling, storage, conservation, and application. The following properties are the most relevant for solid fertilizers:

(a) Hardness, i.e., the resistance to be broken, which is important to prevent the breaking of granules during handling and to avoid powder formation due to abrasion.
(b) Fluidity which means a low risk of caking after storage.
(c) Particle size, which must be homogeneous to guarantee a correct application by mechanical spreading.
(d) Humidity must be low to avoid caking.
(e) Density, which is relevant for storage and segregation during the application of compound blended fertilizers with different densities; the distribution of a blend of several fertilizers could result in heterogeneous products if compounds with very different densities are blended.

25.5.2 Chemical Properties

Chemical properties determine the speed of action of the fertilizer and the side effects on crops and soil properties. The main chemical properties to be considered are the following:

(a) Solubility determines how fast nutrients enter the soil solution and are thus available for root absorption. It is measured in water for N and K fertilizers. For P, usually less soluble, besides water, ammonium citrate or citric acid has been used to characterize its solubility trying to mimic the effect of plant roots in soil (exudation of low molecular weight acids). Solubility in water is critical for fertilizers used in fertigation to avoid clogging of drippers. Solubility increases with increasing temperature and acidity. Some mixtures can promote precipitation, like Ca fertilizers mixed with phosphates.
(b) Reaction of fertilizer in the soil, which may be acid or basic. It has been measured by the "acidity index" which is the equivalent amount of CaO that neutralizes the effect of a fertilizer with acid reaction or promotes the same soil pH increase when the reaction is basic. The fertilizer reaction can be the result of (i) its chemical composition, e.g., anhydrous ammonia is a base, or base (e.g., Ca) which is the counterion in the nitric fertilizers; (ii) its reactions in soil, e.g., nitrification of ammonium in the soil produces acidity, or the decomposition of calcic cyanamide forms $Ca(OH)_2$ which increases pH; or (iii) presence of impurities such as sulfuric acid in ammonium sulfate.

(c) Salt index, which measures the effect of the fertilizer on the osmotic pressure; it is a relative value compared with sodium nitrate which receives an arbitrary value of 100.
(d) Hygroscopicity: It is the ability to absorb atmospheric moisture and is measured as the relative humidity value at which the fertilizer starts to absorb water. In many cases, hygroscopicity is proportional to the solubility of the fertilizer. Water absorption causes the dissolution of the particles, which melts the physical structure of the fertilizer and converts it to clumps instead of the initial granules which worsens the mechanical distribution.

25.5.3 Nutrient Concentration in Fertilizers

The nutrient concentration in a fertilizer is the amount of nutrients per unit weight of the product. After estimating the nutrient requirements of the crop, this information is basic to calculate the amount of fertilizers to be applied. The concentration of nutrients in fertilizers is usually expressed in the following form, according to the legislation:

(a) Nitrogen, as elemental N.
(b) P, K, Ca, Mg, Na, and S as oxides (K_2O, P_2O_5, CaO, MgO, Na_2O, and SO_3) but elemental forms should be used instead. The use of oxides is an archaic custom of interest only to fertilizer companies, which is now being left behind. In some countries, both the concentrations in elemental and oxide forms appear on the label (e.g., UK) and in some, only the elemental basis is used (e.g., Australia).
(c) Other nutrients, such as micronutrients, in elemental form.

The concentration of primary nutrients of a compound or complex fertilizer or fertilizer grade is usually indicated by three numbers separated by hyphens that correspond to the percentages of N, P_2O_5, and K_2O.

Example 25.1
A ternary 15-15-15 fertilizer has concentrations of 15, 15, and 15% of N, P_2O_5, and K_2O, respectively. If we express the concentrations in elemental form, we have:

N	15%
P	15% × 62 kg P/142 kg P_2O_5 = 6.5%
K	15% × 78 kg K/94 kg K_2O = 12.45%

The factor of conversion is calculated as the ratio of the element mass to the molecule mass.

The content of secondary nutrients or micronutrients in a compound fertilizer is expressed by another number with the percentage of the nutrient and indication of the nutrient. For example, if the ternary mentioned above has 2% MgO, this should be indicated in the following way: 15-15-15-2 MgO.

The usual nutrient concentrations of different fertilizers are presented in Table 25.2.

Table 25.2 Most relevant mineral fertilizers and their macronutrient concentration

	N (%)	P_2O_5 (%)	P (%)	K_2O (%)	K (%)
Straight N fertilizers					
Sodium nitrate	15.5				
Calcium nitrate	16				
Magnesium nitrate	10.5				
Ammonium sulfate	21				
Urea	46				
Calcium cyanamide	16–20				
Anhydrous ammonia	82				
Pressured ammonia solutions	41%				
Ammonium sulfate	21				
Ammonium nitrate	32				
Calcium ammonium nitrate	20.5–30				
Ammonium nitrosulfate	26				
N solutions	20–32				
Slow-release fertilizers					
Urea-formaldehyde (UF)	38				
Isobutylidene diurea (IBDU)	32				
Crotonylidene diurea (CDU)	31				
Straight P fertilizers					
Superphosphate		18–21	8–9		
Triple superphosphate (TSP)		45	20		
Phosphoric acid		54	24		
Superphosphoric acid		76	33		
Dicalcium phosphate		40	17		
Calcium metaphosphate		64	28		
Calcined phosphate		18–28	8–12		
Basic slags		15	7		
Ground phosphate rock		25–40	11–17		
Straight K fertilizers					
Potassium chloride				60	50
Potassium sulfate				50	41.5
Complex fertilizers					
Binary NP					
Monoammonium phosphate (MAP)	10–12	48–60	21–26		
Diammonium phosphate (DAP)	18	46	20		
Ammonium polyphosphates (APP)	10–11	34–37	15–16		
Nitrophosphates	20	20	9		
Binary PK					
Potassium phosphates		52	23	34	28
Binary NK					
Potassium nitrate	13			44	36.5

25.6 Straight N Fertilizers

25.6.1 Fertilizers with Nitrate

The nitrate fertilizers are very soluble in water, and the nitrate ion, an N form in which plants readily absorb this nutrient, is not fixed by soil particles when applied to the soil, so it remains in the soil solution. Therefore, N applied in this form is easily absorbed by plants but may be leached and lost from the soil. It can be considered a fast-action N fertilizer but should therefore be applied split and when the crop has a high demand for the nutrient to avoid losses (typically topdressing applications). These fertilizers show high hygroscopicity and a slightly basic reaction. Besides this reaction of nitrate fertilizers, nitrate can have an effect of increasing the pH of plant apoplast or rhizosphere as its absorption into cells is coupled with H^+ which decreases the acidity of these media.

The main fertilizers in this group are calcium nitrate (16% N) and sodium nitrate (Chilean nitrate, obtained from mining) (15.5% N). This group also includes magnesium nitrate (10.5% N), very soluble and used in fertigation, sometimes as solution fertilizer.

25.6.2 Fertilizers with Ammonium

Ammonium supplied with these fertilizers is a cation that is readily adsorbed by the soil exchange complex and is therefore not leached when percolation occurs. Thus, this type of fertilizer is recommended for preplant applications in winter crops when a high risk of leaching and low extraction by crops occurs at the beginning of the growing season. Although ammonium can be absorbed by plants, the progressive nitrification of ammonium (microbial transformation to nitrate) enhances its use by plants. At high rates, ammonium can be toxic to crops. At basic pH, there is an increased risk of losses to the atmosphere by volatilization (loss of gaseous NH_3). This risk is increased if fertilizer is not mixed with the soil, thus making it less suitable for topdressing applications, and when soil is dry. In hydroponics, a portion of N should be applied in ammonium form (10–20%) to avoid pH rising in the solution due to nitrate absorption which can result in decreased availability of other nutrients such as Fe.

This group includes ammonium sulfate (21% N, 24% S), anhydrous ammonia (gas, 82% N), and pressured solutions of ammonia (41%) which have to be injected into the soil at 15–20 cm depth, with moderately wet conditions. Anhydrous ammonia requires special machinery for its application and is difficult to store and handle.

25.6.3 Fertilizers with Nitrate and Ammonium

These fertilizers combine the advantages of both forms of N, rapid availability of nitrate, and soil retention of ammonium that progressively transforms into nitrate.

They do not depend entirely on nitrification to provide nitrate, so they can be used in low-temperature periods when the nitrification rate is low. They are used primarily in winter and in spring for topdressing.

This group includes ammonium nitrate (32% N) and ammonium nitrosulfate (26% N). One of the main concerns in the use of ammonium nitrate is its application for producing explosives like *ANFO*, which is used in mining and may be homemade by mixing ammonium nitrate (AN) with fuel in the right proportions. It has been thus the choice for terrorists which has led to strict regulations in many countries regarding the purchase of AN or its commercial formulation. For instance, in Ireland and Northern Ireland, AN fertilizer is marketed as a mixture of ammonium nitrate and calcium carbonate. This mixture is one of the formulations called calcium ammonium nitrate (CAN), which can be also obtained by mixing calcium nitrate and ammonium nitrate, with typical N contents ranging between 21% and 27%.

25.6.4 Urea and Related Products

Urea (46% N) and calcium cyanamide (around 20% N in commercial products) are included in this group. Urea has N in ureic form and cyanamide is transformed into urea in the soil. It has an acidic reaction, and it is very soluble and hygroscopic. Urea is a white crystalline solid that can be purchased as prills or as a granulated material. The importance of granules is increasing as they are larger, harder, and more resistant to moisture. Urea is rapidly hydrolyzed to ammonium through the activity of the urease enzyme, present in soils. This requires a certain temperature and humidity. Urea is highly soluble, so it may be leached before hydrolysis. Application to the soil surface may involve volatilization losses of ammonia formed during hydrolysis, so it is advisable to incorporate urea by tillage or irrigation. Urea is widely used both for basal applications and topdressing because of its low cost per unit of N applied. It can also be applied as solution that may also contain ammonium nitrate. Its high solubility makes feasible its use in fertigation and foliar sprays, which are recommended in tree orchards when soil conditions are not appropriate for N absorption by roots (e.g., dry soil). The content of biuret (condensation product) in urea fertilizers must be controlled since it is phytotoxic, particularly for foliar sprays with a maximum recommended content of 0.25%. To reduce ammonia losses, urease inhibitors can be added to urea. On the other hand, to reduce leaching risk, slow-release fertilizers based on urea coating have been developed. These are based on either reducing the solubility (larger granules, special coatings such as paraffin or sulfur) or adding nitrification inhibitors.

Calcium cyanamide reactions in soil release urea and calcium hydroxide, which explains its strong basic reaction. It is expensive, can be phytotoxic, and releases slowly available N; thus it is only recommended as basal fertilizer.

25.7 Straight P Fertilizers

Phosphate fertilizers are produced by physical (grounding, calcination) or chemical (acid attack) of phosphate rock. The most important feature of straight phosphate fertilizers is the reduced solubility in water of many of them. This low solubility in water does not necessarily imply that plants cannot use them as P sources. As mentioned above, organic acids exuded by roots, such as citrate, contribute to the mobilization of P by solubilizing many of the precipitates of this nutrient in the soil. The sum of the water-soluble and citrate-soluble P in the fertilizer is considered to be the amount available to plants, and it is given on the fertilizer label. Usually, the citrate-soluble component is less than the water-soluble component. According to solubility, three main groups of phosphate fertilizers can be distinguished:

(a) Mostly soluble in water, including single superphosphates (18–21% P_2O_5, 8–9% P, 85% soluble in water), triple superphosphate (45% P_2O_5, 20% P, 85% soluble in water), phosphoric acid (54% P_2O_5, 24% P), and superphosphoric acid (76% P_2O_5, 33% P). The two acids are only used in fertigation (see Chapter 26).
(b) Mostly soluble in ammonium citrate, such as dicalcium phosphate (40% P_2O_5, 17% P) and calcium metaphosphate (64% P_2O_5, 28% P).
(c) Insoluble, including calcined phosphate (18–28% P_2O_5, 8–12% P), basic slags (or Thomas slags, byproduct of iron and steel industry) (15% P_2O_5, 7% P), and ground phosphate rock (25–40% P_2O_5, 11–17% P, from mining without chemical treatment in the industry).

The more soluble fertilizers are to be incorporated in granular form and localized when possible to enhance their efficiency, particularly in P-poor soils or in soils with a high P-fixing capacity. The less soluble forms are available as powder or fine granules which should be mixed with the soil to enhance its dissolution.

25.8 Straight K Fertilizers

Potassium fertilizers also come from mining resources, which are not as limited as phosphate rock. Although potassic fertilizers are very soluble in water, K ions are usually adsorbed to the soil exchange complex, which reduces the risk of losses. As with phosphate fertilizers, localization in bands is recommended in K-deficient soils with high cation exchange capacity to saturate it and maintain a high availability of K in the soil solution.

The two fertilizers with only K as a primary nutrient are potassium chloride (60% K_2O, 50% K) and potassium sulfate (50% K_2O, 41.5% K). The former is cheaper and more soluble but should be avoided under saline conditions to avoid the negative effects of chloride.

25.9 Compound Fertilizers

This group includes binary and ternary fertilizers. Binary are usually complex forms, i.e., one chemical compound containing two macronutrients, and ternary are compound fertilizers obtained from blending, i.e., mixture of straight and complex fertilizers. Compound fertilizers facilitate the simultaneous application of several nutrients, avoiding self-made mixtures of fertilizer by farmers which can be less effective and adequate for a homogeneous distribution and can have problems of compatibility between blended products. The selection of compound fertilizers must be based on the relative proportion of N, P, and K needed by the crop and on the price per nutrient unit applied. Blending of fertilizers to produce compound fertilizers must consider basic rules of incompatibility: avoiding mixtures of P fertilizer with products with Ca to avoid P precipitation and the mixtures of ammonium fertilizers with basic reaction products to avoid volatilization of ammonia.

(a) Binary NP fertilizers include ammonium phosphates, mono- (MAP) or diammonium phosphate (DAP), ammonium polyphosphates, and nitrophosphates. DAP (18-46-0) is the most widely used P fertilizer in the world. It is highly soluble and promotes a basic reaction around the granule in the soil. MAP (10/12-48/60-0) is less soluble than DAP but its reaction is acidic, which makes it a better choice in fertigation. Ammonium polyphosphates (APP, 10/11-34/37-0) have part of the P as polyphosphates which must be hydrolyzed by the action of enzymes in the soil to pass to the available orthophosphate form which takes a few weeks with adequate temperature and water content. APP is frequently used in fluid fertilizers among other reasons by its acidic reaction. Nitrophosphates (20-20-0) have only a portion of water-soluble P and N in nitric and ammonium form. Ammonium phosphates are typical fertilizers used in basal applications, particularly if no K is necessary. The combination of ammonium and phosphate seems to enhance P uptake by plants compared with other P sources.

(b) Binary PK fertilizers are mixtures of phosphates and potassium chloride or potassium sulfate, or potassium phosphates and polyphosphates. Potassium phosphate (0-52-34) is soluble and has a slight acid reaction. It can be used in fertigation and foliar sprays. It is more expensive than other binary fertilizers with P.

(c) Binary NK fertilizers include blends of straight N and K products and only one complex fertilizer, potassium nitrate (13-0-44). This is a very soluble product recommended for fertigation and foliar sprays. It can be applied as topdressing if additional K (besides the preplant application) is required.

(d) Ternary NPK fertilizers are solid or liquid mixtures of straight and compound fertilizers with a wide range of grades and presentations. They are used for preplant broadcast applications. Although the amount of N applied as ternary products is modest, they can provide all the P and K required by crops. Depending on each particular product, the nutrients can be present in different chemical forms.

25.10 Fertilizers and Products with Secondary Nutrients

Although crops can take up large amounts of secondary nutrients, their application is not frequent because available pools in the soil can cover plant extractions. Its application usually follows a "sufficiency" strategy, which means that nutrient is applied only if an increased yield can be expected from its application.

Calcium can be extracted in high amounts by crops, its concentration in leaves being sometimes higher than that of N (e.g., in citrus). The need to apply Ca as a fertilizer is rare; its deficiency is typical in acidic soils with low base saturation of the exchange complex. Seldom, antagonistic problems with Mg make its application advisable. Fertilizers with significant amounts of Ca are:

(a) N fertilizers: calcium ammonium nitrate (10–20% CaO, 7–14% Ca), calcium cyanamide (54% CaO, 39% Ca), and calcium nitrate (28% CaO, 20% Ca)
(b) Phosphate fertilizers: superphosphate (17–28% CaO, 12–20% Ca, mostly present as gypsum), slags (45–50% CaO, 32–36% Ca), and dicalcium phosphate (32% CaO, 23% Ca)

Ca is usually added in the amendments used for the reclamation of sodic or acid soils, which implies a nutrient supply that can overcome Ca deficiency in crops. Magnesium is required in lower amounts than Ca. Its deficiency is frequently due to an antagonism with Ca, and sometimes with K when K fertilizers are applied in high amounts, particularly in K-rich soils. Its concentration is low in most fertilizers. When needed it may be added as dolomite (20% MgO, 12% Mg), magnesium oxide (90% MgO, 54% Mg), magnesium chelates (foliar application), and magnesium sulfate (16% MgO, 10% Mg). The latter can be applied by foliar sprays.

Sulfur extraction by crops can be as high as that of P, being particularly high in legumes (e.g., more than 45 kg/ha in alfalfa) and cruciferous crops. It is present in many fertilizers, such as ammonium sulfate (24% S), ammonium nitrosulfate (12% S), and superphosphates (12% S in single superphosphate), which have been a traditional source of S for crops. However, the decreasing trend in the use of ammonium sulfate, superphosphates, and elemental S as fungicide is leading to S deficiencies. The need for adding S is not common, but if necessary it can be applied as sulfuric acid (30% S), elemental sulfur (30–99% S), potassium sulfate (17% S), and urea-sulfur (19% S).

25.11 Fertilizers and Products with Micronutrients

Micronutrients are usually applied following a "sufficiency strategy," which means that their application is done if a deficiency is expected. Frequently, micronutrient deficiency is the consequence of soil conditions promoting a failure in the mobilization, absorption, or transport mechanisms of plants, not the result of a lack of nutrients in the soil. The paradigmatic case is iron deficiency chlorosis, related to alkaline and calcareous conditions, not to the lack of iron in soil. The most common

Table 25.3 Products commonly used for correcting micronutrient deficiency

Element	Chemical	% Element	Preferred use
Boron	H_3BO_3	17	
	$Na_2B_4O_7 \cdot 5\ H_2O$	20	
	$Na_2B_4O_7 \cdot 10\ H_2O$	11	
	$Ca_2B_6O_{11} \cdot 5\ H_2O$ (**)	10	
Copper	$CuSO_4 \cdot 5\ H_2O$	25	Foliar
	CuO (*)	50–75	Soil
Iron	$Fe\ SO_4 \cdot 7\ H_2O$	20	Foliar
	FeHEDTA	5–9	Soil
	FeEDDHA[a]	6	Soil
Manganese	$Mn\ SO_4 \cdot 4H_2O$	24	Foliar
	MnO (*)	41–68	Soil
	Mn oxysulfate	30–50	Soil
Molybdenum	$Na_2\ MoO_4 \cdot 2\ H_2O$	39	Foliar
	$(NH4)_2MoO_4$	49	
	MoO_3	66	Soil
Zinc	$Zn\ SO_4 \cdot H_2O$	36	Foliar
	Complex $Zn\ SO_4 – NH_3$	10–15	
	ZnO (*)	60–78	Soil
	Zn oxysulfate	18–50	Soil
	Zn EDTA	6–14	Soil

[a]For correction of Fe deficiency chlorosis in calcareous soils, most of Fe present in EDDHA-Fe should be orto-orto. All products are soluble in water except those marked with * (insoluble) or ** (slightly soluble)

fertilizers in the market do not contain significant amounts of trace elements except Chilean nitrate and slags. Micronutrients are not usually added to other fertilizers because of the risk of toxicity. The deficiencies, when detected, are treated with specific products (Table 25.3).

Iron deficiency is called "iron deficiency chlorosis" and is related typically to calcareous soil and sensitive plants. The application of inorganic Fe salts (sulfates and carbonates) to the soil is usually not effective due to the rapid oxidation of Fe in the soil which results in the precipitation of insoluble Fe(III) oxides. These products are more effective by foliar sprays or injections to the trunk. The only inorganic salt effective in overcoming the problem (for several years) is vivianite (ferrous phosphate). Siderite (Fe carbonate) with colloidal size can also be effective. The easiest to use and most effective products are Fe-chelates, although they have the constraints of high price and low residual effect (three to four applications per growing season are usually needed). Fe-chelates are Fe complexed by organic compounds (usually synthetic amino carboxylic acids) which provide a supply of Fe that is maintained available in the soil and also have a positive effect on the Fe transport mechanism through plasma membranes. Accurate selection of Fe-chelate is necessary depending on soil conditions, e.g., chelates applied to calcareous soils may be stable in conditions of high Ca concentration and pH in the soil solution. In calcareous soils, the most used Fe-chelate is FeEDDHA. Fe-chelates can be applied directly to the soil or by fertigation; care should be taken with foliar sprays since the chelates are not always photostable. Other types of Fe complexes can be obtained using natural organic matter or organic byproducts of the paper industry (lignosulfonates) as complexing compounds. According to legislation, fertilizer labels should indicate the complexing agent and the content of micronutrients. In the case of Fe-chelates, the content of isomers is mandatory since the efficiency varies depending on the isomer. In the case of FeEDDHA, the Fe(o,o-EDDHA) is the most effective in overcoming Fe deficiency chlorosis.

Zinc deficiency, in addition to Fe chlorosis, is the micronutrient deficiency contributing most to decreased agricultural yields in calcareous soils. This deficiency is particularly relevant in cereals, which decreases not only yields but also grain quality for human consumption (low Zn concentration). Manganese and copper deficiencies can also occur, more frequently in calcareous soils where their solubility is low. Unlike Fe, there are no commercial specific complexing agents for Zn, Mn, and Cu, EDTA and DTPA being the most usual. The low specificity makes these chelates unstable, in particular in calcareous soils. For controlling Zn, and Mn deficiencies, sulfates have been the most usual products, although other inorganic forms (nitrates, chlorides, oxides) can be applied. Inorganic fertilizers can be combined with chelates for controlling the deficiency of these micronutrients. As for Fe, lignosulfonates and natural complexing agents can be used for producing complexes of these micronutrients.

The deficiency of molybdenum is usual in strongly acid soils, where its solubility is significantly decreased. If needed it is applied as inorganic salts such as ammonium or sodium molybdate. Amendments to increase soil pH in acidic soils can contribute to an increased availability of this nutrient.

The deficiency of boron occurs often in the most demanding crops (alfalfa, beet, cauliflower, sunflower, olive). High pH can promote B deficiency in low organic matter sandy soils. The main products are sodium tetraborate (borax, 11% B), boric acid (17% B), and sodium octaborate (Solubor®, 20% B) in foliar or soil application. Boron bound to ethanolamine or triethanolamine can be also used.

25.12 Slow-Release Fertilizers

Slow-release fertilizers were produced first for N to reduce nitrate leaching, particularly in sandy soils. Later, slow-release products have been developed for other nutrients, including P and K. Today, a new line of products, whose solubilization is enhanced under rhizosphere conditions (e.g., increased organic acid concentration), is being developed.

Slow N-release fertilizers can be classified into different categories:

(a) Natural organic sources such as manures, which contain part of the N in organic form which must be mineralized to be used by plants (see Sect. 25.11).
(b) Products derived from urea that must be hydrolyzed first to release urea. The hydrolysis rate depends on temperature, humidity, and microbial activity. The main products are urea-formaldehyde reaction products (UF, up to 38% N

and maximum decomposition at pH 6.1–6.5), isobutylene diurea (IBDU, 31% N, maximum decomposition at pH 4), crotonylidene diurea (CDU, 31% N, maximum decomposition at basic pH), and triazone (cyclic compounds with ammonium).

(c) Urease inhibitors slow down the production of ammonium from urea, which reduces volatilization. The most common products are N-(n-butyl) thiophosphoric triamide (NBPT) and N-(n-propyl) thiophosphoric triamide (NPPT).

(d) Products with a slow release of N achieved by physical coating of urea prills. Coatings are usually composed of sulfur, wax, or resins, which form a semipermeable membrane that allows a slow dissolution of covered fertilizers. Some commercial products have different contents of primary and secondary nutrients and micronutrients covered in plastic polymers with pores that allow a slow release.

(e) N fertilizers based on urea or ammonium mixed with nitrification inhibitors whose effect lasts several weeks and may reduce N_2O and NO emissions associated with nitrification and denitrification. The most common products are dicyandiamide (DCD), 3,4-dimethylpyrazole phosphate (DMPP), and pronitradine.

25.13 Organic Fertilizers

Organic fertilizers are products containing organic C of biological origin which contain enough plant nutrients to be useful as fertilizer. They are obtained from animal or plant material transformed (e.g., composting) or not. The organic fertilizer may also serve as a soil improver (organic amendment) when significant amounts of C are added to the soil (Chap. 30). Organic fertilizers include residues from the meat industry, manure and other farm residues, compost from different origins, byproducts of agroindustry, and guano.

The minimum content of carbon and nutrients is regulated by law for the trading of organic fertilizers. For example, in the EU, solid organic fertilizers must contain at least 15% organic carbon, and the minimum content in primary macronutrients can vary between 1% and 2.5% depending on the nutrient and the combination of nutrients declared. Nutrients in the organic fertilizer, such as N, P, and S, can be at least partly in organic form. An organo mineral fertilizer is a co-formulation of one or several inorganic fertilizers and one or more materials containing organic C and nutrients. Particular attention is usually paid in the legislation to pollutants such as heavy metals and pathogen microorganisms.

In-farm organic byproducts and wastes can be used as fertilizers and/or soil amendments but are out of trading regulations. They may have a relevant role in recycling nutrients at the farm scale, decreasing the need for external inputs and improving nutrient balances. These products include animal wastes (slurries, dung, manure, and poultry litter) and plant materials (crop and pruning residues and green manure).

Manure has relevance as fertilizer and in the recycling of nutrients. As an example, the amount of P applied in Europe and part of the USA as manure is higher than that applied as mineral fertilizer. The direct application of farm residues or the direct deposition of slurries/manure in the field by the animals has several drawbacks:

- High water content and low nutrient concentration which increases the application cost per unit of nutrient applied when compared with mineral fertilizers (with high nutrient concentration).
- Uneven distribution.
- High losses of N by volatilization of ammonia, particularly if they are not incorporated. These products should be injected or incorporated into the soil just after spreading.
- Bad smells and potential chemical and microbial contamination of surface waters if the product is washed away after heavy rainfall.
- Addition of weed seeds, pathogenic microorganisms, and insect larvae (e.g., flies).
- Fermentation in the field of fresh organic residues can reduce seed germination and seedling growth due to the production of phytotoxic compounds or to decreased oxygen partial pressure around the seedlings.
- Some residues with a high C/N ratio, such as fresh manure or cereal straw, can promote an initial N immobilization which may decrease temporarily plant N availability (Chap. 26).

Many of these problems are greatly reduced if the residues are previously composted, i.e., subjected to aerobic decomposition with temperatures between 40 and 65 °C. Composting implies an increase in the density and a reduction in the C/N ratio. For instance, for cow manure C/N goes from more than 50 to less than 20. Residues or composts should be applied well before planting (2–3 months for fresh manures or crop residues) and incorporated into the soil. Basic reaction products such as lime should be avoided then, as ammonia volatilization would increase. It should be noted here that only plant residues generate stable soil organic matter (humus) (Chap. 30).

The main overall limitations in the use of organic fertilizers are the following:

- Organic fertilizers have low nutrient concentrations, thus forcing the application of high rates or the addition of mineral fertilizers. For example, the application of 20 t/ha of cow manure may provide only 60 kg N/ha, 30 kg P/ha, and 80 kg K/ha.
- Nutrient concentration in organic fertilizers is highly variable depending on the nature and processing of the product. In the case of manures, the composition is affected by animal species (Table 25.4), age, proportion of litter bed, diet, and composting time. Thus, it is difficult to know the amounts of nutrients applied with organic fertilizer unless each batch applied is analyzed.

Table 25.4 Total manure produced for several species and average macronutrient concentration on a fresh weight basis (compiled from various sources)

		Manure (fresh)	N	P	K	Total N	Total P	Total K
		kg/animal/year	%			kg/animal/year		
Dairy	Cow	17883	0.48	0.11	0.40	85.8	19.5	71.2
	Heifer	10367	0.53	0.17	0.51	54.9	17.7	53.3
Beef	Cow	9925	0.6	0.16	0.33	59.6	16.0	32.9
	Feeder	8275	0.55	0.19	0.45	45.5	15.5	37.1
	Stocker	2867	0.51	0.14	0.41	14.6	3.9	11.9
Swine	Finishing	2350	0.76	0.31	0.46	17.9	7.4	10.7
	Growing	3317	0.55	0.18	0.35	18.2	5.9	11.6
	Nursery	495	0.55	0.20	0.32	2.7	1.0	1.6
	Gestating sow	2110	0.78	0.37	0.43	16.5	7.7	9.1
	Sow and litter	4963	0.45	0.20	0.32	22.3	9.8	15.6
Poultry	Layer	46.2	1.32	0.47	0.53	0.6	0.2	0.2
	Broiler	24.4	1.98	0.66	0.87	0.5	0.2	0.2
	Turkey	112	1.89	0.78	0.91	2.1	0.9	1.0
	Duck	50	1.01	0.45	0.56	0.5	0.2	0.3
	Goose	100	1.1	0.26	0.41	1.1	0.3	0.4
Others	Horse	8600	0.57	0.11	0.45	49.0	9.4	38.5
	Sheep	610	0.94	0.17	0.65	5.7	1.0	3.9
	Goat	1100	0.99	0.24	0.89	10.9	2.6	9.8
	Rabbit	56	1.56	0.53	0.71	0.9	0.3	0.4

Usually, the ranges in N, P, and K concentrations in manure are 3–8, 0.7–1.3, and 3–6 kg/t, respectively. In poultry litter, N and P concentrations are twice that in other animal wastes.

- Part of the nutrients in these products are in organic form, particularly N and P. Thus, their release is not immediate, since it requires the mineralization of organic matter, which may take several years to be completed. It is assumed that N in manures is released in 3–5 years; in slurries, a greater portion of N is readily available in the first season after application (60–70%). This slow release of nutrients reduces N leaching but may limit nutrient availability. On the other hand, the application of P in organic forms or with an organic matrix is more efficient in increasing the P soil available pool than mineral fertilizers.
- The nutrient equilibrium in organic fertilizers rarely matches the equilibrium required by crops. For instance, cereals usually have an N/P/K requirement around 8:1:5 (if the straw is exported out of the farm), so meeting the crop N requirement with cow manure (average 3.5:1:3) implies an excess application of P. This is another reason for complementing organic with mineral fertilizers.

In organic or ecological farming systems, only natural (mostly organic) fertilizers are allowed. This often leads to reduced yields due to the limited supply of nutrients, although this may be compensated by the higher prices of organic crops.

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Nitrogen Fertilization I: The Nitrogen Balance

26

Miguel Quemada, Antonio Delgado, Luciano Mateos, and Francisco J. Villalobos

Abstract

Nitrogen is usually the most limiting nutrient for plants in agroecosystems. The natural input of N in agricultural soils comes from the atmosphere by N fixation which implies the transformation of gaseous N_2 in NH_4^+. Fixation is mainly a biological process, and the most relevant organisms involved are *Rhizobium* bacteria that infect the roots of legumes. Organic N becomes inorganic through mineralization, and then inorganic N is absorbed by plants. Soil microorganisms may capture temporarily inorganic N when residue with high C/N ratio decomposes (immobilization). Ammonium in the soil is converted to NO_3^- through nitrification, a microbial process greatly reduced in waterlogged soils. In the latter, denitrification generates gaseous N forms that are lost. Nitrate leaching is proportional to deep percolation and to nitrate concentration in the soil solution. A Leaching Index may be calculated as a function of rainfall and soil type to quantify the risk of leaching.

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26.1 Introduction

The N source for terrestrial plants is the N_2 gas which constitutes 78% of the atmosphere. As plants cannot convert N_2 to organic molecules, it has to be transformed first following one of the following paths:

1. Fixation by microorganisms living in symbiosis with the roots of legumes.
2. Fixation by free-living soil microorganisms.
3. Fixation as oxides by electrical discharges in the atmosphere.
4. Fixation as NH_3 and further transformation to NO_3^-, urea, or other fertilizers by manufacturers.

The contribution of atmospheric N_2 is in dynamic equilibrium with the forms fixed in the soil. While various processes fix N_2, other chemical and microbiological processes release N_2 to the atmosphere (Fig. 26.1). Except for industrial fixation or combustion, all other processes are natural but can be altered by soil and crop management.

Understanding the N cycle in the soil-crop system is the key to optimizing nitrogen fertilizer management, maximizing profitability, and minimizing negative environmental impacts on water (nitrate pollution) and the atmosphere (emission of greenhouse gases and NH_3). The main sources of N for crops are inorganic and organic N fertilizers and symbiotic N_2 fixation.

Although N_2 in the atmosphere can be considered an infinite source of N for fertilizer production, this industrial process requires huge amounts of energy. Thus, N for industrial production of mineral fertilizers cannot be considered a renewable

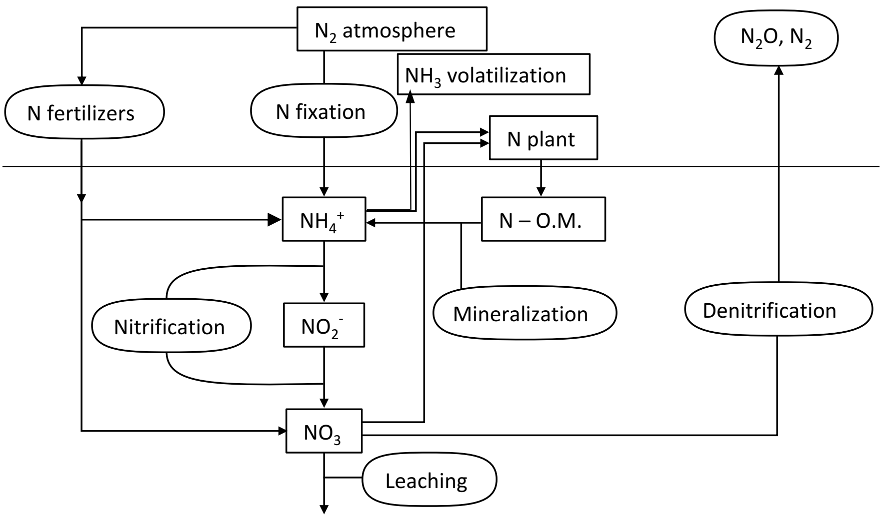


Fig. 26.1 Nitrogen cycle

resource since it depends on nonrenewable energy. Efforts to use renewable energies to produce ‘green ammonia’ and decarbonize the fertilizer industry are currently on going.

26.2 N Forms in the Soil

The soil N concentration ranges from 0.02% (subsoil) to 2.5% (peat) with a typical range 0.03–0.4%. This N can be inorganic or organic, with the latter being predominant.

Organic N appears as proteins, amino acids, amino sugars, and other N compounds. Inorganic forms include ammonium (NH_4^+), nitrite (NO_2^-), nitrate (NO_3^-), nitrous oxide (N_2O), nitric oxide (NO), and N_2. The first three are important for soil fertility and derive from fertilizers or organic matter mineralization. The other three are gases lost in denitrification.

26.3 N Forms Absorbed by Plants

Plants absorb NH_4^+ and NO_3^- although having both often improves plant nutrition. The nitrate concentration is generally higher than that of ammonium and is in the soil solution, so it reaches the roots with the water flow (mass transport flow). Plant preference for one or the other form of inorganic N depends on the species, plant age, environmental conditions, and other factors. For instance, cereals and beets absorb either NO_3^- or NH_4^+. The *Solanaceae* (potato, tobacco, tomato) benefit from a high NO_3^-/NH_4^+ ratio in the soil solution. Species adapted to acid soils are used to low NO_3^-/NH_4^+ ratio, as NH_4^+ tends to accumulate due to nitrification slowing down.

In terms of energy, NO_3^- uptake is less efficient than that of NH_4^+, as the nitrate has to be reduced to ammonium before the N becomes part of the organic compounds. However, NH_4^+ absorption leads to acidification of the rhizosphere and decreases the absorption of Ca^{2+}, Mg^{2+}, and K^+, while it increases the absorption of $H_2PO_4^-$, SO_4^{2-}, and Cl^-. On the other hand, NO_3^- uptake is co-transported with H^+ contributing to rhizosphere and apoplast alkalinization. This effect can decrease Fe uptake. Small amounts of organic N are absorbed by plants mainly as amino acids, but the contribution to the plant N nutrition is meagre.

26.4 Symbiotic N Fixation

Symbiotic N fixation involves the reduction of atmospheric N_2 to NH_3 by an enzyme (*nitrogenase*) in aerobic microorganisms (mainly *Rhizobium* bacteria) that form nodules on the legume roots. This mechanism has been the principal source of N for agriculture until the appearance of cheap synthetic N fertilizers.

The *Rhizobium*-legume symbiosis is specific, i.e., each *Rhizobium* species will only infect a type of legume. Therefore, it is often necessary to inoculate the seeds with the adequate species or strain of *Rhizobium*.

The mere presence of nodules on the roots does not imply fixation activity. For example, in alfalfa, active nodules are large (2–4 × 4–8 mm) and grouped in the primary roots. The red color inside the nodules denotes the presence of leghemoglobin, an N and O carrier required for the activity of the *Rhizobium*.

The factors that affect the rate of N fixation by *Rhizobium* are pH, the concentration of nutrients in the soil, photosynthesis, climate, and overall crop management. Soil acidity restricts the presence and activity of *Rhizobium*, although the different species differ in sensitivity. For example, pH below 6 reduces nodulation of *Rhizobium meliloti* in alfalfa, while pH between 5 and 7 hardly affects *R. trifoli* in clover.

An excess of NO_3^- in the soil reduces nitrogenase activity and thus N fixation. The maximum fixation occurs when with little inorganic N in the soil. However, small doses of N fertilizer may ensure good seedling establishment of legumes, while the *Rhizobium* nodulation is accomplished. Applications of N may be also necessary at the beginning of the spring, when the demand for N by the plant exceeds the supply by *Rhizobium* due, for example, to low temperatures. In some legumes (i.e., beans in certain soils), fixation is so poor that it is necessary to apply N fertilizer systematically.

In general, high photosynthetic activity is required for high N fixation, so water stress, low temperature, or any other stress reducing photosynthesis will also decrease N_2 symbiotic fixation.

26.5 Quantifying N Fixation

Perennial crops fix between 110 and 225 kg/ha/year, although the values may be above or below that range depending on environmental conditions. Annual legumes fix between 50 and 110 kg/ha/year.

As a first approximation, the amount of N fixed by a legume crop can be estimated as:

$$N_{\text{fixed}} = \left(1 + f_{NR}\right)\, Y \left(NC_h + \frac{1-HI}{HI} NC_r\right) F_{NBF} \tag{26.1}$$

where f_{NR} is the ratio of N in roots and N in shoots, Y is yield, NC_h and NC_r are the N concentrations in the harvested product and the residues, respectively, HI is harvest index, and F_{NBF} is the fraction of N resulting from biological fixation. The value of f_{NR} lies between 0.05 and 0.25. F_{NBF} depends on the availability of soil N, which in turn is related to fertilizer application rate and the type of legume. When soil N availability is low, most crop N comes from fixation (Table 26.2). If the soil organic matter content is high, the lower values of the proposed intervals should be used. On the other hand, the N concentrations in the harvested product and the residues may be measured or taken from Table 26.1.

Table 26.1 N concentration in different crop species

Crop species	DM%	N min	N max	N typical		DM%	N min	N max	N typical
Alfalfa (hay)	85.0	2.80	3.80	3.30					
Apple	18	0.25	0.45	0.35					
Barley (2-row)	88.5	1.50	1.80	1.60	Straw	90	0.58	0.88	0.70
Bean (*Phaseolus*) (dry seed)	89	3.50	4.50	4.00	Straw	89	1.10	1.40	1.20
Cotton	91	2.32	2.75	2.53	Residues	92.5	0.90	1.00	0.98
Grapes (wine)	19	0.50	0.60	0.57					
Lettuce	6	4.00	4.40	4.27					
Maize (silage)	30	1.10	1.45	1.25					
Millet	90			2.20	Residues	91.5			0.80
Olives (60% canopy cover)*	50	0.20	0.40	0.30	Vegetative	70	1.00	2.00	1.50
Orange	18	1.00	1.40	1.20					
Palm trees	79			1.25					
Peach	12	0.80	1.20	1.00					
Peas (dry harvest)	90	4.00	4.30	4.20	Straw	88.5	1.20	1.40	1.30
Potato	23.5	1.20	1.90	1.60	Residues	51	2.00	2.40	2.20
Rapeseed, canola	91	3.40	4.30	3.90	Residues	82.5	0.55	0.90	0.80
Rice	94			1.33					
Sorghum (grain)	87.5	1.45	2.00	1.90	Residues	92	0.60	0.80	0.70
Soybeans	87.5	6.10	6.90	6.50	Residues	89	1.00	1.00	0.85
Sugar beet	21	0.90	1.10	1.05	Residues	18	1.80	2.80	2.30
Sugarcane (virgin)	25			0.13		26			0.41
Sunflower	91.5	2.20	3.20	2.95	Residues	87	0.40	1.10	0.80
Tomato	6	2.30	3.10	2.60	Residues	20			1.80
Winter wheat	87.5	1.85	2.30	2.10	Straw	90.5	0.40	0.85	0.65

Most values in the literature fall in the range defined by maximum (N max) and minimum (N min) concentrations, shown when available. Also, the dry matter content (% over fresh mass) is indicated

Example 26.1

The expected yield of an alfalfa crop is 8 t/ha (15% moisture) on a soil with 1% organic matter. Initial soil inorganic N is 40 kg/ha and expected N mineralization during the growing season is 35 kg N/ha. We assume that *HI* is 0.9 and that residues have the same N concentration as the harvested part.

In Table 26.1 we find that the N concentration of alfalfa is 3.3 kg N/100 kg dry matter. As water content is 15%, harvested dry matter biomass is 6800 kg dry matter/ha.

Available N in the soil will be the sum of initial inorganic N (40 kg/ha) and expected mineralized N (35 kg/ha):

40 kg N/ha + 35 kg N/ha = 75 kg N/ha.

(continued)

Example 26.1 (continued)

Table 26.2 Percent of crop N obtained from symbiotic fixation in legumes as a function of legume type, % soil organic matter, and soil inorganic N

		Available inorganic N (kg/ha)			
% O.M.	Type	55	55–110	110–225	>225
>3	Annuals	70	50	30	5
	Perennials	80	60	50	10
<3	Annuals	95	80	60	40
	Perennials	95	90	80	50

Adapted from Meisinger and Randall (1991)

So we are in the 55–110 kg/ha interval of Table 26.2, implying that 60–90% of N comes from fixation. As soil organic matter content is low (1%), we use the upper limit (0.90). We also take f_{NR} = 0.2, which means that the total fixed N is:

$$N_{\text{fixed}} = \left(1 + f_{NR}\right) Y \left(NC_h + \frac{1-HI}{HI} NC_r \right) F_{NBF}$$
$$= \left(1 + 0.2\right) 6800 \left(0.033 + \frac{0.1}{0.9} 0.033 \right) 0.9 = 269 \, \text{kg N/ha}$$

26.6 Transformations of N in the Soil

26.6.1 Mineralization and Immobilization

Dead plant materials (senesced leaves, residues left after harvest) decompose, i.e., the structure breaks into unrecognizable organic matter (Chap. 30). This is performed by bacteria and fungi that get energy from the respiration of the residue's C. The decomposition rate increases with temperature up to 32–35 °C and with water content up to field capacity, so residues decompose faster when buried into the soil. In general, decomposition rate is proportional to N concentration in the residue, which explains why legume residues decompose faster than those of cereals.

N mineralization is the conversion of organic N to NH_4^+. After the decomposition of plant residues, N mineralization occurs in two stages, aminization (breaking up of proteins to amino acids, amines, and urea, with release of CO_2) and ammonization (conversion of amines and amino acids to NH_4^+). This transformation is performed by heterotrophic microorganisms (fungi and bacteria) and is based on aerobic and, to a lesser extent, anaerobic respiration.

Fig. 26.2 Response of N fixation, N mineralization, and nitrification to soil water content

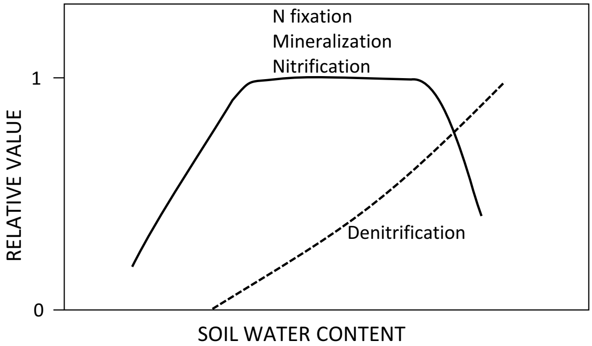
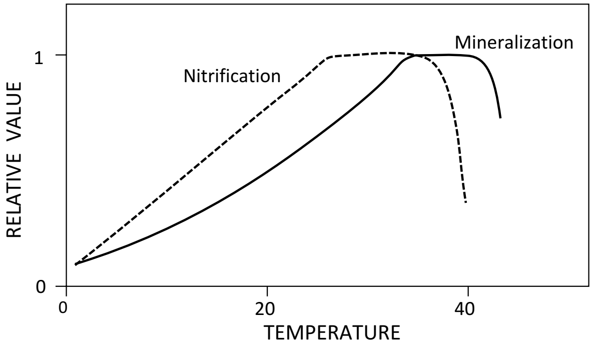


Fig. 26.3 Response of N mineralization and nitrification to soil temperature



Mineralization is favored by high soil water content, without reaching saturation to ensure oxygen supply (Fig. 26.2). The decomposition does occur in waterlogged conditions but at a lower rate. The temperature coefficient, Q_{10}, for mineralization is 2 in the range of 5–35 °C, i.e., the mineralization rate is doubled by raising the temperature to 10 °C. The optimum temperature is around 35 °C (Fig. 26.3).

Immobilization is the conversion of inorganic N (NH_4^+ and NO_3^-) to organic N being basically the reverse of mineralization. If decaying organic matter contains little N relative to C, the microorganisms use (immobilize) soil mineral N. Microorganisms require a C/N ratio of about 8:1, therefore the soil inorganic N may decrease rapidly during waste decomposition, and the crop may experience N deficiency. When the residue with low N content is finally decomposed, C availability as an energy source for microbes is decreased, so their activity stops.

The predominant process (mineralization or immobilization) depends on the C/N ratio of decomposing organic matter. At the start of the decomposition of organic residues, there is a rapidly growing population of heterotrophic microorganisms which is detected in the increased release of CO_2. If the C/N is greater than 30, immobilization occurs. As decomposition proceeds, the C source decreases, and so does the C/N ratio, until the microorganisms begin to die. Finally, a new equilibrium is reached that starts with the mineralization of N and ends with a higher inorganic

N level and C/N ratio of around 10. The time required depends on the amount of added organic residue, the availability of inorganic N, the resistance of the residue to be decomposed (i.e., its lignin content), and the temperature and soil water content.

Example 26.2
After the harvest of a cereal, we incorporate 3000 kg/ha of straw with 45% C and 0.75% N (C/N = 60) to the soil. The total amounts of C and N are:

3000 kg/ha × 0.45 = 1350 kg C/ha
3000 kg/ha × 0.0075 = 22.5 kg N/ha.

We assume that 35% of C will be used in the growth of microorganisms while 65% of C is lost as respired CO2. The amount of C accumulated in the microbial biomass will be:

1350 kg C/ha × 0.35 = 472.5 kg C/ha

The C/N ratio of the microorganisms is 8, so N accumulated will be:

472.5 kg/ha / 8 = 59 kg N/ha

And the amount of immobilized N is:

59 kg N/ha − 22.5 kg N/ha =36.5 kg N/ha

The C/N in the surface layer of natural soils is between 8 and 12, with 10 being the most common value. These soils have a relatively stable microorganism population and deposition of organic residues (and thus mineralization) is also constant. If this soil is tilled, decomposition and mineralization will speed up, which will decrease the soil organic matter.

Example 26.3
A soil has 2% organic matter in its surface layer (0.20 m) and a bulk density of 1.3 t/m3. This organic matter has C/N = 10 and N concentration of 5%. Therefore the total amount of organic N in this layer is:

1.3 103 kg soil/m3 soil × 0.20 m x 104 m2/ha × 0.02 kg O.M./kg soil × 0.05 kg N/kg O.M. = 2600 kg organic N/ha

If mineralization rate is 1%/year, the amount of inorganic N released will be:

2600 kg organic N/ha × 0.01 kg N/kg organic N/year = 26 kg N/ha/year.

26.6.2 Nitrification

The NH_4^+ transformation to NO_3^-, called nitrification, is performed by bacteria (*Nitrosomonas* and *Nitrobacter*) in two stages:

$NH_4^+ + O_2 > NO_2^- + H_2O + H^+$ (*Nitrosomonas*).
$NO_2^- + O_2 > NO_3^-$ (*Nitrobacter*).

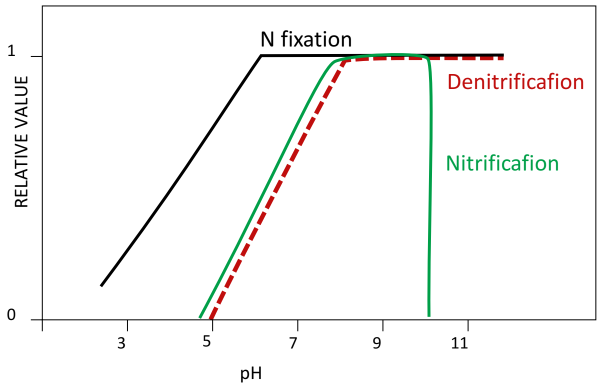
Both *Nitrosomonas* and *Nitrobacter* are autotrophic bacteria, although some heterotrophic organisms are also involved in both processes. The second stage is faster than the first, which prevents the accumulation of NO_2^-, which is toxic to plants.

The main factor affecting the nitrification rate is the substrate concentration (NH_4^+) that depends on fertilization and mineralization. The need for oxygen implies that a good aeration is required (optimum O_2 concentration is 20%), so waterlogging is undesirable. However, nitrification is high with relatively high water content and is maximized when 80–90% of the soil pores are full of water. The optimum conditions for nitrification are temperature between 25 and 35 °C and neutral to slightly alkaline soil pH, but it can occur in the range of 4.5–10 (Fig. 26.4). Therefore, lime application to acid soils will increase nitrification and mineralization and improve N supply to crops.

The product of nitrification (NO_3^-) is very soluble in water and is hardly adsorbed by soil colloids, so it may be lost by leaching.

Nitrogen fertilizer management has to take into account the facts stated above. In regions with low soil temperatures and/or low winter rainfall, NH_4^+ applications in the fall, before planting, save time and money with little risk of nitrate leaching. If air temperatures are below 4–5 °C or mean soil temperature is below 10 °C, the preplant applications of ammonium in the autumn are efficient since nitrification rates are low. If soil temperature is above 10 ºC, care should be taken to avoid soil NO3- accumulation and losses if the nitrate is not up taken by a vegetative cover.

Fig. 26.4 Response of N fixation, nitrification, and denitrification to soil pH



Nitrosomonas activity is very sensitive to many compounds, so the fertilizer industry has developed nitrification inhibitors that are blended into the fertilizer granules or added to manures and slurries. The inhibitors slow down the nitrification process, controlling nitrate accumulation in the soil and thus nitrate losses.

26.6.3 Denitrification

Denitrification is not the opposite of nitrification but the reduction of nitrate into volatile N compounds. When soil oxygen availability is reduced because of high water content, soil compaction, or the application of easily decomposable organic matter, the rate of denitrification increases. Anaerobic micro-zones containing still a source of labile C appear, and a broad number of microorganisms (mainly bacteria such as *Pseudomonas*, *Bacillus*, and *Paracoccus* but also some fungi) are able to use NO_3^- and NO_2^- as electron acceptors for oxidizing organic C releasing gaseous N forms to the atmosphere:

$$NO_3^- > NO_2^- > N_2O > NO > N_2$$

The incomplete reduction promotes the emission of N_2O, a very reactive greenhouse gas that also favors ozone destruction. The reaction is fast and is shown by peaks of N_2O emission after application of organic or synthetic fertilizers. Denitrification was thought to occur only under waterlogging, but more recent research has shown that it's the main N loss to the atmosphere under a broad range of environmental conditions.

Soil water content is one of the main factors affecting denitrification. Waterlogging prevents the O_2 diffusion and thus enhances denitrification (Table 26.3). Because of that, the highest denitrification N losses from agriculture have being reported in rice paddy fields, with losses of up to 16 kg N/ha in the day after soil saturation.

Table 26.3 Denitrification losses (% of inorganic N) for different cases and soil types as a function of soil organic matter content

		Arid and semiarid rainfed crops					Irrigated crops or humid areas				
		Rate of drainage									
Case	% O.M.	Very high	High	Medium	Low	Very low	Very high	High	Medium	Low	Very low
N from	<2	1	1.5	3	5	10	2	3	6	10	20
fertilizer.	2–5	2	2	4	7.5	12.5	4	4	8	15	25
Tilled	>5	3	3	6	10	15	6	6	12	20	30
N from	<2	1	1.5	3	5	10	2	3	6	10	20
fertilizer.	2–5	2	2	4	7.5	12.5	4	4	8	15	25
No tillage	>5	3	3	6	10	15	6	6	12	20	30
N from	<2	2	3	6	10	20	4	6	12	20	40
manure.	2–5	4	4	8	15	25	8	8	16	30	50
Tilled ([a])	>5	6	6	12	20	30	12	12	24	40	60

[a]The same values apply to N from fertilizer in tilled soils when a compacted impervious layer is present below the plow depth

Adapted from Meisinger and Randall (1991) and Delgado et al. (2008). Ecol. Engin, 32:108–120

A strategy to control losses in paddy fields is the application of urea or ammonium-based fertilizers. The N will remain in the soil as NH_4^+ and only small amounts will be transformed to NO_3^- close to the roots where oxygen is available. Therefore, denitrification will be limited by lack of substrate. In well-aerated soils, however, nitrification rate is high and denitrification will only occur in anaerobic micro-zones of the soil (e.g., cattle dung). The combination of inorganic N fertilizers with manure application may also promote denitrification. Recently, a leak on the first stage of the nitrification has been identified as a source of N_2O (between 0.03 and 1% of the oxidized N is lost to the atmosphere), adding uncertainty to gaseous emissions in well-aerated soil. Quantification of denitrification is complicated as it is hard to tell apart from the atmospheric N_2. Table 26.3 shows the effect of organic matter on denitrification rate for different soil types.

Many of the bacteria responsible for denitrification are very sensitive to acidity (Fig. 26.4). Thus, in soils with pH below 5, denitrification is negligible, while it can be high in basic soils. However, in soils with pH > 7, most of the N oxides are

Table 26.4 Ammonia volatilization loss (% of N applied) for soils as a function of soil pH, *CEC*, and climatic conditions

			CEC > 250 meq/kg			*CEC* < 100 meq/kg[a]		
			Rainfall after application and climate type					
			>12 mm in 2 days	<6 mm in 7 days	No rain in 7 d	>12 mm in 2 days	<6 mm in 7 days	No rain in 7 d
	N source	Application method	Humid	Subhumid	Dry	Humid	Subhumid	Dry
pH > 7	Urea	Surface broadcast	0	2	2	20	30	40
		Surface localized	0	2	2	15	20	30
		Incorporated	0	0	0	10	10	10
	Ammonium sulfate	Surface broadcast	0	2	5	40	50	60
		Incorporated	0	0	0	10	20	30
	Ammonium nitrate	Surface broadcast	0	2	5	20	25	30
		Incorporated	0	0	0	10	15	20
	Anhydrous ammonia	Injected	0	0	0	2	3	5
pH < 7	Urea	Surface broadcast	0	5	5	5	30	40
		Surface localized	0	2	2	5	20	30
		Incorporated	0	0	0	0	2	2
	Ammonium sulfate	Surface broadcast	0	0	0	0	2	2
		Incorporated	0	0	0	0	2	2
	Ammonium nitrate	Surface broadcast	0	0	0	0	2	2
		Incorporated	0	0	0	0	2	2
	Anhydrous ammonia	Injected	0	0	0	0	2	2

[a]The same values apply in no tilled soils with more than 50% surface residue cover
Adapted from Meisinger and Randall (1991)

reduced to N_2, whereas in acid soils most of the N loss occurs as N_2O. Moreover, the denitrification is very sensitive to temperature and increases rapidly as soil temperature goes from 2 °C to 60 °C, above which it is inhibited.

26.6.4 Ammonia Volatilization

The ammonium ion in solution is in equilibrium with ammonia (NH_3), which is volatile. Ammonia volatilization occurs naturally in soils but at a slow rate. However, volatilization losses of N fertilizer can be very important, depending on the type of fertilizer, application form, the cation exchange capacity, soil pH, and climatic factors (Table 26.4). The set of conditions with higher ammonia losses would be the surface application of urea on a soil with basic pH and low *CEC* under dry conditions. Volatilization risk can also be high with surface application of manures since a relevant fraction of N can be ammonium. To reduce ammonia volatilization, incorporation of ammonium fertilizers/urea/manure is recommended by tillage or irrigation within 2 days of fertilization.

The general ranges of volatilization loss of ammonia fertilizer are 2–50% (pH > 7) and 0–25% (pH < 7). The NH_3/NH_4^+ equilibrium is pH dependent. In acidic and neutral conditions, the equilibrium is shifted to NH_4^+ which explains the lower losses.

26.7 Crop N Uptake

Nitrogen is an essential nutrient for crops. It is a constituent of proteins, nucleic acids, chlorophyll, and other intermediate metabolites. If the N supply is limited, crop growth is reduced and so is intercepted radiation. A more severe N deficiency leads to lower radiation-use efficiency. Therefore, N availability will limit biomass accumulation and yield. There is an optimum N concentration range, above which excess N can decrease yield. For instance, in indeterminate crops, high N concentration promotes vegetative growth at the expense of reproductive growth which results in a lower harvest index. At a global level, N is the second limiting factor (after water) in crop production.

Nitrogen uptake is parallel to biomass accumulation, so it shows a typical sigmoid curve with an initial exponential increase followed by a fast linear accumulation phase. In this rapid phase, accumulation may be up to 3–5 kg N/ha/day. The concentrations of N in the different organs are high when the plants are young and decrease with age. Therefore, the crop response to N depends not only on the amount absorbed but also on the translocation capacity to the growing organs (and finally to the grain or harvestable part).

In most crops, N concentration decreases with increasing aboveground biomass, and the decline is described by a negative power function called the nitrogen dilution curve (Fig. 26.5). The critical nitrogen dilution curve has been developed for

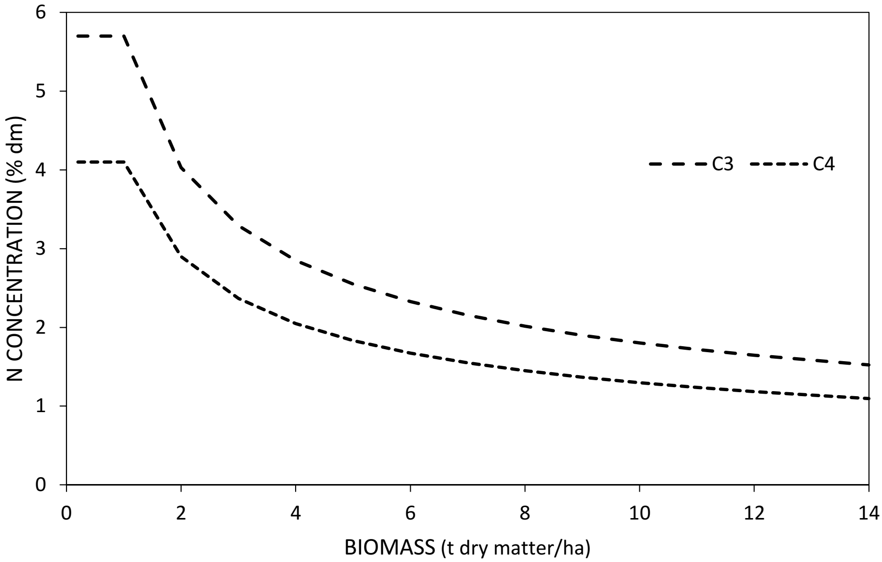


Fig. 26.5 Critical nitrogen concentration curve for various crops. (Adapted from Gastal and Lemaire, J Exper Bot 53: 789–799, 2002)

many species ($NC_{\text{crit}} = a\,B^{-b}$) based on datasets of N concentration and biomass (B) under different fertilization regimes. The critical N concentration of a crop (NC_{crit}) is defined as the minimum crop N concentration (%) allowing maximum biomass production. The coefficient a is crop N concentration when biomass equals 1 t/ha, and b is a dimensionless parameter governing the slope of the relationship. The critical nitrogen dilution curve can be used to determine the crop N status: if crop N concentration is close to the NC_{crit} corresponding to the current biomass, it indicates that N is not limiting crop growth, while when it is below, it indicates a N deficiency. The ratio between the actual crop N concentration and the NC_{crit} for a given biomass is known as the N nutrition index (NNI):

$$NNI = \frac{NC_{\text{actual}}}{NC_{\text{crit}}} = \frac{NC_{\text{actual}}}{a\,B^{-b}} \qquad (26.2)$$

where B is crop biomass (t/ha). In general, C4 species have a lower NC_{crit} for a given biomass than C3 species, presumably related to a lower content of photosynthetic proteins. The dilution curves are generally accepted because of their simplicity for modeling crop growth during vegetative stages; however, when other factors different from N limit growth (i.e., drought, disease), the curve may depart greatly from the model, and so the adoption of crop biomass as the independent variable may be misleading. The actual N concentration for a given species depends primarily on the distribution of dry matter among leaves, stems, and reproductive structures.

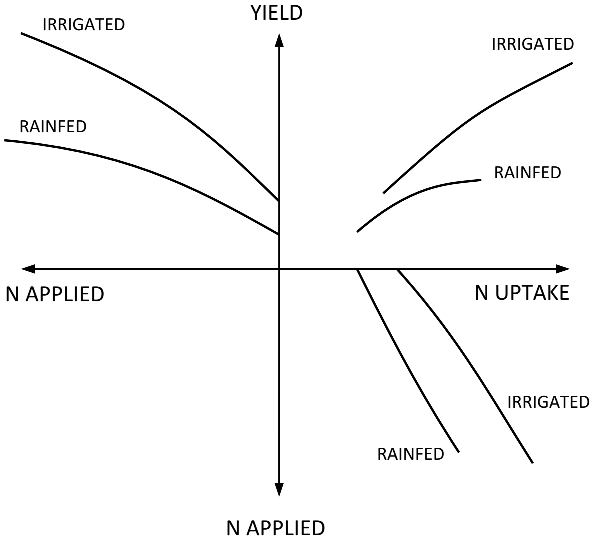


Fig. 26.6 Response of sunflower yield to N applied and N uptake

When crops start, they are mainly composed of young leaves, which have a high N content. Later on, the fraction of stems and other structures increases, and leaves may lose part of their N which explains that the ratio of crop N and biomass will tend to decrease with time. Other techniques based on crop N status have been developed for fertilizer recommendation and will be discussed in Chap. 27.

The relationship between yield and N uptake is generally linear until the maximum yield is reached. From that point, if there is N available in the soil, absorption continues, but it does not result in a higher yield. This limit depends on environmental conditions and crop management. Figure 26.6 shows a linear relationship between yield and N uptake for an experiment conducted with sunflower crops in Córdoba with different levels of irrigation and N fertilizer. The maximum yields, where the yield-N uptake relation saturates, increased with irrigation levels. Therefore, despite the linear relationship between yield and N uptake when no other factor is limiting, it is important to set the objective yield to define the maximum level of N uptake.

For a set of environmental conditions, the relationship between yield and applied N is curvilinear (Fig. 26.6). Therefore, the agronomic efficiency of the N fertilizer, i.e., the yield per unit of applied N, decreases with increasing the dose. When this dose reaches a certain value, an increase in fertilizer does not result in a yield increase, and in some cases, it may even be detrimental for crop growth or quality. Furthermore, the amount of residual soil N will be greater, which increases the risk of nitrate leaching.

The yield response to N applied depends on the initial availability of soil N and the mineralization potential during the season, besides the production potential of the crop. Thus, in very fertile soils, the crop may not respond to the application of N or the response may be negative. If another factor (i.e., water) is limiting, the high N input will not bring yield increases. Figure 26.6 illustrates this behavior in the sunflower experiment mentioned earlier. As the irrigation amount was higher, so were yields for any dose of N. The response to applied N was also higher under irrigation, at least for low N doses.

As a framework for understanding the responses to fertilization, de Wit proposed to represent in different quadrants the curves of N uptake and yield in response to the N application (Fig. 26.6). In the first quadrant yield is plotted as a function of N applied for different irrigation regimes of the sunflower experiment. This yield corresponds to an amount of N absorbed (second upper quadrant), which in turn corresponds to a rate of N application (second lower quadrant). Each line of the lower quadrant is characterized by its slope and its intercept. We see that both the intercept and the slope of the N uptake-N applied curve increased with applied irrigation. This means that irrigation increased N availability because either NO_3^- was applied in irrigation water, the mineralization rate was enhanced by irrigation, or N uptake was facilitated in a wetter soil. Furthermore, as the level of irrigation increased, the curves of N uptake did not show saturation, i.e., a ceiling of N absorption was not reached. Water and N are the main limiting factors in many irrigated systems, so a combined management should be followed for successful crop performance.

In any case, the criterion for choosing the dose of N fertilizer should be economical, i.e., the optimal dose will be that leading to maximum profit. This dose will be lower than that required for maximum yield and may be calculated as the point where the marginal profit of fertilization practice is zero.

The results of the sunflower experiment mentioned above contrast with other previous experiments on sunflower fertilization in Córdoba, which did not show a response to N fertilization. In the experiment mentioned, the soil had been "cleaned" of mineral N with a previous unfertilized cereal crop. Initial fertility conditions and other environmental factors (i.e., water supply) greatly affect crop responses to N application. This is why production functions of yield versus N applied cannot be extrapolated to other situations. To emphasize this concept, results from a rainfed experiment conducted in three adjacent fields in Navarra (Spain) showing the response of wheat to increasing rates of N fertilizer application are presented in Fig. 26.7. No yield response was observed when high initial inorganic N (>140 kg N/ha) was present in the soil (top 0.9 m) before planting, whereas yield response increased for the medium (90 kg N/ha) and low (30 kg N/ha) inorganic N fields. Because of that, the determination of available N in soil samples taken before planting or before side-dress applications is a recommended practice to avoid overfertilization in many regions.

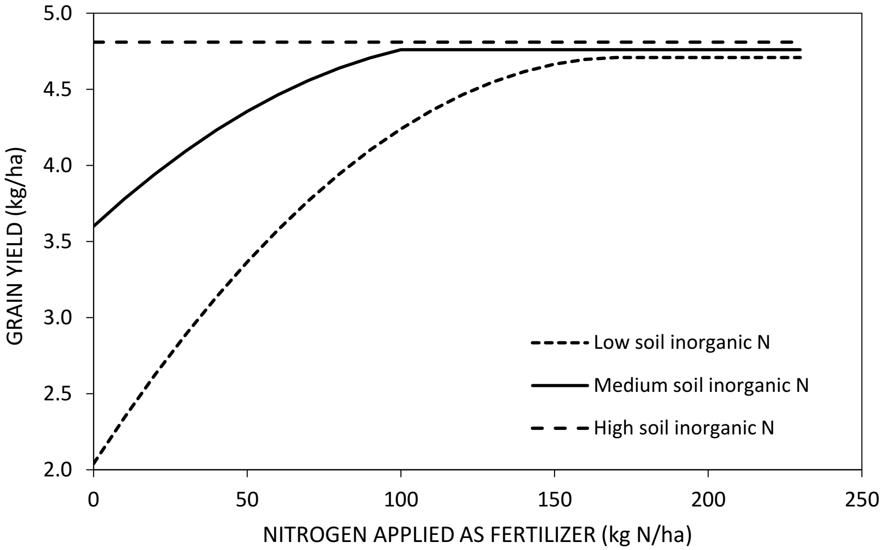


Fig. 26.7 Wheat response to N fertilizer application based on the soil inorganic N content determined in the upper 0.9 m of soil

26.8 Nitrate Leaching

The consequences of N losses from agricultural systems to water bodies are a major social concern in developed countries, with special attention to aquifer contamination by nitrate and excessive N availability in lakes and estuaries. Potential harmful effects of nitrate on human health (cyanosis, risk of cancer) have led to the establishment of maximum allowable concentrations of nitrate in drinking water of 50 g NO_3^- m^{-3} (World Health Organization). The EU and the USA have identified regions affected by excessive nitrate contamination and passed legislation to prevent it (i.e., the EU Nitrate Directive which is part of the EU Water Framework Directive (2000/60/EC); USA Congress, 1978). As the main contributor to nitrate pollution is agriculture, restrictions to the use of N fertilizers and agricultural practices that may enhance nitrate leaching have been implemented in many countries.

Nitrate leaching occurs as soil water containing dissolved nitrate drains below the root zone. Therefore leaching will be proportional to deep percolation and to nitrate concentration in the soil solution. Deep percolation will depend on the components of the water balance (rain and irrigation), the water retention of the soil, and its hydraulic conductivity. Soils with high water retention capacity and low conductivity (e.g., fine-textured) will have therefore a lower percolation and leaching potential. Apart from soil characteristics and climatic conditions, fallow periods between successive crops in the rotation are the most dangerous for leaching. Nitrate left in the soil at harvest plus that originated from mineralization and nitrification during the fallow period remains available for leaching during drainage episodes after heavy rains. The absence of a crop extracting water and nitrate is ideal for keeping a high risk of leaching (high water content, high nitrate concentration). This has led to the introduction of "catch" crops to fill the gap of fallow periods as they reduce water content and absorb inorganic N which is thus fixed in organic form and can be incorporated again into soil with crop residues. Other possible measures for reducing leaching would be earlier plantings (to reduce fallow periods), reducing basal N applications in the autumn, or using slow-release fertilizers (Chap. 25). In irrigated systems, it is extremely important to follow irrigation schedules based on the water balance with corrections at the end of the season to deplete soil water as much as possible.

To evaluate the risk of leaching, we may use the Leaching Index (*LI*; mm). It is an estimate of the percolation below a soil depth of 1 m and was proposed by the USDA (Williams & Kissel, 1991). The *LI* is calculated as the product of a Percolation Index (*PI*) and a Seasonal Index (*SI*):

$$LI = PI \cdot SI \tag{26.3}$$

The Percolation Index is calculated as:

$$PI = \frac{\left(P - {}^{10160}\!/_{CN'} + 101.6\right)^2}{P + {}^{15240}\!/_{CN'} - 152.4} \qquad if\ P - {}^{10160}\!/_{CN'} + 101.6 > 0 \tag{26.4}$$

where *P* is annual rainfall (mm) and *CN'* is a modified curve number with values 28, 21, 17, and 15 for hydrologic groups A, B, C, and D, respectively (Chap. 8). If the condition stated in Eq. 26.4 is not met, PI = 0.

The Seasonal Index represents the concentration of rainfall during the winter period:

$$SI = \left(\frac{2P_w}{P}\right)^{1/3} \tag{26.5}$$

where P_w is total rainfall (mm) during autumn and winter (1 October–31 March in N latitudes, 1 April–30 September in S latitudes).

The Leaching Index is only indicative of potential losses by leaching but not of actual losses. If the *LI* is high, adequate crop and soil management may lead to low actual leaching. On the contrary, with low *LI* we may expect low actual leaching independently of actual management. In other words, measures to reduce the concentration of nitrate will be more effective in reducing leaching in locations with high *LI*.

Example 26.4

Let's calculate the *LI* for two locations, Adelaide (Australia) and Dublin (Ireland), for a soil of hydrologic class A (*CN'* = 28) using the monthly rainfall shown below:

Month	1	2	3	4	5	6	7	8	9	10	11	12	Year
Adelaide, Australia	19	20	22	38	57	50	67	51	40	37	23	24	448
Dublin, Ireland	69	50	54	51	55	56	50	71	66	70	64	76	732

Applying Eq. 26.4 to Adelaide (P = 448 mm, Pw = 303), we obtain PI = 41.5 mm and SI = 1.1 (Eq. 26.5), so LI = 45.9 mm.

For Dublin (P = 732 mm, Pw = 383 mm), the PI = 197 mm and SI = 1.02, so LI = 200 mm. The risk of leaching is much higher in Dublin than in Adelaide.

We will now illustrate how we can convert LI values to approximate leaching values. Let's assume that the soil has water contents at field capacity and saturation, $\theta_{FC} = 0.25\ m^3m^{-3}$ and $\theta_{SAT} = 0.45\ m^3m^{-3}$. We also assume that during percolation the soil water content is the average of those values, i.e., $0.35\ m^3m^{-3}$. We can compare situations of low and high nitrate content at the start of the winter period (e.g., 25 versus 100 kg N/ha in 1 m depth) by assuming that all percolation occurs during winter. The N leached can be calculated as:

$$N_{\text{leached}} = N_{\text{init}}\left[1-\exp\left(-\frac{LI}{Z\,\theta_{\text{mean}}}\right)\right] \tag{26.6}$$

where N_{init} is the initial soil N content (kg N/ha), Z is soil depth (mm), and θ_{mean} is the average water content during percolation ($0.35\ m^3m^{-3}$ in this soil). Applying this equation we deduce that leaching could be between 3 and 12 kg N/ha in Adelaide and between 11 and 44 kg N/ha in Dublin. In the latter, the reduction in leaching by reducing soil N would be 33 kg N/ha, while in the former the reduction would only be 9 kg N/ha.

26.9 Soil Acidification Induced by N Fertilization

Nitrogen fertilizers can contribute to soil acidification directly due to the ions added to the soil and indirectly via atmospheric deposition. At a global scale, the increase in N fertilizer use in the last century has produced a significant acceleration of soil acidification. This issue is particularly relevant in soils with pH < 7 in which increasing acidity may impair plant growth and soil health, resulting in a rise of limestone requirements to neutralize the effect.

Ammonium-based fertilizers, such as urea or ammonium sulfate, are oxidized in the soil forming nitrate (nitrification) and releasing H^+ that lowers the soil pH. Similarly, organic fertilizers such as manures or slurries can reduce soil pH by oxidation of the ammonium added or by the acids released during the decomposition of the organic compounds. The increased H^+ concentration resulting from ammonium oxidation is balanced by the crop uptake of NO_3^- which is coupled to that of H^+. Net acidification occurs when nitrate is not absorbed by crops but lost through leaching. Therefore, in soils with acidity risk, it is better to use both ammonium and nitrate and monitor soil pH, applying limestone if required. When N fertilization is well adjusted to crop requirements, H^+ released during nitrification is offset by root H^+ absorption; therefore, soil acidification is only relevant when N fertilizers are applied in excess leading to a high concentration of nitrate in soil which is not absorbed or when it is leached.

Atmospheric deposition of NH_3 and NO_3^- can also enhance soil acidification. Even if the major contributor to acid rain is SO_2, the NH_3 volatilized from fertilizers and manures can be a significant source. Part of the N gasses emitted from denitrification, such as NO_2 and NO, are oxidized in the atmosphere to NO_3^-. Further, these N compounds can return to the soil by means of dry or wet deposition, contributing indirectly to soil acidification.

Appendix

Nitrogen concentration in different crop species. Most values in the literature fall in the range defined by maximum (N max) and minimum (N min) concentrations, shown when available. Also the dry matter content (% over fresh mass) is indicated.

Crops		DM%	N min	N max	N typical		DM%	N min	N max	N typical
Cereals and pseudocereals										
Barley 2-row	Grain	88.5	1.50	1.80	1.60	Straw	90	0.58	0.88	0.70
Barley 6-row	Grain	86.5	1.90	2.40	2.20	Straw	90.5	0.58	0.88	0.70
Buckwheat	Seed	94.85			2.96					
Maize	Grain	86	1.35	1.75	1.60	Residues	87	0.90	1.10	0.97
Maize	Silage	30	1.10	1.45	1.25					
Millet (finger)		90			2.20	Residues	92			0.67
Millet (pearl)	Grain	89.5			2.00	Residues	91.5			0.80
Millet (proso)	Grain	90.5			2.30		92			0.80
Oat	Grain	91	1.50	1.80	1.60	Straw	89.5	0.60	0.80	0.70
Quinoa	Seed	94.5			2.43					
Rice	Grain	94			1.33					
Rice (milled)	Grain	87.5	1.05	1.65	1.40	Straw	90	0.50	0.80	0.70
Rye	Grain	87	2.00	2.40	2.20	Straw	90.5	0.35	0.65	0.50
Sorghum	Grain	87.5	1.45	2.00	1.90	Residues	92	0.60	0.80	0.70
Sorghum	Silage	26	0.70	1.30	1.00					
Sorghum	Green	20	1.30	1.40	1.37					
Triticale	Grain	89	2.20	2.50	2.45	Straw	90	0.60	0.90	0.70
Wheat (bread)	Grain	87.5	1.85	2.30	2.10	Straw	90.5	0.40	0.85	0.65
Wheat (durum)	Grain	87.5	2.05	2.70	2.40	Straw	90.5	0.40	0.85	0.65
Sugar, oil, and fiber crops										
Castor bean	Seed	95			2.70					
Cotton	Seed	91	2.32	2.75	2.53	Residues	92.5	0.90	1.00	0.98
Flax	Seed	93.5	3.30	4.30	3.80	Straw	93	1.00	1.20	1.06
Opium poppy	Capsule	87.5	2.30	3.10	2.60	Straw	90	0.80	1.20	1.00
Rapeseed	Grain	91	3.40	4.30	3.90	Residues	82.5	0.55	0.90	0.80
Safflower	Seed	92	2.60	2.80	2.70	Residues	90			0.60
Sugar beet	Root with crown	20	1.20	1.40	1.30	Residues	18	1.80	2.80	2.30
Sugar beet	Root w/o crown	21	0.90	1.10	1.05	Residues	18	1.80	2.80	2.30
Sugarcane	Tops	25			0.13		26			0.41
Sunflower (oil)	Seed	91.5	2.20	3.20	2.95	Residues	87	0.40	1.10	0.80

Sunflower (seed)	Seed	91.5	2.80	3.60	3.20	Residues	87	0.40	1.10	0.80
Tobacco Burley	Leaf + stem	75	3.80	4.20	4.00					
Tobacco flue	Leaves	8	2.00	2.30	2.10	Stalk	9	0.75	1.00	0.80
Legumes										
Bean (dry)	Seed	89	3.50	4.50	4.00	Straw	89	1.10	1.40	1.20
Black-eyed pea	Seed	90	4.00	4.20	4.10	Straw	90			1.25
Chickpea (desi)	Seeds	89.5			3.50	Straw	89.5			0.85
Chickpea (desi)	Seeds	89.5			3.60	Straw	89.5			0.85
Faba bean dry	Grain	90	3.00	4.90	3.70	Straw	85	0.80	2.50	1.60
Groundnut	Fruits	93	4.10	4.30	4.25	Residues	90.5	1.50	1.70	1.65
Groundnut	Seeds	92	4.70	4.90	4.85	Residues	90.5	1.50	1.70	1.65
Lentil	Grain	89	4.20	4.40	4.30	Straw	91			1.10
Pea	Seed	90	4.00	4.30	4.20	Straw	88.5	1.20	1.40	1.30
Soybean	Grain	87.5	6.10	6.90	6.50	Residues	89	1.00	1.00	0.85
Forages										
Alfalfa (green, vegetative)	Biomass	25.0	3.05	4.05	3.55					
Alfalfa (green, flowering)	Biomass	25.0	2.10	3.10	2.60					
Alfalfa (hay, vegetative)	Biomass	85.0	2.80	3.80	3.30					
Alfalfa (hay, flowering)	Biomass	85.0	2.00	3.00	2.50					
Kentucky bluegrass (hay) *Poa pratensis*	Biomass	89.1			1.60					
Bromegrass (hay) *Bromus* sp.	Biomass	91.1			1.53					
Reed canary grass (hay) *Phalaris arundinacea*	Biomass	89.0			1.70					
Alsike clover (hay) *Trifolium hybridum*	Biomass	87.4			2.27					
Crimson clover (hay) *Trifolium incarnatum*	Biomass	88.3			2.65					
Red clover (hay) *Trifolium pratense*	Biomass	86.1			2.51					
White clover (hay) *Trifolium repens*	Biomass	90.3			3.09					
White/ladino clover (hay) *Trifolium repens*	Biomass	89.2			3.32					
Fescue (hay) *Festuca* or *Lolium* sp.	Biomass	90.0			1.51					
Meadow fescue (hay) *Lolium pratense*	Biomass	88.4			1.19					
Tall fescue (hay) *Lolium arundinaceum*	Biomass	91.6			2.31					
Grass (hay) *Poaceae*	Biomass	89.1			1.52					
Grass (silage) *Poaceae*	Biomass	24.9			1.84					

(continued)

Crops		DM%	N min	N max	N typical		DM%	N min	N max	N typical
Foxtail millet (silage) *Setaria italica*	Biomass	27.6			1.59					
Pearl millet (silage) *Pennisetum glaucum*	Biomass	21.6			1.54					
Oat (hay) *Avena sativa*	Biomass	89.8			1.37					
Orchardgrass (green chop) *Dactylis glomerata*	Biomass	25.9			2.37					
Orchardgrass (hay) *Dactylis glomerata*	Biomass	89.2			1.71					
Rye (hay) *Secale cereale*	Biomass	92.6			1.21					
Perennial ryegrass (hay) *Lolium perenne* ssp. *perenne*	Biomass	87.3			1.49					
Sweet clover (hay) *Melilotus* sp.	Biomass	89.6			2.65					
Timothy (hay) *Phleum pratense*	Biomass	90.5			1.20					
Bird's-foot trefoil (hay) *Lotus corniculatus*	Biomass	90.0			2.52					
Turnip (green chop) *Brassica rapa* var. *rapa*	Root	13.5			3.30					
Vetch (green) flowering	Biomass	25.0	2.60	3.40	3.00					
Vetch (hay) *Vicia sativa*	Biomass	87.8			2.60					
Vetch (hay) flowering	Biomass	85.0	2.50	3.30	2.90					
Hairy vetch (hay) *Vicia villosa*	Biomass	87.9			3.68					
Wheatgrass (hay) *Poaceae*	Biomass	91.6			1.34					
Horticultural crops										
Artichoke	Fruit	17	2.40	2.60	2.50					
Asparagus (green)	Stems	8	5.40	5.60	5.50					
Asparagus (white)	Stems	7	4.20	4.40	4.30					
Bean (green)	Pods	30	3.00	3.70	3.30	Straw	89	1.10	1.40	1.20
Beet	Root	12	2.10	2.20	2.15	Residues	12	3.60	3.80	3.70
Broccoli	Stems	45	3.30	3.40	3.35					
Brussels sprouts		13	4.90	5.10	5.00					
Cabbage	Cabbage	9	3.00	3.50	3.30	Residues	14	2.60	2.80	2.70
Carrot	Root	12	1.40	1.60	1.50	Leaves	16	2.30	2.40	2.35
Cauliflower		9	4.30	4.50	4.40					
Celery	Leaves	5	2.30	2.50	2.40					
Chicory	Leaves	6	3.10	3.30	3.20					

Cucumber	Fruit	4	2.40	2.60	2.50					
Eggplant	Fruits	7	2.40	2.60	2.50					
Endive	Leaves	5	4.10	4.20	4.15					
Faba bean green	Fruits	19	4.60	4.80	4.70	Straw	25			2.20
Garlic	Heads	39	2.50	2.80	2.60					1.50
Leek	Bulb	17	1.30	1.50	1.40	Leaves	20			0.90
Iceberg lettuce	Leaves	5	2.40	2.70	2.55					
Romaine lettuce	Leaves	6	4.00	4.40	4.27					
Melon	Fruit	12	0.80	1.00	0.90					
Musk melon	Fruit	10	1.40	1.60	1.50					
Onion	Bulb	10	1.90	2.50	2.20	Leaves	8	3.80	4.10	4.00
Parsley	Leaves	10	3.30	3.60	3.50					
Pea (green)	Fruits	12.5	2.20	3.70	3.00	Straw	25	1.90	2.10	2.00
Pea (green)	Seeds	21	4.30	4.50	4.40	Straw	25	1.90	2.10	2.00
Pepper green	Fruit	10.5	2.10	2.40	2.30					
Pepper red	Fruit	12.5	1.40	2.00	1.90					
Pumpkin	Fruit	9	2.50	2.70	2.60					
Radish	Root	6	1.50	1.70	1.60					
Spinach	Leaves	9	5.10	5.30	5.20					
Squash (immature)	Fruit	5.5	2.70	3.84	3.20					
Squash (mature)	Fruit	14	0.90	1.00	0.91					
Strawberry	Fruit	9	1.10	1.60	1.35					
Sweet corn dry	Grain	90.5	1.90	2.10	2.00	Residues	91	0.90	1.10	1.05
Sweet corn fresh	Grain	35	1.50	1.70	1.60	Residues	23	1.10	1.30	1.20
Tomato	Fruit	6	2.30	3.10	2.60		20			1.80
Watermelon	Fruit	9	1.00	1.50	1.25					
Fruit trees, vines, and shrubs										
Almond	With hull	85	3.00	3.60	3.30					
Apple	Fruit	18	0.25	0.45	0.35					
Apricot	Fruit	14	1.50	1.70	1.65					
Avocado	Fruit	27	1.10	1.30	1.20					
Banana	Fruit	26	0.60	0.70	0.65					

(continued)

Crops		DM%	N min	N max	N typical		DM%	N min	N max	N typical
Cherimoya	Fruit	26	0.70	0.90	0.78					
Cherry	Fruit	19	1.00	1.20	1.07					
Date palm	Fruit	77	0.35	0.45	0.40					
Fig	Fruit	21	0.50	0.60	0.57					
Grape	Fruit	19	0.50	0.60	0.57					
Grapefruit	Fruit	11	0.70	0.80	0.75					
Hazelnut	Fruit	94.5	2.10	2.30	2.20					
Kiwi	Fruit	17			0.80					
Lemon	Fruit	13	1.30	1.70	1.50					
Mango	Fruit	18			0.50					
Oil palm	Kernel	79			1.25					
Olive	Fruit	50	0.20	0.40	0.30	Vegetative	70	1.00	2.00	1.50
Orange	Fruit	18	1.00	1.40	1.20					
Peach	Fruit	12	0.80	1.20	1.00					
Pear	Fruit	18	0.30	0.50	0.40					
Persimmon	Fruit	20			0.55					
Plum	Fruit	15	0.80	0.90	0.85					
Pomegranate	Fruit	25			0.60					
Quince	Fruit	16			0.54					
Walnut	Fruit	93			0.20					
Roots, tubers, and bulbs										
Cassava	Root	68.8			0.42					
Chinese yam	Tuber	59.3			1.39					
Potato	Tuber	23.5	1.20	1.90	1.60	Residues	51	2.00	2.40	2.20
Sugar beet	Root with crown	20	1.20	1.40	1.30	Residues	18	1.80	2.80	2.30
Sugar beet	Root w/o crown	21	0.90	1.10	1.05	Residues	18	1.80	2.80	2.30
Sweet potato	Tuber	65			0.88					
White yam	Tuber	63.1			0.94					
Yellow yam	Tuber	58.3			0.99					

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Nitrogen Fertilization II: Fertilizer Requirements

27

Miguel Quemada, Antonio Delgado, Luciano Mateos, and Francisco J. Villalobos

Abstract

The N balance allows the calculation of the fertilizer requirement that depends on crop N absorption, inorganic N in the soil at sowing or produced by mineralization, and N losses. A fertilization plan should consider the variability of environmental factors, especially rain, to distribute the N with flexibility to match the specific conditions of each year. Doing so, we will avoid yield reductions due to N deficiency and the negative environmental impact of excess application. Fertilization of trees should be based on the nutrient balance (mature trees) or the growth rate expected from actual transpiration.

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27.1 Calculation of N Fertilizer Doses Using the N_{min} Method

The crop response to N fertilization depends on the amount of soil inorganic N available before fertilization. Thus, N fertilizer needs are lower when soil available N is abundant. The N_{min} method is based on sampling soil mineral N at the end of winter, so N rates will decrease as soil N increases. A set of field trials with similar environment (soil + climate) and crop management, including different levels of mineral N in the soil, are needed to establish this relationship. The model fitted is:

$$N_f = A_f - B_f\, N_{min} \tag{27.1}$$

where N_f is the optimum economic dose of N, the parameter A_f represents the total N fertilizer requirement, and B_f is the amount of N provided by the soil per unit N in the sampled soil depth.

Sometimes, the method is simplified by only determining soil nitrate since most of inorganic N is in that form at the end of the winter, although ammonium may be relevant after cold winters or in acid soils. Another common simplification that can result in serious errors is taking soil samples only in the top 30 cm layer, which is clearly insufficient to represent the actual root depth of most crops (Chap. 20). Modifications of the method are used in Europe (N_{min} method) and in the USA, where it is known as "preplant nitrate test" (*PPNT*).

Some additional factors have to be considered:

- Winter crops: The method is applied at the end of winter, before topdressing application. If crop growth during winter is slow, basal N fertilizer application is not recommended to avoid nitrate losses by leaching or denitrification. In warm areas where crop growth and N uptake are important before topdressing, a small fraction of fertilizer (15–30%) might be applied before planting.
- Spring crops: The method is applied before planting, and the fertilizer is split in a preplanting application and topdressings during the growth cycle, as performed for sugar beet in Northern Europe or for maize in Southern Europe.
- The method is strictly empirical, thus only valid for environmental and management conditions for which it was developed. Changes in management, such as adding manure or incorporation of crop residues, will require adapting the model coefficients.

27.2 Calculation of N Fertilizer Dose Using the N Balance

The estimation based on a nutrient mass balance is the recommended strategy for mobile nutrients, such as N, which are not retained in soils and can be lost through leaching or gaseous emissions. The mass balance approach is directed to preplant estimates of N needs. The increase in soil inorganic N (i.e., the difference between final (N_{end}) and initial (N_i) soil inorganic N content) for a nonleguminous crop cycle may be written as:

$$N_{end} - N_i = N_f + N_m + N_{irr} + N_{dep} + N_{seeds} - N_c - N_l - N_d - N_v \tag{27.2}$$

where N_f, N_m, N_{irr}, N_{dep}, and N_{seeds} are N inputs as fertilizer applied, N mineralized, N in irrigation water, N in atmospheric deposition, and N in seeds, respectively. The outputs are N absorbed by the crop, N lost by leaching, N lost by denitrification, and N lost by ammonia volatilization. The N balance equation can be simplified to:

$$N_{end} - N_i = N_f + N_m + N_{other} - \left(N_{biom} + N_{root}\right) - N_{loss} \tag{27.3}$$

where N_{loss} includes all losses of N, and N_{other} includes other minor inputs (irrigation, deposition, seeds) and N fixation in the case of legumes. The equation now separates the two components of crop N, that accumulated in aboveground biomass (N_{biom}) and that accumulated in roots (N_{root}).

27.2.1 Crop N Uptake (N_c)

Crop N content of the aboveground biomass (N_{biom}, kg N/ha) is calculated as a function of expected aerial biomass production (yield and residues) and N concentration of biomass components:

$$N_{biom} = Y \cdot NC_{yield} + \left(B - Y\right) NC_{res} = Y\left(NC_{yield} + \frac{1 - HI}{HI} NC_{res}\right) \tag{27.4}$$

where Y is dry matter yield (kg/ha), B is aerial biomass (kg/ha), HI is harvest index, and NC_y and NC_r are N concentrations in the harvested organ and the residues, respectively. To calculate total N accumulated by the crop (N_c), we add the N in roots as follows:

$$N_c = N_{biom}\left(1 + f_{NR}\right) = \left(N_{yield} + N_{res}\right)\left(1 + f_{NR}\right) \tag{27.5}$$

where f_{NR} is the ratio of N in roots and shoots and N_{yield} and N_{res} are the amounts of N in yield and residues, respectively.

If biomass is overestimated, the same will happen with N applied and N losses will be enhanced. On the other hand, underestimation of biomass will lead to insufficient N and thus, N will become the limiting yield factor. Usually, N in roots accounts for 5–25% of N in aboveground biomass, so 15–20% can be considered acceptable for field crops and up to 25% for horticultural crops.

The estimated yield (also called target yield) should be based on previous years' yields with inputs similar to those the farmer intends to use. If the crop is new in the farm, the target yield should be estimated based on data from neighboring farms. Additionally, for N it is always useful to set the maximum and minimum expected yields to establish maximum and minimum values of N_c and so decide the most appropriate strategy, which we will discuss later.

The crop N concentration can be determined a posteriori by analyzing the biomass produced. However, to design the fertilization program, it is necessary to have estimates of N concentration a priori. Table 26.1 lists the N concentrations for different crop species and dry matter content data required to convert commercial to dry matter yields. When we plan to apply less N than needed or when other factors are not limiting (rainy year or under irrigation), we must choose the lower values of the ranges given in Table 26.1.

27.2.2 Initial and Final Soil N and Mineralization

The initial soil inorganic N content can vary greatly and values between 30 and 500 kg N/ha in the upper 1 m soil have been reported. It is the result of the N fertilizer not absorbed by the previous crop and other processes during the fallow period (mineralization, atmospheric deposition). The common strategy in fertilization management will seek to deplete soil N during the crop cycle, i.e., try to make soil inorganic N at the end of the cycle (N_{end}) as low as possible. The N_{end} is also called the residual N, and below a threshold value (between 10 and 70 kg N/ha depending on soil texture and depth), it cannot be recovered by the crop.

Mineralization of soil organic N may be an important source of N. The N mineralized during the crop campaign is the net result of the mineralization of the stable soil organic matter (SOM) and the residues and roots from the previous crops. This contribution is hard to estimate, and many alternative methods have been proposed. Some practices accelerate SOM mineralization, like the conversion of prairies into cultivated land or the transformation of rainfed to irrigated farms. If a reduction in SOM is expected, we should counteract it with organic or green amendments. We will assume that the SOM is in steady state and calculate mineralization as a function of N in the residues and roots of the previous crop as follows:

$$N_m = k_m F_{res} N'_{res} + N'_{root} = k_m F_{res} N'_{res} + f_{NR}\left(N'_{yield} + N'_{res}\right) \qquad (27.6)$$

where F_{res} is the fraction of residues that are left in the field and N'_{yield} and N'_{res} refer to N accumulated in the harvest and residues of the previous crop, respectively. The coefficient k_m has a maximum value of 1, if all the aboveground residues are mineralized with no loss. Lower values are expected if the residues are not incorporated by tillage or when the residue N concentration is low. We propose $k_m = 0.9$ for legumes with tillage, 0.7 for legumes left on the ground and for nonlegumes with tillage, and 0.5 for nonlegumes left on the ground. This assumes that N_m decreases when residues remain on the ground (i.e., under reduced or no-till) since mineralization slows down and the risk of losses (volatilization, wind, and runoff) increases. Note that N in roots is assumed to be fully available to the next crop.

27.2.3 Fertilizer Requirement Calculation According to the N Balance

From Eqs. 27.3 and 27.6, N fertilizer requirements may be calculated as:

$$N_f = \frac{\left(N_{end} - N_i\right) + \left(1 + f_{NR}\right)\left(N_{yield} + N_{res}\right) - k_m F_{res} N'_{res} - f_{NR}\left(N'_{yield} + N'_{res}\right) - N_{other}}{\left(1 - n\right)} \quad (27.7)$$

N_{other} is the total N received by atmospheric deposition (5–10 kg N/ha, as a conservative value), irrigation water, and N in seeds. The coefficient n is the fraction of applied N lost (leaching, volatilization, denitrification) and f_{NR} is the ratio N in roots/N in shoots. N_i can be determined with a soil analysis just before sowing at the expected rooting depth. If we do not measure N_i, we may assume it is nil to avoid underestimating N requirements. In some regions, N_i values based on experience are provided depending on the precedent crop, soil type, and fall-winter rainfall.

The approach described here has been implemented in software packages like *FertiliCalc*, which is available for personal computers (Windows version, https:/www.uco.es/fitotecnia/fertilicalc.html) or smartphones (Android and iOS versions, www.fertilicalc.com).

Box 27.1: N Fertilizer Efficiency

There are several ways to calculate the efficiency of fertilization. The most used, which we may call E_f, is the fraction of applied N that is finally accumulated in the aerial part of the crop and is equal to the slope of the relationship between N uptake and N applied (Chap. 26, Fig. 26.6). However, this definition does not take into account N in roots. Usual values of E_f are typically in the range 0.4–0.75, and values between 0.5 and 0.7 are usually acceptable. A second definition of efficiency (E_{fR}) would include roots, so it would be the fraction of total N applied that is accumulated in the crop shoots and roots. In mathematical terms:

$$E_{fR} = E_f\left(1 + f_{NR}\right) = 1 - n \quad (27.8)$$

With $f_{NR} = 0.2$, this equation implies that the normal range of E_{fR} is 0.5 to 0.9.

To evaluate the cropping system performance regarding N, we use the nitrogen use efficiency (*NUE*), the ratio of exported N and total N inputs. Higher efficiency means a better use of the resource, with more of the applied N taken up by the crop and a reduction in N losses. Besides agronomic criteria, we may have to consider other constraints. For instance, the dose and types of N fertilizer have been restricted by law in many countries to prevent nitrate pollution.

The N balance method is used to calculate the N supply for a target yield, which depends on environmental conditions and management. However, the recommended N dose should optimize the profit and may differ from the estimated requirements, depending on fertilizer and harvest prices.

Example 27.1
Wheat crop is grown as monoculture in a Mediterranean environment (sown in January and harvested in July) on an acid soil with the following distribution of yields:

2–3 t/ha in 40% of the years
3–4 t/ha in 30% of the years
4–5 t/ha in 20% of the years
5–6 t/ha in 10% of the years

The average yield is therefore 3.5 t/ha.

We assume that all the residues of the previous crop are left in the field ($F_{RES} = 1$) and are incorporated by tillage, so $k_m = 0.7$.

The N concentration in wheat is 2.3% in grain and 0.6% in straw. The harvest index is 0.5. The water content of grains is 10%. We assume $f_{NR} = 0.2$, $N_{other} = 10$ kg N/ha (5 kg N/ha atmospheric deposition + 5 kg N/ha in seeds). Our aim is $1-n = 0.80$ (losses of denitrification and volatilization are low in acid soils) and $N_{end} = 25$ kg N/ha, which can be assumed as a reasonable value for rainfed cereal-based crop rotations with efficient N use.

How would we modify the N fertilizer strategies if the soil mineral N content (N_i) is determined in soil samples every year? Assume that the average value is $N_i = 40$ kg N/ha.

How would we modify the cereal N fertilizer strategy if faba bean (dry yield 1500 kg/ha, $HI = 0.3$) is introduced as a precedente cash crop?

(a) For each interval of yield (taking the midpoint), we calculate the N fertilizer requirement. For instance, for yield 2.5 t/ha:

N_c (N uptake):

Yield (dry matter) = 2500 (1–0.1) = 2250 kg/ha
Residues = $Y \cdot (1-HI)/HI$ = 2250 kg/ha

$N_{yield} = Y \cdot NC_y = 2250 \cdot 0.023 = 51.75$ kg N/ha
$N_{res} = 2250 \cdot 0.006 = 13.5$ kg N/ha

We assume that the previous wheat crop had an average yield (3500 kg/ha):

Yield (dry matter)= 3500 (1–0.1) = 3150 kg/ha
Residues = $Y \cdot (1\text{-}HI)/HI$ = 3150 kg/ha

$N'_{yield} = Y' \cdot NC_y = 3150 \cdot 0.023 = 72.4$ kg N/ha
$N'_{res} = 3150 \cdot 0.006 = 18.9$ kg N/ha

(continued)

Example 27.1 (continued)

$$N_f = \frac{25 + (1+0.2)(51.75+13.5) - 0.7\cdot 1\cdot 18.9 - 0.2(72.4+18.9) - 10}{0.80} = 77\,\text{kgN / ha}$$

For other yield values, we will have:
For $Y = 3.5$ t/ha: $N_f = 116.4$ kg N/ha
For $Y = 4.5$ t/ha: $N_f = 155.6$ kg N/ha
For $Y = 5.5$ t/ha: $N_f = 194.7$ kg N/ha

(b) Possible strategies:

- Apply 77 kg N/ha every year. The crop would always be limited by N, and we would have an average yield of 2500 kg/ha, so the average exported N would be 2250 × 0.023=51.75 kg N/ha. The *NUE* (N exported/N input ($N_f + N_{others}$)) would be 0.59.
- Apply 116 kg N/ha every year. In the best case, yield would be 3500 kg/ha. The average yield is then:

$$0.4\cdot 2500 + 0.6\cdot 3500 = 3100\,\text{kg / ha}$$

So the average exported N would be 64.17 kg N/ha and the *NUE* = 0.51.
- Apply 156 kg N/ha every year. The average yield is then:

$$0.4\cdot 2500 + 0.3\cdot 3500 + 0.3\cdot 4500 = 3400\,\text{kg / ha}$$

So the average exported N would be 70.4 kg N/ha and the *NUE* = 0.42.
- Apply 195 kg N/ha every year. The average yield is then:

$$0.4\cdot 2500 + 0.3\cdot 3500 + 0.2\cdot 4500 + 0.1\cdot 5500 = 3500\,\text{kg / ha}$$

The average exported N would be 72.4 kg N/ha and the *NUE* = 0.35.

The best strategy would depend on the price of the grain and the cost of fertilizer. In any case it is always better to follow a flexible strategy, i.e., basal application lower than 77 kg N/ha and then applying a topdressing 2 months later (to ensure N availability by tillering). The latter would be omitted if the year came bad and would be between 0 and 118 kg N/ha depending on the actual conditions of the year. In years with high yield expectation, the topdressing could be split in two (the second around flowering) to ensure high grain protein content. By following a flexible strategy, if we can exactly match the N requirements of each type of year, we would apply an average amount of N:

$$0.4\cdot 77 + 0.3\cdot 116 + 0.2\cdot 156 + 0.1\cdot 195 = 116\ \text{kg N / ha}$$

while the average exported N is 3500 · (1–0.1) · 0.023 = 72.45 kg N/ha and the *NUE* = 0.58.

(continued)

Example 27.1 (continued)

(c) If N_i = 40 kg N/ha, the new calculation for the lowest expected yield would be:

$$N_f = \frac{(25-40)+(1+0.2)(51.75+13.25)-0.7\cdot1\cdot18.9-0.2(72.4+18.9)-10}{0.80}$$
$$= 27.3\ \text{kg N / ha}$$

For the other yield values, we will have:

For Y = 3.5 t/ha: N_f = 66.4 kg N/ha
For Y = 4.5 t/ha: N_f = 105.6 kg N/ha
For Y = 5.5 t/ha: N_f = 144.7 kg N/ha
Possible strategies:

- Apply 27 kg N/ha every year. The average expected yield would be 2500 kg/ha and the average exported N 51.75 kg N/ha.
- Apply 66 kg N/ha every year. The average expected yield would be 3100 kg/ha and the average exported N 71.34 kg N/ha.
- Apply 106 kg N/ha every year. The average yield is then 3400 kg/ha and the average exported N 78.2 kg N/ha.
- Apply 145 kg N/ha every year. The average yield is then 3500 kg/ha and the average exported N 80.5 kg N/ha.

In the flexible strategy, we would apply a basal application of 27 kg N/ha and then a topdressing 2 months later between 0 and 118 kg N/ha depending on the actual conditions of the year. In years with high yield expectation, the topdressing could be split in two to ensure high grain protein content. By following a flexible strategy, we can better match the N requirements of each type of year. We would apply an average amount of N:

$$04\cdot27+0.3\cdot66+0.2\cdot1.06+0.1\cdot145 = 66\,\text{kg N / ha}$$

The average exported N is 72.4 kg N/ha; therefore, NUE>1. This is a case of soil mining, a common practice when fertilizer prices are high or in areas with nitrate pollution problems. Care should be taken as soil mining is not sustainable in a long term as soil C and quality could be degraded.

(d) After faba bean, the available N at wheat sowing will increase. We calculate N in yield and residues of the faba bean:

$N'_{yield} = Y\,NC_y$ = 1500 · 0.037 = 55.5 kg N/ha
$N'_{res} = Y \cdot (1-HI)/HI \cdot NC_r$ = 1500 · 0.7/0.3 · 0.016 = 56 kg N/ha

$$N_f = \frac{25+(1+0.2)(51.75+13.5)-0.9\cdot1\cdot56-0.2(55.5+56)-10}{0.80} = 40\,\text{kg N / ha}$$

(continued)

Example 27.1 (continued)

which is a relevant reduction in fertilizer application. The amount of N to apply for the other yield classes will be 79, 118, and 157 kg N/ha. Therefore, the basal N application to wheat could be skipped and the topdressing between 40 and 157 kg N/ha would be applied 2 months after sowing. In years with high yield potential, the topdressing could be split in two to ensure high grain protein content.

The N fertilizer savings provided by the introduction of faba bean would be added to other agronomic advantages of crop rotation. The faba bean income will probably be lower than that of the cereal, but the introduction of the legume every 2 or 3 years may increase the sustainability of the cropping system.

Box 27.2: Estimating Final N (N_{end})

Soil N at harvest (N_{end}) is variable and depends on fertilizer dose, climatic and soil conditions that affect crop growth, and, thus, N uptake. In general, N_{end} is higher after a dry year due to reduced N uptake and low leaching. In wet years, N leaching and denitrification favor low N_{end}. At the same time, the risk of leaching are higher in sandy than in clay soils. With efficient management, N_{end} ranges between 10 and 70 kg N/ha, which may account for 10–20% of N fertilizer applied to most crops. Higher values may be expected with high fertilizer dose in clay soils or conditions not prone to leaching (e.g., efficiently irrigated spring crops). A common recommendation in Mediterranean environments is assuming N_{end} = 25 kg N/ha for crops receiving low N fertilizer dose (e.g., rainfed cereals) and 40 kg N/ha for crops receiving high N fertilizer dose (e.g., irrigated field and horticultural crops).

27.3 Within-Season Methods for Improved N Management

The spatial and temporal variability of processes affecting soil N represents a relevant limitation to the N balance, which provides a preplant estimation of N needs for the whole crop cycle. Within-season monitoring tools and methods have been proposed to improve the estimated N requirements. They are based on monitoring the N status of the soil or the crop during the season, assessing the need for additional N, or recommending specific dose of supplemental N.

A good example is the pre-sidedress nitrate test (*PSNT*), performed for maize in the USA. It is a type of N_{min} method based on a soil nitrate analysis (30 cm depth) when plants are 20–30 cm tall. It represents a point-in-time assessment of the spring accumulation of NO_3^- before the crop begins the rapid growth phase. The *PSNT* method takes into account the remaining N from the previous crops, N mineralization, and N losses before the date of sampling, just before large amounts of N are required by the crop.

In addition to the methods based on soil available N, there has been a major development in sensors to determine crop N status to adjust fertilizer application during the growing season. The sensors are based on the radiation transmittance of a leaf or the reflectance of the crop canopy at various wavelengths and can be handheld or tractor mounted. The readings are related with chlorophyll activity and therefore with crop N status. Comparing with a well-fertilized crop strip, a sufficiency index (ratio of crop reading/well-fertilized crop reading) can be developed and used to apply variable fertilizer dose (see Chap. 39).

27.4 Fertilization of Fruit Trees

27.4.1 Mature Orchards

Mature trees are very efficient in translocating N to reserves (e.g., before leaf fall in deciduous species) which will be later made available for new growth. Therefore, in mature orchards the calculation of crop N should only consider the amounts of N exported in yield, or lost by pruning and leaf fall:

$$N_c = Y\,C_{N\,fruit} + B_{pruning}\,C_{N\,shoots} + B_{leaf\ fall}\,C_{N\,senesced} \tag{27.9}$$

Values of N concentration in fruits are presented in Table 26.1. The concentrations for shoots and senesced leaves may be taken as 1%. The amount of leaf fall will be equal to total leaf biomass for deciduous trees and around 50% of leaf biomass for evergreens with leaf life span around 2 years. Note that this is a conservative estimate of crop N uptake as N in pruning residues is only lost when they are burned. The total vegetative biomass production in the growing season (B_v) is the sum of biomass in pruning, senesced leaves, and growth of permanent structures (trunk, main branches). Then, using the definition of harvest index, we may write:

$$B_{pruning} + B_{leaf\ fall} = \beta_{pl}\,\frac{1-HI}{HI}\,Y \tag{27.10}$$

where β_{pl} is the fraction of B_v not used in permanent structures. This parameter is very high (0.8–0.9) for most deciduous species and for evergreens under intensive management. Therefore, we can simplify Eq. 27.9 to:

$$N_c = Y\left[C_{N\,fruit} + \beta_{pl}\,\frac{1-HI}{HI}\,C_{N\,pl}\right] \tag{27.11}$$

where $C_{N\,pl}$ is the average concentration of N in pruning residues and senesced leaves that may be taken as 1%. Data on *HI* of fruit crops indicate that it is usually above 0.5, so if no information is available for a given species, we may take a value of 0.6.

To calculate the amount of fertilizer to apply, we need to consider the fate of the pruning residues. If they are burned or exported, only leaf fall remains on the soil, which will give back mineral N after mineralization, sometime later. In the best case, with zero losses of N from the system, we will recover all N from senesced leaves. Therefore, the minimum amount of fertilizer to apply if residues are burned or exported will be:

$$N_f = \frac{1}{E_{fR}}\left[N_c - 0.5\,Y\,\beta_{pl}\,\frac{1-HI}{HI}\,C_{N\,pl}\right] = \frac{Y}{E_f}\left[C_{N\,fruit} + 0.5\,\beta_{pl}\,\frac{1-HI}{HI}\,C_{N\,pl}\right] \tag{27.12}$$

where E_f is the average efficiency of the fertilizer.

If residues are incorporated, the minimum amount to apply reduces to $Y\,C_{N\,fruit}/E_{fR}$.

Example 27.2
An irrigated vineyard yields 25 t/ha of table grape. Water content is 80% (Table 26.1), so yield is 5 t dry matter/ha. N concentration in fruits is 0.6% (dry matter basis). Now, using Eq. 27.11:

$$N_c = 5000\left[0.006 + 0.9\,\frac{0.4}{0.6}\,0.01\right] = 60\ \text{kg}\,\frac{\text{N}}{\text{ha}}$$

Assuming $E_f = 0.8$, if pruning residues are incorporated, the minimum fertilizer amount would be 37.5 kg N/ha. If residues are exported, we should apply at least 56 kg N/ha. In any case, fertilizer amounts should not exceed 60/0.8 = 75 kg N/ha. A well-established cover crop (e.g., legume or legume/grass mixture) could fix enough N to supply or reduce vineyard requirements. A fraction of the N content in the residues would be available for the vineyard during the growing season after the cover crop is mowed (50%) or incorporated into the soil (70%).

27.4.2 Young Trees

For young orchards, we have to consider the nutrient demand of vegetative growth, which depends on age, species, and environmental conditions. It is not easy to calculate the increase in standing biomass of young trees. For some species, empirical relations have been established between tree biomass and trunk diameter. A more general and simple approach is to relate canopy growth to transpiration using the water use efficiency. We extend Eq. 14.9 to the whole growing season:

$$\Delta B = \sum_{0}^{T} \frac{\alpha_w}{VPD}\,E_{p\,tree} \tag{27.13}$$

where T is the duration of growth, while transpiration is proportional to ET_0, the intercepted radiation equivalent area (REA), and the transpiration coefficient for full ground cover (K_{tf}) (see Eq. 9.19). Therefore:

$$\Delta B = \sum_{0}^{T} \frac{\alpha_w}{VPD}\,ET_0\,REA\,K_{tf} \tag{27.14}$$

Finally, we calculate the N uptake (N_c, g N/tree) required for that increase in biomass assuming a high N concentration (2%) which is an upper boundary for biomass of young trees:

$$N_c = 0.02 \sum_0^T \frac{\alpha_w}{VPD} ET_0 \, REA \, K_{tf} \tag{27.15}$$

For young trees, the fertilizer applied should match the expected uptake, using a proper value of efficiency.

A similar approach for fertilizing young trees with N may be taken for P and K by applying the proper concentrations. For deciduous trees, we may use 0.2% of P and 0.9% of K. For evergreen trees, the values are 0.12% P and 0.9% K.

Example 27.3

In Example 3.5 we calculated the intercepted radiation equivalent area of an olive tree with radius 0.5 m in Córdoba, Spain, in 21 March as $REA = 0.69$ m^2. If ET_0 is 3 mm day^{-1}, taking a value of $\alpha_w = 7.5$ g kPa L^{-1} (Chap. 14) and $K_{tf} = 1$, with $VPD = 1.5$ kPa:

$$N_c = 0.02 \sum_0^T \frac{\alpha_w}{VPD} ET_0 \, REA \, K_{tf} = 0.02 \frac{6.5}{1.5} 3 \cdot 0.69 \cdot 1 = 0.18 \, \text{g} \frac{\text{N}}{\text{tree}}$$

Assuming $E_f = 0.8$, the amount of N fertilizer should be 0.18/0.8 = 0.23 g N/day/tree.

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Fertilization with Phosphorus, Potassium, and Other Nutrients

28

Antonio Delgado, Miguel Quemada, Luciano Mateos, and Francisco J. Villalobos

Abstract

Phosphorus (P) and potassium (K) are primary macronutrients required in significant amounts by crops. Both are nonmobile in the soil since they are retained in the solid fraction and consequently, their management has some common characteristics. Most soil P and K are not available to plants. Reactions involved in their cycle in the soil imply that a significant fraction of applied P and K is not absorbed by the crop. P and K fertilizer management should minimize the transformation of applied nutrients to nonavailable forms and maximize crop absorption. To this end, banding or fertigation may be an alternative to broadcast applications. Management strategies for P and K should be designed in the medium and long term, contrasting with mobile nutrients such as N, whose management strategies are designed in the short term, i.e., for each growing season. The efficient use of P and K is gaining interest since both nutrients are nonrenewable resources, particularly P whose future scarcity will limit food security.

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Other nutrients are usually applied according to a sufficiency strategy, i.e., when deficiency is expected. Deficiencies in Ca and Mg are mostly likely in acidic soils. Mg deficiencies may be promoted by high Ca saturation in the exchange complex or by excessive K fertilization due to antagonism. The deficiency of micronutrients is not usually caused by a low soil concentration, but rather by soil properties that affect their solubility and the plant's ability to mobilize, absorb, and transport these nutrients.

28.1 Introduction: Phosphorus and Potassium as Essential Nutrients

Phosphorus and potassium are the two primary macronutrients nonmobile in the soil (see Chap. 2). When applied as fertilizer, both nutrients are quickly fixed in the soil solid fraction, mainly by adsorption or precipitation. Thus, in contrast to N, leaching risk is usually negligible, except in soils with very low adsorption capacity (e.g., very sandy soils). On the other hand, retention reactions in soils imply that only a fraction of applied nutrients remains available to plants. Fertilizer management must be aimed at achieving maximum efficiency in the use of applied nutrients by crops. To this end, loss risk (e.g., leaching or volatilization) should be minimized in the case of N, while for P and K, we should minimize the fraction of applied nutrients fixed in the soil as nonavailable forms (retrogradation).

In terrestrial and aquatic systems, when N is non-limiting, P is usually the limiting nutrient for plant growth. Phosphorus is involved in many biological processes in plants. It has a structural role as part of nucleic acids or membrane phospholipids. It is involved in phosphorylation reactions, crucial in energy transfer in cells and the modulation of enzyme activity or in signal transduction. Plants absorb P actively, primarily in the forms $H_2PO_4^-$ and HPO_4^{2-}.

Phosphorus is stored in plants as inorganic phosphate or polyphosphate or in organic form as phytate, the latter being the usual storage form of phosphorus in seeds. This storage in seeds is the consequence of a massive translocation at the end of the growing season for guaranteeing critical resources for the initial growth of the next generation. This explains that, as for N, most of shoot P is stored in seeds in grain crops (> 60%), so it will be exported at harvest. Phytate has an impact on the efficiency of using P since it is not a digestible source of P for nonruminant animals including humans. Thus, manure and wastewater are major flows of P, equivalent to around 75% of total P applied in agriculture in Europe. When applied to the soil, phytate is mostly stabilized by adsorption, not contributing significantly to crop P uptake. Furthermore, phytate decreases intestinal absorption of Zn and Fe, negatively affecting the nutrition of animals and humans.

Phosphorus deficiency has a strong negative impact on crop growth, with leaf expansion being more sensitive than P concentration. It may also cause a higher root/shoot ratio and, in some species, an alteration in root morphology ("cluster roots"). Given the high mobility of P within the plant, deficiency symptoms are first detected in older leaves that senesce prematurely. Anthocyanin pigments (purple) frequently accumulate in P-deficient plants. Normal concentrations in leaves vary greatly among species in the range of 0.05–0.3% P (dry matter basis) (Table 28.1).

Excessive P fertilization leads to soil enrichment, mostly in nonavailable forms to plants. This excess has been common in North America and Europe since the middle of the twentieth century. It is estimated that 70% of croplands in Europe have soil P high enough to show no response to P fertilizer and an increased risk of Zn and Fe deficiencies. P-rich soils will also lose P by soil erosion that will end in water bodies triggering eutrophication, the explosive growth of algae and weeds that has dramatic impacts on aquatic animals.

Potassium is absorbed actively as cation and the flux is controlled by the internal concentration. Once absorbed it is transported mainly to young growing tissues. In plants, it is present predominately as a free ion. It acts as an osmoregulator and is involved in stomatal control. It plays a crucial role in charge balance in cell organelles and ribosome structure and function and, thus, in protein synthesis. It indirectly promotes photosynthesis and transport of assimilates and has a direct role in the activity of at least 50 enzymes. Potassium is also involved in plant tolerance to biotic and abiotic stresses such as frost and drought. Contrasting with P, only a minor fraction of K is exported with the grains, so it will be mostly recycled within the farm in crops such as cereals when residues are incorporated to the soil.

Potassium is usually required in high amounts like N. Its deficiency is more common in sandy, saline, and acidic soils. Deficiency causes a reduction in plant growth. As it is highly mobile, symptoms appear first on the oldest leaves, with chlorosis and necrosis on the margins. In cereals, K deficiency increases lodging risk. Table 28.1 shows the common and threshold concentrations of K in the leaves of different crops.

Table 28.1 Critical concentration and sufficiency range for P, K, Ca, and Mg in leaves or shoots of crops

		Nutrient concentration (% over dry mass)					
		P		K		Ca	Mg
Crop	Stage	Critical	Adequate	Critical	Adequate	Adequate	Adequate
Cotton	45 DAS		>0.4		>3.2		0.65–0.8
Faba	Flowering	0.19–0.24	0.3–0.55	1.8–2	2.2–4	0.6–1.2	0.24–0.5
Linseed*	53 DAS		0.37–0.69		2.5–3.5	0.96–1.7	0.36–0.65
Oat	Tillering	0.24–0.29	0.3–0.5	4.3–4.9	5–5.7	0.21–0.4	0.13–0.3
Rice*	Tillering		0.37–0.55	1.6	1.6–3	0.1–0.30	0.14–0.21
Sugar beet	50–80 DAS	<0.45	0.45–1.1	2	2.0–6.0	0.5–1.5	0.25–1
Wheat	Tillering	<0.35	0.35–0.49	<2.3	2.4–4	0.21–0.4	0.13–0.3
Apple	Summer	0.10–0.14	0.15–0.2	0.8–1.1	1.2–1.5	1.1–2.0	0.21–0.25
Apricot	Summer	0.09–0.13	0.14–0.25	1.0–1.9	2.0–3.5	2.0–4.0	0.30–0.85
Citrus spp.		0.09–0.11	0.12–0.16	0.4–0.69	0.7–1.5	3.0–6.0	0.26–0.60
Olive	Summer		0.1–0.3	0.4–0.8	>0.8	>1.0	>0.1
Peach	Summer	0.09–0.13	0.14–0.25	1.0–1.9	2.0–3.0	1.8–2.7	0.30–0.80
Pear	Summer	0.10–0.13	0.14–0.20	0.7–1.1	1.2–2.0	1.5–2.2	0.3–0.5
DAS, days after sowing		* whole shoot					

As mentioned in Chap. 25, P and K fertilizers are nonrenewable resources obtained ultimately from mining. The prospects are worse for P not only because of scarcity but also because of new alternative uses.

28.2 P in the Soil

Phosphorus is not abundant in Earth's crust and soils, with concentrations below 1 g/kg. It is mainly present as phosphate, found in organic (mostly esters) or mineral forms. Mineral and organic forms can be found in the soil solution or bound to the solid fraction. Plants absorb phosphate (dissociated forms of phosphoric acid) from the soil solution, where it is in equilibrium with specifically adsorbed forms (see Chap. 2) on hydroxylated surfaces (Fe and Al oxides and, to a lesser extent, borders of clay minerals and carbonates) and with precipitated metal phosphates (mainly Fe, Al, and Ca phosphates, depending on soil pH). Thermodynamically stable metal phosphates, such as apatite type in soils with high pH and high Ca saturation, are insoluble, thus contributing little to P in the soil solution; other less abundant and less stable precipitates can contribute more to P in the soil solution (Fig. 28.1). Precipitation as insoluble metal phosphates and adsorption reactions explain that a minor fraction of applied P fertilizers is available to plants. Organic forms are mainly phosphomonoesters and phosphodiesters and can be adsorbed, sometimes more strongly than inorganic phosphate, and they can precipitate as well. As in the case of N and other elements, P can be used by soil microorganisms and be immobilized, at least temporarily. The reverse process, mineralization, requires the hydrolysis of ester bonds and is catalyzed by phosphatases. These enzymes can be produced by plant roots and some soil microorganisms. Organic P may account for a significant fraction (usually between 25 and 75%) of the total P in the soil even in Mediterranean soils with low organic matter concentration. Mineralization of this organic P through phosphatase activity can contribute to its supply to plants in P-poor soils.

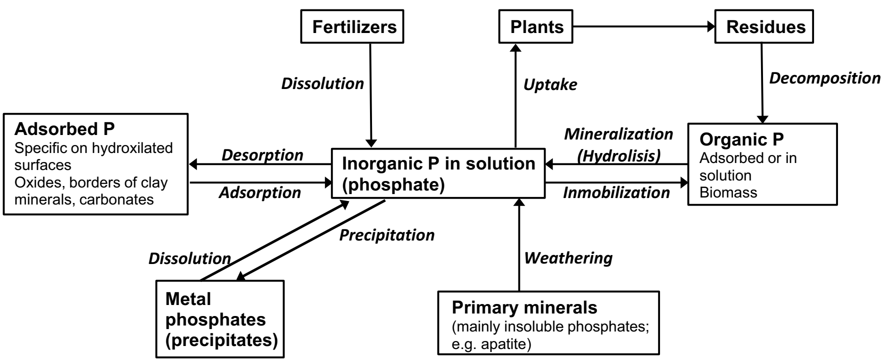


Fig. 28.1 P soil cycle. In italics: physical, chemical, or biological processes involved

Phosphorus concentration in the soil solution of agricultural soils is usually very low, below 1 mg/L. This concentration decreases by plant absorption, forcing its replenishment from adsorbed or precipitated forms. The relationship between adsorbed P and P in the soil solution is determined by the soil buffer capacity that depends, among other factors, on the soil adsorption capacity (Fig. 28.2). A high buffer capacity indicates a good ability of the soil to replenish P of the solution as it is absorbed by the crop. If the buffer capacity is low, the concentration of P in the solution may be high, but the soil's ability to replenish that used by the crop is limited. On the other hand, applied P fertilizer initially passes to the soil solution but will shift to fixed forms at a rate proportional to the buffer capacity. This means that to restore a P deficiency, higher doses of fertilizer are required in soils with higher soil buffer capacity.

The degree of ionization of phosphates depends on the pH (Fig. 28.3). In acid soils, monovalent ions predominate, while in neutral soil the ratio between monovalent and divalent forms is about 1:1. Plants absorb P mainly as $H_2PO_4^-$ and HPO_4^{2-} and

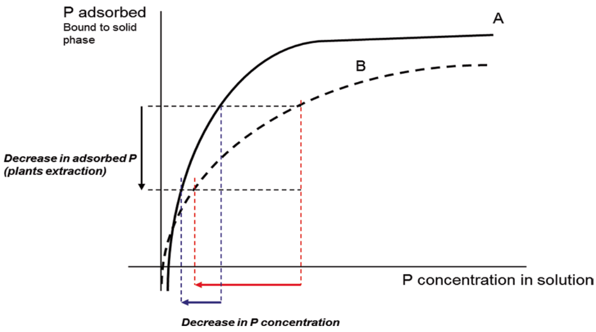


Fig. 28.2 P buffering capacity in soils. A, soil with high buffering capacity; B, (dashed line) with low buffering capacity. The red arrow represents the decrease in P concentration in solution for soil B and the blue arrow the decrease in soil A for the same decrease in adsorbed P

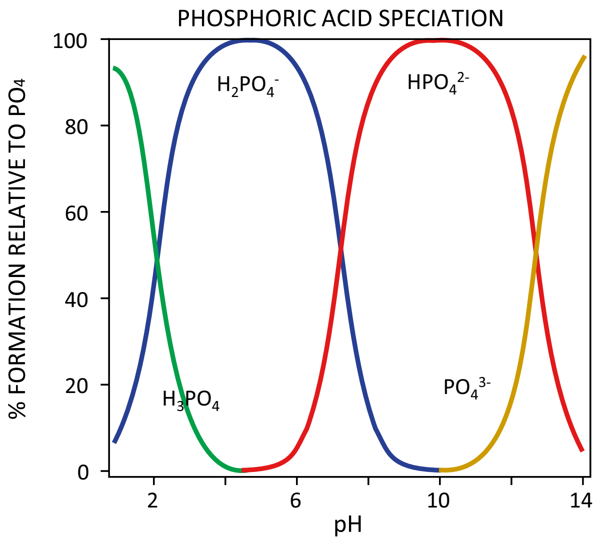


Fig. 28.3 Phosphoric acid speciation

the latter much more slowly. Therefore, the absorption of P is faster in acid soils. Plants can secrete organic acids to the rhizosphere, which release adsorbed P and dissolve precipitated P, and phosphatases that contribute to mineralizing organic P. Microorganisms can also release organic acids and phosphatases. Symbiotic mycorrhizae can also increase the absorption surface for P.

28.2.1 Plant Available P in the Soil: The Soil P Test

Labile P in the soil is that P in the solid phase that is easily released to the soil solution. Plant available P (PAP) is the sum of P in the soil solution and labile P (see chap. 2). PAP is usually a minor fraction of total P, frequently less than 10%. PAP can be measured by extraction by consecutive crops until evident deficiency (P starvation assays) but this is not practical. Some chemical extraction methods may indicate if PAP in soil is enough to cover crop needs. These methods are known as *P availability indexes* or *soil P tests* (Table 28.2).

Table 28.2 Different extraction methods applied as soil P tests

Method	Restrictions	Countries	Threshold mg P/kg
Olsen	Recommended in slightly acidic to basic soils	UK, part of USA, Mediterranean EU countries, North Africa, West Asia	8–25[a]
Mehlich I	Multinutrient extraction (ME) for soils with low CEC	Part of USA	10–15
Mehlich III	ME for wide range of soils; well correlated with Bray I, Mechlich I, and Olsen	Part of USA	15–25[b]
Bray I (Bray-Kurtz)	Soils with acidic and neutral pH	Acidic soils in some countries (e.g., USA)	20–25
Bray II	Soils with acidic and neutral pH		70–180
Egnér et al. (ammonium lactate)	ME	Scandinavia, central and East Europe, Portugal	40–60[c]
Egnér-Riehm (double lactate)	ME	Germany, Poland	45
Schüller (calcium lactate)		Germany, Austria	31–47
Morgan	ME for acidic soils with low CEC	Ireland	4–6
Morgan modified	ME for acidic soils with low CEC	East coast of USA	10
Soltanpour (AB-DTPA)	ME for P, cations, and micronutrients; mainly for calcareous soils	Not official in any country	5–15

[a]See Sect. 28.3

[b]Fifteen for corn and soybean and 25 for wheat and alfalfa according to tri-state recommendations; in soils with pH < 6, these levels could be slightly higher

[c]In Scandinavian countries, 40–50; 60 in Hungary; for each country range depends on soil properties

Soil P tests are not a measure of PAP. For each soil P test, *threshold values* should be defined, i.e., the value above which crop yield does not respond to P fertilization. Thus, below this value, the soil can be considered P-deficient. Threshold values for a given soil P test can vary among soil types and crops. There is no universal soil P test since its accuracy for fertilizer requirement estimation is strongly affected by soil properties. Only in Europe, more than six official P indexes are used in different countries, with Olsen and lactate being the most common. Olsen, Mechlich (I and III), and Bray are the methods preferred in the USA.

28.3 Estimating the Threshold Values for the Olsen P Test

The soil test level threshold for Olsen P (STL_t) varies depending on soil properties and climatic factors affecting the water regime in the soil. The threshold decreases with increased clay and pH. Thresholds are usually 8–10 mg/kg for clay soils and 12–20 mg/kg for sandy soils. Environmental factors are more relevant than crop type. Most crops have thresholds in the range of 8–17 mg/kg, except in root crops (potato and sugar beet) that show higher values (17–25 mg/kg). A higher threshold should be expected with higher yields (larger P extractions), but this is not easy to quantify. A simple model has been proposed to estimate the Olsen P threshold:

$$STL_t = 49 - 0.016\,\mathrm{Clay} - 3.81\,\mathrm{pH} \tag{28.1}$$

where the clay content is expressed as g/kg. This model can be used also in acidic soils where Olsen was not recommended in the past. In acidic sandy soils, estimated thresholds may be higher than 30 mg/kg. In root and tuber crops, the STL_t should be increased by 6–8 mg/kg. In rice under flooding, the threshold values are very low (3–5 mg/kg) due to the reduction of adsorbent surfaces enhancing P release to the soil solution.

28.4 Potassium in the Soil

Potassium is abundant in the soil (0.3–3% in mass) since it is a component of primary soil minerals such as feldspar and mica. From these minerals, potassium is slowly released by weathering. Potassium is found in soluble, exchangeable, and non-exchangeable forms. In the soil solution, it is in equilibrium with exchangeable K retained by electrostatic attraction to the negatively charged sites on clays and soil organic matter. Non-exchangeable K (fixed K) is found within the interlayers and on the edges of 2:1 clay minerals and is not readily available to plants (Fig. 28.4). A fraction of K supplied as fertilizer becomes fixed in proportion to the fertilizer rate and the 2:1 clay content of the soil. Adsorption as exchangeable or non-exchangeable forms explains the little mobility of K in the soil.

The plant available K is the sum of K in the soil solution and the exchangeable pool. The K concentration in the solution is typically between 0.2 and 10 meq/L, usually less than 1% of exchangeable K and can be quickly depleted by plant uptake.

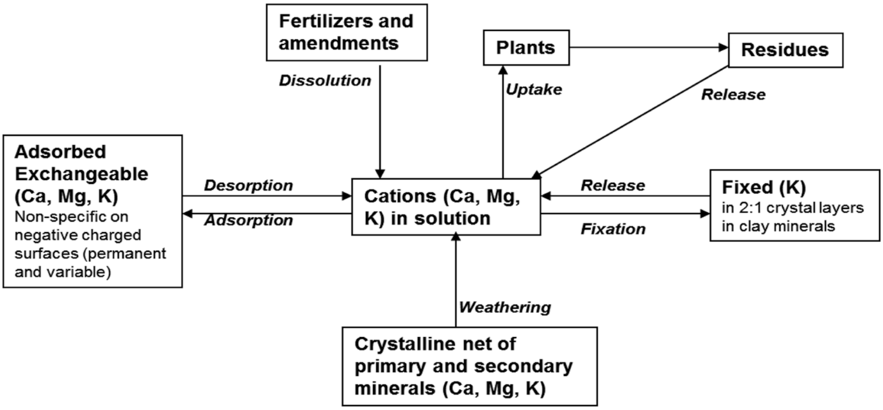


Fig. 28.4 K, Ca, and Mg cycled in soil. In italics: physical, chemical, or biological processes

Table 28.3 Threshold levels (STL_t) for ammonium acetate extractable K in soils as a function of cation exchange capacity (cmol(+)/kg) and the texture

Cation exchange capacity (CEC)	Threshold levels		Threshold levels
cmol(+)/kg	mg K/kg soil	Texture	mg K/kg soil
10	150	Sandy	100
20	180	Loamy	150–175
30	210	Clay	200–300
40	240		

The thresholds can be calculated using $STL_t = 75 + 2.5\ CEC$ (tri-state recommendation for corn, wheat, soybean, and alfalfa) or $STL_t = 110 + 2.5\ CEC$ (general recommendation)

Plants absorb K only in cationic form. As defined for P, the soil buffering capacity for K is the ability to replenish K in the soil solution from that bound to soil particles, and it is critical to maintain K concentration in the solution in appropriate ranges for plants. Potassium buffer capacity mainly depends on clay content and mineralogy, being the highest in clay soils with 2:1 as dominant clay minerals.

28.4.1 Plant Available Potassium in the Soil

As for P, K fertilizer management must be based on availability indexes, commonly based on the estimation of exchangeable K. The most widespread method is extraction with ammonium acetate solution at pH 7 (Table 28.3), which shows a good correlation with crop response to soil K. Other methods such as buffered $BaCl_2$ or unbuffered NH_4Cl provide similar results. For acidic soils, methods based on extraction with acids (e.g., Mehlich or Morgan) have been proposed, generally with good correlations with results obtained with ammonium acetate.

28.5 Response of Crops to P or K Fertilizer

The production functions of yield versus applied nutrient (P or K) show similar responses with decreasing slope (Figs. 28.5 and 28.6). The relationship between yield and P uptake is similar to that described for N, i.e., linear initially and then may reach a ceiling (Fig. 28.7). The relationship between fertilizer doses and P uptake is linear first and can reach a ceiling where the absorption is saturated (Fig. 28.7). The intercept with the y-axis of the linear portion is the total P absorbed from sources other than fertilizer, and the slope of the straight line has been termed recovery efficiency.

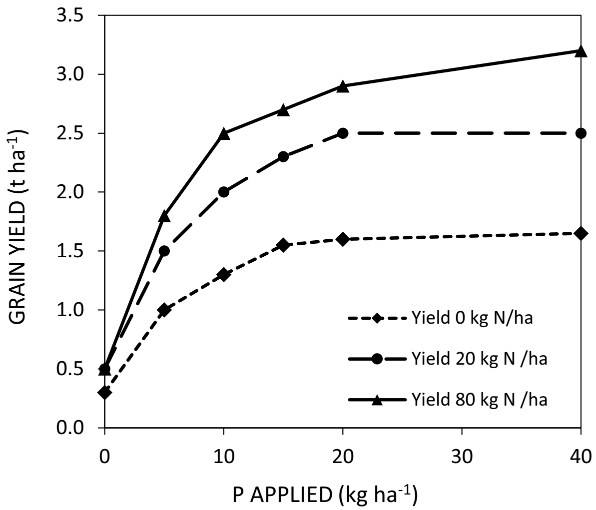


Fig. 28.5 Wheat grain yield response to P fertilizer application with increasing rates of N fertilizer in Australia. (Adapted from Brennan and Bolland (2009). Crop Pasture Sci 60:566–577)

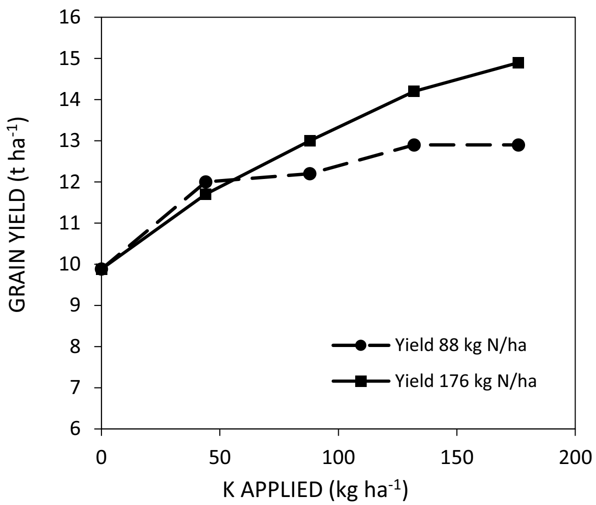
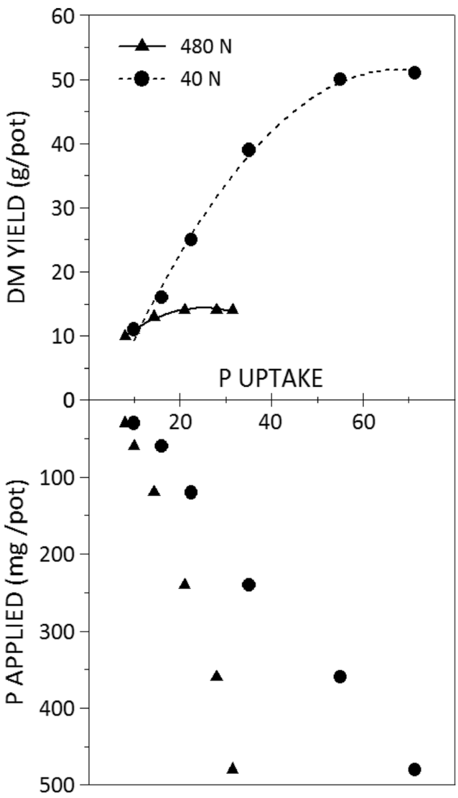


Fig. 28.6 Rice grain yield response to K fertilizer application with increasing rates of N fertilizer in Arkansas. (Adapted from Slaton et al. (2011). Potassium requirements and fertilization of rice and irrigated soybeans. Arkansas Agric Extension Service Res FSA 2165. Available at https://www.uaex.uada.edu/publications/PDF/FSA-2165.pdf)

Fig. 28.7 Response of maize biomass production to P uptake and of P uptake to P applied for different levels of N supply



The relationship between yield and applied K is similar to those described for N and P (Fig. 28.6). The examples shown in Figs. 28.5 and 28.6 indicate that these relations described for P and K may vary with N fertilizer applications or soil management systems. This reveals that nutrition and fertilization for a given nutrient cannot be considered isolated. Synergistic effects with other nutrients, such as N, explain that accumulation of P and K can be faster if an appropriate N supply is performed; this also implies a better response in yield to P or K supply. Adequate water supply improves the uptake of P and K and, thus, yield for a given amount of fertilizer. Soil water content is critical in explaining nutrient flux to the roots, particularly in those that move through diffusion due to their low concentration in the solution, such as P and K. The key role of water content in nutrient uptake explains why in Mediterranean dryland areas (annual rainfall 300–500 mm), the threshold Olsen may increase from 4–5 in rainy years to 8–9 mg/kg in dry years.

28.6 P and K Fertilization Strategies

P and K fertilization plans are based on soil tests but the interpretation differs among countries. Two main strategies are defined based on soil tests, sufficiency, and buildup and maintenance. The main objective of the sufficiency approach is the maximum short-term profitability from applied fertilizer and minimum risk of environmental impact related to excess fertilizer by accepting some risk of yield loss. On the other hand, the buildup and maintenance approach seeks long-term profitability from fertilization and no risk of yield loss due to low fertility.

Due to the complex reactions of P and K fertilizers in soils, optimal P or K supply to plants is only ensured with soil test levels above the threshold; then, the soil's available reserve of nutrients is enough for an optimal supply (no fertilizer response). Below threshold values, optimal P or K supply to crops is not guaranteed even with fertilization due to the uncertainty on the fraction of applied fertilizer that can finally remain available to plants. Therefore, according to both strategies, the soil test level should stay above the threshold.

28.6.1 Buildup and Maintenance Approach

According to this strategy, if the soil test level (*STL*) is below the threshold (STL_t), the soil should be corrected to bring it above (Tables 28.2 and 28.3). The increase in P or K may take several years, in proportion to the buffering capacity. The buildup rate for a given strategy could vary from soil to soil since P and K reactions in the soil cannot be predicted accurately.

After reaching an adequate level of fertility above the threshold value, fertilizer applications should compensate the exports of nutrients by the crop. Nutrient exports are calculated as the product of the biomass leaving the field and its nutrient concentration (Table 28.4). Soil analysis should be performed every 3–4 years to check the trends in fertility and correct the fertilizer rates if needed.

A formulation of the buildup and maintenance strategy could be (Fig. 28.8):

$STL < STL_t$	Add exported nutrient + more (according to STL).
$STL_t < STL < 2\ STL_t$	Add only exported nutrient.
$STL > 2\ STL_t$ (*maintenance limit*)	Add less than exported (e.g., 50%) or do not fertilize.

A model to estimate P fertilizer rate based on the tri-state fertilizer recommendation is:

$$P\,\text{rate}\left(\text{kg}\frac{\text{P}}{\text{ha}}\right) = \text{Exported}\,P + \frac{10\,\rho_b\,Z}{N_{\text{year}}}\left(STL_t - STL\right) \tag{28.2}$$

The first component in the model compensates for crop exports, and the second component (buildup) is intended to promote a progressive increase of soil P up to the threshold. *STL* and STL_t are given in mg/kg, ρ_b is bulk density (t/m^3), and *Z* is soil depth to correct (m). N_{year} is the number of years of buildup, considering that the amount of buildup per year should not exceed 30 kg P/ha.

Table 28.4 Average P and K concentration (% dry weight) in different harvested organs and residues for different species

	Concentration (% dry matter)			Concentration (% dry matter)		
Crop species	Part harvested	P	K	Part not harvested	P	K
Alfalfa (hay)	Biomass	0.26	2.10			
Apple	Fruit	0.05	0.75			
Barley	Grain	0.42	0.54	Straw	0.1	1.8
Bean (*Phaseolus*) dry seed	Seed (dry)	0.54	2.7	Straw	0.14	1.3
Coffee	Bean					
Cotton	Fiber + seed	0.41	0.49	Residues	0.1	1.6
Grapes (wine)	Fruit					
Lettuce	Leaves	0.75	6.67			
Maize (grain)	Grain	0.32	0.34	Residues	0.1	1.5
Millet	Grain	0.38	0.39	Residues	0.04	1.6
Olives	Fruit	0.14	1.25			
Orange	Fruit	0.14	1.35			
Palm trees	Fruit bunch	0.09	0.75			
Peach	Fruit	0.12	1.55			
Peas (dry harvest)	Seed (dry)	0.48	1.3	Straw	0.3	1.2
Potato	Tuber	0.25	2	Shoot	0.2	3.95
Rapeseed, canola	Grain	0.62	0.98	Residues	0.1	0.8
Rice	Grain	0.29	0.28	Straw	0.09	1.5
Sorghum (grain)	Grain	0.33	0.39	Residues	0.13	0.73
Soybeans	Seed	0.66	1.5	Residues	0.06	0.57
Sugar beet	Root without crown	0.25	1.54	Shoot	0.22	5.8
Sugarcane (virgin)	Stalks	0.01	0.2	Leaves + stems	0.07	0.12
Sunflower	Grain	0.63	0.72	Residues	0.14	2.52
Tomato	Fruit	0.47	4.28	Residues	0.1	1.9
Winter wheat	Grain	0.37	0.46	Straw	0.06	1.2

A more complete list is provided in Appendix

In soils with a high P fixation capacity (high Fe oxide content or clayish and calcareous), the application of rates equal to crop exportations (when $STL_t < STL < 2\ STL_t$) could lead to a long-term decrease in *STL*. In this case, P rates 10–30% above crop exportations could be recommended. Nevertheless, periodic soil analyses are needed to detect possible errors.

In the case of K, the buildup component is corrected by a factor f_K that depends on the soil's K interlayer fixing capacity (Table 28.5).

$$K\ \text{rate}\left(\text{kg}\,\frac{\text{K}}{\text{ha}}\right) = \text{Exported}\ K + \frac{10\,\rho_b\,Z\,f_K}{N_{\text{year}}}\left(STL_t - STL\right) \tag{28.3}$$

where ρ_b is bulk density (t/m^3), Z is soil depth to correct (m), and N_{year} is the number of years to reach STL_t. N_{year} is adjusted so the buildup component is lower than 60 kg K/ha. The model is similar to that described for P, but the factor f_K takes into account the fraction of K that does not remain available to plants.

Massive applications of P and K are less effective in terms of the ratio of available/applied nutrients. This is why the fertilizer rates should not exceed 30 or

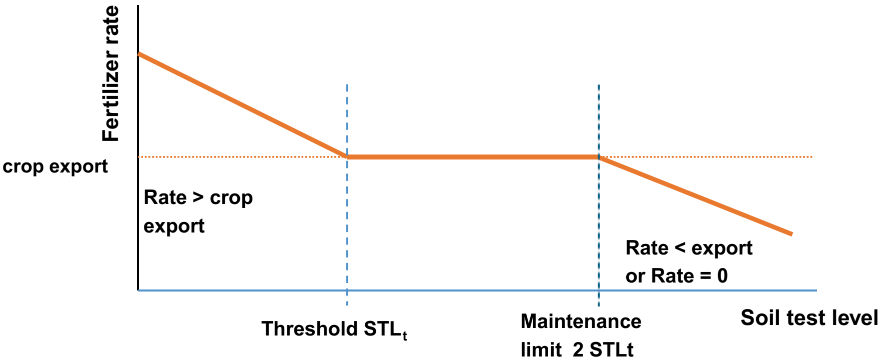


Fig. 28.8 Schematic representation of the buildup and maintenance fertilizer strategy for nonmobile nutrients

Table 28.5 Correction factor f_K for buildup strategy in K fertilization

Soil texture	f_K range
Sandy and sandy loam	1.1–1.2
Loam and silt loam	1.5–1.7
Clay loam	2
Clay	2.5–5

Alternatively, it can be calculated as $f_K = 1 + 0.05\ CEC$ where CEC is the cation exchange capacity (cmol(+)/kg)

60 kg/ha, of the P and K exports, respectively. In some US states, 100 kg P/ha and 275 kg K/ha are the annual limits recommended in a buildup and maintenance strategy.

Above a certain level, defined as the maintenance limit, rates lower than crop exportation (e.g., 50%) or no fertilizer are applied. The maintenance limit can be calculated as twice the threshold value.

Example 28.1

The soil P concentration (Olsen) in the top 25 cm is 7 mg/kg and the K concentration is 100 mg/kg (ammonium acetate). We grow maize with an expected yield of 15 t/ha (14% moisture). Soil bulk density is 1.4 t/m³. The texture is clay (45% clay) and pH = 7. Calculate P and K fertilizer rates following a buildup and maintenance strategy. Calculate also if Olsen P is 27 mg/kg and K is 300 mg/kg.

Exported dry matter:

15,000 kg/ha · (1–0.14) = 12,900 kg grain /ha.

(continued)

Example 28.1 (continued)

Now, according to Table 28.4, P and K concentrations in maize grain are 0.32% and 0.34%; thus, the amounts of P and K removed in grain are:

12,900 kg/ha · 0.0032 kg P/kg = 41.25 kg P/ha
12,900 kg/ha · 0.0034 kg K/kg = 43.8 kg K/ha.

Estimate of Olsen P threshold according to Eq. 28.1:

$STL_t = 49–0.16·45–3.81·7 = 15$ mg/kg.

Now we use Eq. 28.2:

P rate = 41.25 + 10 · 1.4 · 0.25 · (15–7) = 41.24 + 28 = 69.3 ≈ 69 kg P/ha (340 kg triple superphosphate/ha).

The buildup component is 28, below the 30 kg/ha limit.

If Olsen P is 27 ppm, as it is below the maintenance limit (30 mg/kg), we may apply only the exported nutrient:

P rate = 41.25 ≈ 41 kg P/ha (e.g., 205 kg triple superphosphate/ha).

For K:

For a clay soil, we can consider a threshold value of 250 mg/kg of acetate extractable K (Table 28.3).

Increase in K = 250–150 = 100 mg/kg.

From Table 28.5 for clay soil, we have a range of f_K between 2.5 and 5. We take $f_K = 3$.

K rate (kg K/ha) = 43.8 + 10 · 1.4 · 0.25 · 3 · (250–150) = 43.8 + 1050.

The buildup component is much higher than the maximum of 60 kg K/ha.

To stay below the limit, we would need 17.5 years. Taking $N_{year} = 18$:

K rate (kg/ha) = 48.3 + [(10 · 1.4 · 0.25 · 3)/18] (250–150) = 106.6 ≈ 107 kg K/ha.

which may be supplied with 258.3/0.5 = 214 ≈ 210 kg potassium chloride.

If soil K is 300 ppm, as it is above the threshold and below the maintenance limit, then we should compensate only the exported nutrient:

K rate = 43.8 kg K/ha (e.g., 87.6 ≈ 90 kg potassium chloride).

28.6.2 Sufficiency Approach

If initial STL is lower than the threshold, this strategy would begin by buildup applications which may be applied in several years as in the case of the buildup and maintenance strategy. Once the soil test is above threshold values, it is tested every year, and fertilizer is only applied when the nutrient level is below this value. The sufficiency approach was initially recommended to avoid environmental problems derived from an excessive P enrichment of soil which leads to high P concentration in water bodies triggering eutrophication effects. Beside this, it has another advantage: it promotes an increased use of residual P and K in the soil, i.e., a progressive starvation of P and K levels in soils may enhance the transformation of nonavailable forms to available forms and thus enhance use by plants of nonavailable forms. In any case, this can be understood as a depletion of soil nutrient reserves which in the long term may imply the application of increased rates of fertilizer.

28.7 Calcium and Magnesium

The application of Ca, Mg, and S usually follows a sufficiency strategy, so they are applied only if their deficiency is expected. Calcium and Mg have a similar cycle to that described for K (Fig. 28.4). Available amounts are also the sum of nutrients in solution plus the exchangeable pool. All extraction methods used for K can be useful as Ca and Mg availability indexes. Threshold *STLs* for Ca and Mg according to the ammonium acetate extraction are 250–500 and 30–60 mg/kg, respectively. The thresholds increase in proportion to *CEC*. Low availability of Ca can be found in acidic sandy soils with low base saturation.

Fertilization with K, Ca, or Mg must take into account the available levels of the other alkaline or alkaline earth nutrients since antagonistic effects may appear. Exchangeable K/Mg ratios above 0.5 can induce Mg deficiency and values lower than 0.1 promote K deficiency. On the other hand, Ca/Mg ratios above 10 may promote Mg deficiency, which may be a consequence of liming. When the Ca/Mg ratio is lower than 2, Ca deficiency may appear.

28.8 Sulfur

Sulfur is a component of amino acids, proteins, and vitamins. Plant sulfur concentration is 1.0–1.5%. The concentration of S increases to more than 3% in saline soils. Total S uptake is similar to that of P, with a large variability among crops, i.e., legumes and cruciferous plants require more S than P. High concentrations of S in harvested organs (>7 g S/kg dry matter) are found in *Brassica oleracea* (cabbage, broccoli), soybean, onion, tomato, and castor bean (Table 28.6). Fruits and tubers show low values (<1 g S/kg d.m.). Most S in plants is associated to N with ratios N/S between 5 (nuts) and 15 (legumes).

S deficiency has become frequent due to the reduction in S atmospheric depositions, the increase in yields, the reduction in the use of pesticides and fertilizers containing S, and losses by soil erosion and leaching. The latter will occur mostly in nonacidic soils, where S is a mobile nutrient. Residue burning causes the loss of most N and S to the atmosphere while P and K remain.

More than 95% of soil S is in organic form, composed of organic sulfates and C-bonded S. The ratio N/S in soil organic matter is 8:1. Most soil inorganic S is sulfate which is the predominant form absorbed by roots. Availability of S improves by no tillage and adding organic amendments. Microbes play a critical role in

Table 28.6 Average sulfur concentration and ratio N/S in harvested organs classified by crop groups

Group	g S/kg d.m.	N/S
Cereals (grain)	1.95	10
Cereals (straw)	1.02	8.5
Forages (legumes)	1.93	14.9
Forages (nonlegumes)	2.04	7.6
Oilseeds	3.39	9.3
Pulses	3.00	15.1
Nuts	1.00	4.7
Fruits	0.51	13.5
Roots and tubers	0.70	13.5

oxidizing S to sulfate during the growing season and depending on the availability of soil C.

Adsorption of sulfate by oxides is negligible at pH > 6.5, so liming in acidic soils increases S availability. Phosphate fertilization also contributes to S availability in acidic soils by the competition of phosphate for sorption sites.

Soil analyses of sulfur hardly correlate with actual S availability during the growing season, so they are rarely performed. It is then advisable to follow a maintenance approach to keep steady-state values of soil S.

If needed, S is added as sulfate in straight or compound fertilizers. For instance, cruciferous crops may be fertilized with K_2SO_4 instead of ClK, or with ammonium nitrate sulfate instead of ammonium nitrate. S-enriched mineral fertilizers are more expensive, so organic fertilizers rich in S might be incorporated into the fertilization program.

28.9 Micronutrients

Micronutrient availability to plants is not only determined by their content in the soil, which is dictated by the soil forming process. This availability is affected by soil properties affecting their solubility and the ability of plants to mobilize, absorb, and transport them. The effect of pH is critical. The availability of Fe, Cu, Mn, and Zn is constrained by basic pH, which in turn is controlled by carbonates. Soil organic matter affects the availability of micronutrients to plants since it may have a complexing effect that affects their solubility. Excessive P fertilization can promote Fe and Zn deficiency. B retention in soils increases with pH, so it will be deficient in calcareous soils. Molybdenum is the only micronutrient whose deficiency risk increases in acidic soils.

The paradigmatic case is Fe, an abundant element in soils whose availability is strongly reduced in calcareous soils. Iron deficiency, known as Fe deficiency chlorosis, is the consequence not only of the insolubility of Fe compounds at basic pH but also of the failure of the mechanisms involved in its accumulation in plants. Iron chlorosis is a relevant agronomic problem in calcareous soils whose typical symptom is interveinal yellowing (chlorosis) of young leaves. However, the susceptibility of plants to Fe chlorosis varies widely. Due to the low solubility of Fe compounds in soil, plants have mechanisms for mobilizing Fe from soil minerals like the exudation of low molecular weight acids. In sensitive plants, these mechanisms are not effective. In addition, cell membrane transporters may fail with basic pH in the apoplast conditioned by soil pH. This leads to an accumulation of Fe in the apoplast but not inside the cell and consequently to an accumulation in the plant while deficiency symptoms appear. This is called the "iron paradox"; Fe accumulates in the plant without physiological activity. Plants tolerant to Fe chlorosis exudate Fe-specific chelating compounds (phytosiderophores), able to mobilize it from soil and facilitate its transport through membranes.

Zinc is the second micronutrient in terms of nutritional problems in calcareous soils, especially for cereals, tolerant to Fe deficiency. In calcareous soils, Zn is fixed on carbonates and iron oxides, decreasing its plant availability. Organic ligands from decaying organic matter or root exudates can improve Zn availability to plants in soils poor in organic matter. The deficiencies of Cu and Mn are less usual, and the latter is related to soils with Mn-poor parent material.

The deficiency of Zn is not only an agronomic problem but also a human health problem when diets are based on cereals with low Zn concentration. Increasing the concentration by agricultural practices or plant breeding is called biofortification.

Soil microorganisms can affect micronutrient availability to crops. Microorganisms have mobilizing mechanisms usually based on organic acid and chelating compound exudation. Many microorganisms produce specific chelating compounds for Fe that increase its availability to plants. Competition for Fe may occur between plants and microorganisms, the latter being more competitive. The availability to plants of other nutrients such as Zn can be affected also by microorganisms.

Due to the relevant role of carbonates in Fe deficiency, the "active calcium carbonate," an index related to their reactivity, has been used to predict its deficiency. The most usual soil test for micronutrients is the extraction with the chelating agent DTPA (Table 28.7).

Table 28.7 Availability index (soil test) for micronutrients and threshold values. AB-DTPA, ammonium bicarbonate-DTPA (Sultanpour)

Micronutrient	Method	Threshold (mg/kg)	Conditions of use
Boron	Hot water	0.1–2	
Copper	AB-DTPA	0.5–2.5	Basic soils
	DTPA	0.1–2.5	Basic soils
Iron	AB-DTPA	4.0–5.0	Basic soils
	DTPA	2.5–5.0	
	Fast ammonium oxalate	350–900	Basic soils; thresholds depend on crop sensitivity to Fe deficiency (e.g., 350 olive and grapevine)
	Non-buffered hydroxylammonium	10	Basic soils; threshold defined for sensitive crops to Fe deficiency
Manganese	AB-DTPA	0.5–5.0	Basic soils
	DTPA	1.0–5.0	
Molybdenum	Ammonium oxalate pH 3.3	0.1–0.3	
Zinc	AB-DTPA	0.5–1.0	Basic soils
	DTPA	0.2–2.0	

28.10 Increasing the Efficiency of P and K Fertilizer Applications

Phosphorus fertilizers have traditionally been used as basal fertilizers before sowing, spreading over the soil surface and incorporating with tillage. They can also be applied at planting with adequate sowing machinery that incorporates the fertilizer into the soil in bands parallel to the crop rows. This application at planting is the only chance for incorporating fertilizers under no tillage. Furthermore, incorporation decreases the risk of accidental P losses and avoids enriching the surface layer with P that would facilitate losses by runoff or erosion. The time from P application to sowing should increase for low-solubility fertilizers, not less than 3 months for rock phosphate.

Fractionation of P fertilizer is uncommon and could be justified to avoid leaching in very sandy soils saturated with P. Fractionation with soluble P fertilizer may be interesting in soils very low in P and high in calcium or for crops with high P demand. The main limitation for P applications after planting is the low mobility in the soil, as they would enrich P in the soil surface, increasing P loss risk and reducing P available in depth. Thus, P fractionation is only possible when fertilizer can be incorporated into the soil, particularly close to the root system. Fertigation (Chap. 29) meets these requirements and favors P flux to the roots, improving the efficiency of applied P as compared to traditional basal applications.

As P shows low mobility in the soil, band application at sowing, particularly in low-P soils, is recommended. Localized applications reduce retrogradation by saturating the fixation capacity of a more reduced soil volume, locating the fertilizer closer to the roots, and usually promoting the early growth of crops ("starting" effect). The amount of P that can be banded is not limiting except if P is applied as ammonium phosphate since ammonium can be phytotoxic at high rates; in this case, less than 40 kg N/ha as ammonium should be applied. Banded fertilizer at sowing must be located in bands 5 cm to the side and 5 cm below the seed to avoid injuries due to high salt concentration.

Application of P as organic amendments/fertilizer or with organic matter should be considered also for improved efficiency. Organic matter competes with P for adsorption sites and decreases the precipitation as insoluble metal phosphates, thus clearly enhancing the recovery of applied P. This explains why greater improvements of soil P have been found with manure applications when compared with soluble inorganic fertilizers. The application of P as organic by-products is also gaining interest nowadays as a P recycling strategy.

K fertilizer is also applied before or at sowing. Fractionation decreases interlayer fixation and localized application in bands contributes to saturating the soil and keeping a high concentration in the soil solution. However, no improvement in recovery efficiency can be expected with the joint application with organic matter, except in very sandy soils, since the only contribution of organic matter to the soil K cycle is to provide a more charged surface and thus more retention capacity if clay content is very low.

As for micronutrients, soil biological factors affect the uptake of P and K by plants. Mycorrhiza improves the uptake of both nutrients by increasing the absorption surface and the organic P hydrolysis through phosphatase activity. In the case of P, free-living microorganisms can also contribute by exudation of acids and organic ligands promoting the dissolution of almost insoluble precipitates or with phosphatase activity. Plant breeding for increased production of phosphatases has also been attempted. All these biological factors are relevant for improved use of the nonavailable P forms in soils.

Appendix

Average P and K concentration (% dry weight) in different harvested organs and residues for different species.

Cereals and pseudocereals		Concentration (% dry matter)			Concentration (% dry matter)		
		Part harvested	P	K	Part not harvested	P	K
Barley (2-row)	*Hordeum vulgare*	Grain	0.35	0.49	Straw	0.08	2.1
Barley (6-row)	*Hordeum vulgare*	Grain	0.42	0.54	Straw	0.1	1.8
Buckwheat	*Fagopyrum esculentum*	Seed	0.35	0.46			
Maize	*Zea mays*	Grain	0.32	0.34	Residues	0.1	1.5
Foxtail millet	*Setaria italica*	Grain	0.34	0.35	Residues		1.6
Pearl millet	*Pennisetum glaucum*	Grain	0.38	0.39	Residues	0.04	1.6
Proso millet	*Panicum miliaceum*	Grain	0.34	0.48	Residues		1.6
Oats	*Avena sativa*	Grain	0.36	0.44	Straw	0.1	2.3
Quinoa	*Chenopodium quinoa*	Seed	0.41	1.12			
Rice	*Oryza sativa*	Grain	0.29	0.28	Straw	0.09	1.5
Rice (milled)	*Oryza sativa*	Grain	0.3	0.45	Straw	0.09	1.5
Rye	*Secale cereale*	Grain	0.38	0.52	Straw	0.09	0.97
Sorghum	*Sorghum bicolor*	Grain	0.33	0.39	Residues	0.13	0.73
Triticale	*X Triticosecale rimpaui*	Grain	0.34	0.57	Straw	0.03	1.2
Wheat spelt	*Triticum spelta*	Grain	0.42	0.44	Straw	0.13	1.4
Wheat-bread-hard type	*Triticum aestivum*	Grain	0.43	0.45	Straw	0.06	1.2
Wheat-bread-soft type	*Triticum aestivum*	Grain	0.37	0.46	Straw	0.06	1.2
Durum wheat	*Triticum durum*	Grain	0.42	0.5	Straw	0.06	1.2
Legumes							
Bean	*Phaseolus* spp.	Seed (dry)	0.54	2.7	Straw	0.14	1.3
Chickpea (desi)	*Cicer arietinum*	Seeds	0.4	1.2	Straw	0.16	2.3
Chickpea (kabuli)	*Cicer arietinum*	Seeds	0.4	1.2	Straw	0.16	2.3
Cowpea	*Vigna unguiculata*	Seed	0.52	1.5	Straw	0.28	1.55
Faba bean	*Vicia faba*	Seed	0.47	1.2	Straw	0.2	1.6
Lentil	*Lens culinaris*	Seed	0.43	0.86	Straw	0.14	1.15

(continued)

Cereals and pseudocereals		Concentration (% dry matter)			Concentration (% dry matter)		
		Part harvested	P	K	Part not harvested	P	K
Pea	*Pisum sativum*	Seed (dry)	0.48	1.3	Straw	0.3	1.2
Peanut	*Arachis hypogaea*	Pods	0.35	0.56	Straw	0.14	1.38
Soybean	*Glycine max*	Seed	0.66	1.5	Residues	0.06	0.57
Forages							
Alfalfa (hay)	*Medicago sativa*	Biomass	0.26	2.10			
Kentucky bluegrass (hay)	*Poa pratensis*	Biomass	0.28	1.92			
Bromegrass (hay)	*Bromus* sp.	Biomass	0.16	1.64			
Reed canary grass (hay)	*Phalaris arundinacea*	Biomass	0.28	2.99			
Clover (white) (hay)	*Trifolium repens*	Biomass	0.35	2.30			
Alsike clover (hay)	*Trifolium hybridum*	Biomass	0.25	2.48			
Crimson clover (hay)	*Trifolium incarnatum*	Biomass	0.22	2.76			
Red clover (hay)	*Trifolium pratense*	Biomass	0.26	1.89			
White clover (hay)	*Trifolium repens*	Biomass	0.35	2.25			
White (ladino) clover (hay)	*Trifolium repens*	Biomass	0.32	2.43			
Tall fescue (hay)	*Lolium arundinaceum*	Biomass	0.32	2.36			
Grass (hay)	*Poaceae*	Biomass	0.22	1.45			
Grass (silage)	*Poaceae*	Biomass	0.32	1.88			
Maize (silage)	*Zea mays*	Biomass	0.20	1.00			
Foxtail millet (silage)	*Setaria italica*	Biomass	0.18	1.94			
Pearl millet (silage)	*Pennisetum glaucum*	Biomass	0.26	1.63			
Oat (hay)	*Avena sativa*	Biomass	0.24	1.26			
Orchardgrass (green chop)	*Dactylis glomerata*	Biomass	0.18	2.64			
Orchardgrass (hay)	*Dactylis glomerata*	Biomass	0.25	2.80			
Rye (hay)	*Secale cereale*	Biomass	0.22	1.24			
Perennial ryegrass (hay)	*Lolium perenne* ssp. *perenne*	Biomass	0.20	1.42			
Sorghum	*Sorghum bicolor*	Biomass	0.21	1.10			
Sweet clover (hay)	*Melilotus* sp.	Biomass	0.24	1.65			
Timothy (hay)	*Phleum pratense*	Biomass	0.17	1.63			
Bird's-foot trefoil (hay)	*Lotus corniculatus*	Biomass	0.23	1.89			
Turnip (green chop)	*Brassica rapa* var. *rapa*	Biomass	0.42	3.02			
Vetch (hay)	*Vicia sativa*	Biomass	0.36	2.24			
Hairy vetch (hay)	*Vicia villosa*	Biomass	0.36	2.23			
Wheatgrass (hay)	*Poaceae*	Biomass	0.07	2.70			
Sugar, oil, and fiber crops							
Cotton	*Gossypium hirsutum*	Fiber + seed	0.41	0.49	Residues	0.1	1.6

(continued)

Cereals and pseudocereals		Concentration (% dry matter) Part harvested	P	K	Concentration (% dry matter) Part not harvested	P	K
Flax	*Linum usitatissimum*	Seed	0.57	0.84	Residues	0.08	1.74
Opium poppy	*Papaver somniferum*	Capsules	0.6	2.4	Leaves, stems	0.3	3.1
Rapeseed	*Brassica* spp.	Grain	0.62	0.98	Residues	0.1	0.8
Safflower	*Carthamus tinctorius*	Grain	0.6	0.75	Residues	–	–
Sugar beet	*Beta vulgaris*	Root without crown	0.25	1.54	Shoot	0.22	5.8
Sugarcane	*Saccharum* spp.	Stalks	0.01	0.2	Leaves + stems	0.07	0.12
Sunflower	*Helianthus annuus*	Grain	0.63	0.72	Residues	0.14	2.52
Tobacco burley	*Nicotiana tabacum*	Leaf + stem	0.31	3.86	Stalks	0.31	3.86
Tobacco Virginia	*Nicotiana tabacum*	Leaves	0.27	2	Stalks	0.27	2
Horticultural crops							
Artichoke	*Cynara scolymus*		0.51	2	Residues	–	–
Asparagus (green)	*Asparagus officinalis*	Stem	0.69	3.4			
Asparagus (white)	*Asparagus officinalis*	Stem	0.74	4			
Beet	*Beta vulgaris*	Root	0.32	2.46	Shoot	0.44	6.26
Brussels sprout	*Brassica oleracea*	Leaves	0.51	3.25			
Cabbage	*Brassica oleracea*	Leaves	0.35	2.73			
Carrot	*Daucus carota*	Root	0.33	2.43	Shoot	0.19	1.88
Cauliflower	*Brassica oleracea*	Head	0.66	3.22			
Celery	*Apium graveolens*	Leaves	0.66	4.8		0.66	4.8
Chicory	*Cichorium intybus*	Leaves	0.23	4			
Cucumber	*Cucumis sativus*	Fruit	0.53	4.25	Residues	–	–
Eggplant	*Solanum melongena*	Fruit	0.31	3	Residues	–	–
Endive	*Cichorium endivia*	Leaves	0.45	5.6			
Faba bean (green)	*Vicia faba*	Fruits	0.5	1.32	Residues	–	–
Leak	*Allium porrum*	Bulb	0.21	1.06	Residues	–	–
Iceberg lettuce	*Lactuca sativa*	Leaves	0.5	2			
Romaine lettuce	*Lactuca sativa*	Leaves	0.75	6.67			
Melon	*Cucumis melo*	Fruit	0.16	2.58	Residues	–	–
Muskmelon	*Cucumis melo*	Fruit	0.36	3.16	Residues	–	–
Parsley	*Petroselinum crispum*	Leaves	0.4	2.7			
Pepper (green)	*Capsicum annuum*	Fruits	0.35	2	Residues	–	–
Pepper (red)	*Capsicum annuum*	Fruits	0.3	2.4	Residues	–	–
Pumpkin	*Cucurbita* spp.	Fruit	0.39	2.78	Residues	–	–
Radish	*Raphanus sativus*	Root	0.4	3.17	Residues	–	–
Spinach	*Spinacia oleracea*	Leaves	0.56	5.66			
Squash	*Cucurbita pepo*	Fruit	0.4	3.5	Residues	–	–
Tomato	*Lycopersicon esculentum*	Fruit	0.47	4.28	Residues	0.1	1.9
Watermelon	*Citrullus lanatus*	Fruit	0.11	1.33	Residues	–	–
Fruit trees, vines, and shrubs							
Almond	*Prunus amygdalus*	Fruit	0.37	0.75			

(continued)

Cereals and pseudocereals		Concentration (% dry matter) Part harvested	P	K	Concentration (% dry matter) Part not harvested	P	K
Apple	*Malus sylvestris*	Fruit	0.05	0.75			
Apricot	*Prunus armeniaca*	Fruit	0.14	2.17			
Avocado	*Persea americana*	Fruit	0.15	2.31			
Banana	*Musa paradisiaca*	Fruit	0.08	1.54			
Cherimoya	*Annona cherimola*	Fruit	0.15	1.17			
Cherry	*Prunus avium*	Fruit	0.01	1.16			
Coconut	*Cocos nucifera*	Copra	0.3	5			
Date palm	*Phoenix dactylifera*	Fruit	0.05	0.84			
Fig	*Ficus carica*	Fruit	0.07	1.11			
Grape (table)	*Vitis vinifera*	Fruit	0.05	1.02			
Grape (wine)	*Vitis vinifera*	Fruit	0.07	0.95			
Grapefruit	*Citrus paradisi*	Fruit	0.11	1.38			
Hazelnut	*Corylus avellana*	Fruit	0.33	0.47			
Kiwi	*Actinidia* spp.	Fruit	0.18	1.43			
Lemon	*Citrus Limon*	Fruit	0.12	1.15			
Mango	*Mangifera indica*	Fruit	0.11	0.95			
Oil palm	*Elaeis guineensis*	Fruit bunch	0.09	0.75			
Olive	*Olea europaea*	Fruit	0.14	1.25			
Orange	*Citrus sinensis*	Fruit	0.14	1.35			
Peach	*Prunus persica*	Fruit	0.12	1.55			
Pear	*Pyrus communis*	Fruit	0.07	0.77			
Persimmon	*Diospyros kaki*	Fruit	0.07	1.01			
Plum	*Prunus domestica*	Fruit	0.07	1.16			
Pomegranate	*Punica granatum*	Fruit	0.1	1.04			
Quince	*Cydonia oblonga*	Fruit	0.1	0.95			
Walnut	*Juglans regia*	Fruit	0.22	0.41			
Roots, tubers, and bulbs							
Cassava	*Manihot esculenta*	Root	0.12	0.77			
Garlic	*Allium sativum*	Bulb	0.44	1.38	Residues	0.2	1.3
Onion	*Allium cepa*	Bulb	0.35	1.2	Shoot	0.38	2.75
Potato	*Solanum tuberosum*	Tuber	0.25	2	Shoot	0.2	3.95
Sweet potato	*Ipomoea batatas*	Tuber	0.15	1.22			
Yam (Chinese)	*Dioscorea opposita*	Tuber	0.15	1.5			
Yam (white)	*Dioscorea rotundata*	Tuber	0.25	2.3			

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Fertigation

29

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Abstract

Fertigation is the joint application of nutrients along with irrigation water. It is best suited for high-frequency drip irrigation although it may be adapted to other irrigation methods. Fertigation requires a dosing system and tanks for the stock solution where nutrients are incorporated. The main characteristics to consider for the fertilizers used in fertigation are concentration, purity, solubility, and pH reaction. Irrigation water quality should also be considered, especially the concentration of bicarbonates and calcium. The calculation of stock solutions is based on the total requirements for N, P, and K and total irrigation to be applied. Specific recipes for fertigation solutions have been developed for several species. Complete nutrient solutions (e.g., Hoagland-Arnon) are easy to calculate considering the actual concentration of salts in irrigation water.

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29.1 Introduction

Fertigation is the joint application of water and nutrients, which requires adding a nutrient-dosing device to the irrigation system. Although this technique can be applied to all types of irrigation systems, it is generally used in drip irrigation systems and to a lesser extent in full-coverage sprinkler systems and irrigation machines.

If handled correctly, fertigation results in a very high efficiency in nutrient application, particularly with high-frequency drip irrigation. This high efficiency is explained by the following:

(a) A localized fertilizer application, which is more efficient in poor-nutrient or high cation exchange capacity (*CEC*) soils. This is relevant for nutrients strongly bound to soil particles such as P and K.
(b) Drip irrigation systems cause a concentration of the root system within the wet bulbs; thus, the nutrient application is concentrated in areas of high root length density, where most nutrient uptake occurs.
(c) The water content in wet bulbs is usually close to the field capacity of the soil; high water content enhances the flux of nutrients to roots through mass flow or diffusion, thus increasing the efficiency of applied fertilizers.
(d) Fertigation with drip irrigation allows frequent application of very low fertilizer doses, which allows matching nutrient supply to plant requirements that can vary depending on the growing stage. This has clear advantages for mobile nutrients such as N since large soil N accumulation is avoided, thus decreasing losses and opening the opportunity for reducing N application. This is seen when fertigation with N is compared with a conventional N fertilization combining one basal and two side-dress applications (Fig. 29.1). With nonmobile nutrients, such as P and K, frequent application of very low doses enhances fixation in forms (adsorption vs precipitation in calcareous soils in the case of P) that are in equilibrium with the soil solution, thus increasing the efficiency of applied nutrients. Additional advantages of fertigation are related to irrigation uniformity (see Chapter 23).

Fertigation can be a cost-effective fertilizer application technique when a drip irrigation system has been installed. Although it requires a dosing device, after this initial investment, the equipment and labor costs for applying fertilizers are usually lower than with other techniques. On the other hand, the fertilizers used are usually more expensive.

29.2 Dosing Systems

Fertigation is usually performed by injecting fertilizer in liquid form (fertilizer solution, commercial or prepared on the farm) into the irrigation water flow to the emitters. Two types of dosing methods can be distinguished:

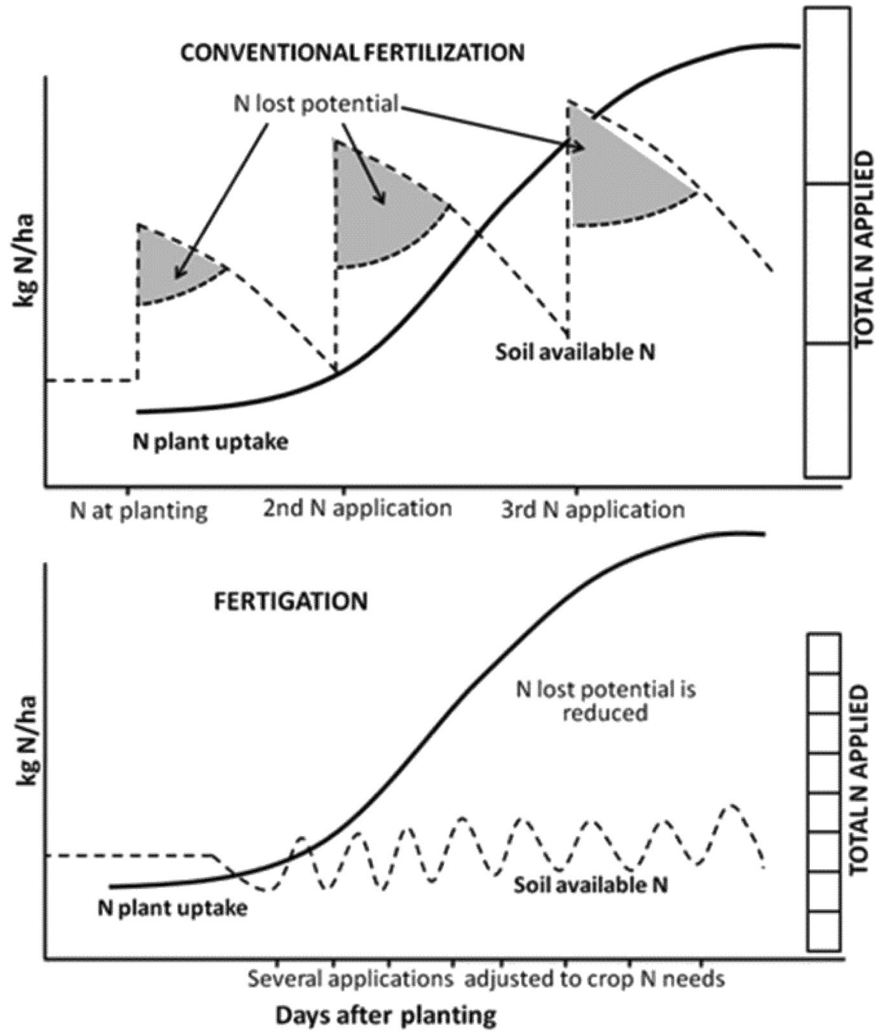

Fig. 29.1 Time course of crop N uptake and soil N availability for conventional fertilization and fertigation. (Adapted from Quemada and Gabriel (2016). Global Food Security, 9: 29–35)

(a) Proportional: It applies a constant nutrient concentration, so the flow of nutrients entering the system has to be proportional to the irrigation flow.
(b) Quantitative: A total amount of nutrients is added to the irrigation system. The concentration varies with time.

Fertilizers may be injected with different types of devices (Fig. 29.2):

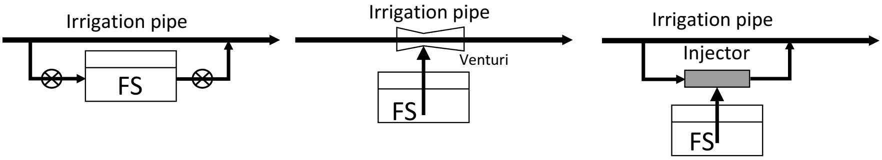

Fig. 29.2 Diagrams of fertigation dosing systems. (**a**) Fertilizer tank with pressure differential (left), (**b**) with Venturi device (center), (**c**) with hydraulic injection pump (right). FS: fertilizer solution

(a) Differential pressure.

A pressure-regulating valve connected to the fertilizer tank is inserted between the inlet and outlet. The pressure difference forces the water to flow through the tank, carrying the nutrients to the main line.

It can add solid or liquid products and serves only for quantitative dosing. It is easy to maintain and does not require additional energy but the pressure in the main pipe is reduced. This method is suited for conditions where fertigation is performed at irregular intervals.

(b) Venturi system. It connects a Venturi device (narrowing) in parallel to the main pipe. The depression in the Venturi causes the suction of the nutrient solution. This system allows proportional dosing. The fertilizer application rate can be adjusted to small amounts but causes pressure loss in the main pipe.

The depression depends on the water velocity; thus the accuracy of a Venturi dosing system depends on the capacity of the irrigation system to maintain a constant flow.

(c) Injection pump. An electric or hydraulic pump may be used. In the latter case, no energy supply will be required. It is easy to install and operate, allows adjusting the dose, and does not involve pressure loss in the main pipe. It can be used for proportional or quantitative dosing.

(d) Direct connection. The irrigation pump inlet is connected to the fertilizer tank. The nutrient concentration is kept constant. If a system for tank automatic filling is added, the concentration will vary with time. This is a simple and inexpensive method best suited for small installations but difficult to automate. The main problems are the risk of sucking air in the pump and the pump damage by corrosion.

Whatever the system chosen, it is advisable to install a filter downstream of nutrient injection and check valves to prevent contamination of the supply line if return flow occurs.

29.3 Alternatives of Fertigation

Different types of fertigation can be defined depending on the combination of nutrients applied in each fertigation.

(a) With complete nutrient solutions: Although it is the usual choice for hydroponic systems on artificial substrates such as rock wool and perlite, it can also be used for crops on soil. The nutrient solution applied in each fertigation should include all macro- and micronutrients. This will require the use of several tanks to avoid incompatibility problems between different fertilizer products:

Tank A: Macronutrients except Ca in an acid medium, usually applying part of N or P such as nitric or phosphoric acid.
Tank B: Fertilizers with Ca in neutral or acid medium.
Tank C: Micronutrients in neutral medium.

Another alternative for the distribution of nutrients:

Tank A: NPK.
Tank B: N, K, Ca, S, and micronutrients.
Tank C: Nitric acid.

Fertigation with N, P, and K in soil may require only one tank. For hydroponics, the better choice is three tanks.

(b) Incomplete solutions: In cropping systems on soil, we may apply P as basal fertilizer before sowing to avoid the high cost of P soluble forms and the high probability of P precipitation in the system. In this case, only N and K are usually applied through fertigation. Only one tank is required since N and K combinations are not problematic. We may apply each primary nutrient from a different tank in different irrigation events. This alternative reduces the risk of precipitation in the tank or irrigation net.

Whatever the type of fertigation tank, its size and the total amount of fertilizer dissolved is determined by the solubility of the less soluble fertilizer.

29.4 Fertilizers for Fertigation

The main properties considered in fertilizers for fertigation are nutrient concentration, purity, solubility, pH effect, and compatibility. The electrical conductivity (*EC*) in the applied solution should not exceed certain thresholds, and the pH should be in the 5.0–6.5 range, so nutrients are available for root uptake. Precipitates can be formed above this range (e.g., Ca compounds with phosphate), while below, the root system may be damaged. The main properties of fertilizers more widely used in fertigation are shown in Table 29.1.

The form in which N is supplied is a critical aspect of fertigation. Nitrogen cannot be supplied exclusively as NH_4^+ because (a) it is phytotoxic at high concentrations in the growing media and (b) it can promote a decreased uptake of other cations such as Ca^{2+}, Mg^{2+}, and K^+. This is caused by competition for absorption

Table 29.1 Properties of the main fertilizers used in fertigation

		Eq weight	Practical solubility	Concentration (mass percentage)					
		g/eq	kg/m^3	N	P	K	S	Ca	Mg
Monoammonium phosphate (MAP)	$NH_4\ H_2\ PO_4$	115	190	12	22.6	0	1.5	1.5	0
Monopotassium phosphate (MKP)	$K\ H_2\ PO_4$	136.1	120	0	22.8	28.7	0	0	0
Ammonium nitrate	$NH_4\ NO_3$	80	480	34	0	0	0	0	0
Ammonium sulfate	$(NH_4)_2\ SO_4$	66.1	380	21	0	0	24	0	0
Calcium nitrate (hydrate)	$Ca(NO_3)_2\ .4H_2O$	118	350	12	0	0	0	17	0
Potassium nitrate	$K\ NO_3$	101.1	80	13.4	0	39	0.2	0	0
Magnesium nitrate (hydrate)	$Mg\ (NO_3)_2.6H_2O$	128.2	380	10.9	0	0	0	0	9.5
Potassium chloride	K cl	74.6	170	0	0	49.8	0	0	0
Potassium sulfate	$K_2\ S0_4$	87.2	60	0	0	41.5	16	0	0
Magnesium sulfate (hydrate)	$Mg\ SO_4.7H_2O$	123.2	50	0	0	0	13	0	9.9
Urea	$CO\ (NH_2)_2$	60.1	260	46	0	0	0	0	0
Phosphoric acid 55%, 1.38 g/cm^3	$H_3\ PO_4$	98	–	0	17.4	0	0	0	0
Phosphoric acid 75%, 1.58 g/cm^3	$H_3\ PO_4$	98	–	0	23.7	0	0	0	0
Nitric acid 57%, 1.35 g/cm^3	$NO_3\ H$	63	–	12.5	0	0	0	0	0
Calcium nitrate	$Ca\ (NO_3)_2$	82	350	17	0	0	0	24	0
Magnesium nitrate	$Mg\ (NO_3)_2$	74.1	350	18.9	0	0	0	0	16.4

The simplest solid fertilizers are included except acids, provided as liquids. Practical solubility refers to the maximum amount of product to dissolve in stock solutions prepared in the farm and is between 25% and 50% of solubility at low temperature

mechanisms and decreasing electrochemical potential through plasma membranes, which induces an increased excretion of H^+ by root cells to maintain an electrochemical gradient. Conversely, when N is provided only as NO_3^-, its absorption promotes the alkalinization of the root apoplast and the rhizosphere due to the absorption mechanism of nitrate (symport with H^+). This effect can impair the absorption of other nutrients such as Fe. Therefore, N should be applied as 80–90% nitrate and 10–20% ammonium to maintain an optimum pH of the rhizosphere while taking advantage of the acidification effect of NH_4^+. Applying N only as NO_3^- could be a good choice for fertigation in acid soils.

Temperature is the critical factor affecting fertilizer solubility, which is proportional to temperature. Thus, the maximum concentration of fertilizers in a solution is determined by the minimum temperature in the tank. Dissolving fertilizers is usually an endothermic reaction that decreases the temperature of the solution. The effect is important for urea and nitrates (ammonium, calcium, and potassium). However, dilution of phosphoric acid is an exothermic reaction that can be used to compensate for the effect of endothermic dissolution reactions, thus increasing the solubility of the fertilizer added afterward.

The most common products are highly soluble, like nitrates (calcium, ammonium, potassium) and potassium chloride. To ensure high purity and solubility, the fertilizer industry produces specific solid fertilizers for fertigation and commercial solutions (e.g., N − 20 solution). Composite solid fertilizers and liquid fertilizer solutions are presented in a wide range of ratios N/P/K, with or without micronutrients. Liquid composite fertilizers have a low nutrient concentration due to solubility limitations.

The use of incompatible fertilizers or the interaction of the fertilizer with irrigation water, especially if it is hard and/or alkaline, can cause precipitation in the fertilization tank and the clogging of drippers and filters. These problems can be avoided with the right fertilizers and adequate irrigation management, i.e., allow for enough leaching, and use acidified fertilizer solutions.

The main incompatibilities among fertilizers in fertigation are those involving the risk of precipitation of Ca and Mg compounds (Table 29.2), such as the following:

Calcium nitrate in combination with phosphates or sulfates leads to precipitation of calcium sulfate or calcium phosphate.
Ammonium phosphate with magnesium sulfate leads to precipitation of magnesium phosphate.

Micronutrient application should consider the stability of the forms in which they are applied, usually as chelates that are affected by pH and by the presence of other

Table 29.2 Compatibility of fertilizers for fertigation

Fertilizer	Compatibility with calcium fertilizers ($Ca(NO_3)_2$, $Ca\ Cl_2$)	Solubility problems with other fertilizers
Nitric acid (HNO_3)	*YES*	
Potassium nitrate (KNO_3)	*YES*	K_2SO_4
Ammonium nitrate ($NH_4\ NO_3$)	*YES*	
Magnesium nitrate (mg(NO_3)$_2$)	*YES*	$NH_4\ H_2PO_4$ $CO(NH_2)_2H_3PO_4$ KH_2PO_4
Ammonium sulfate ($(NH_4)_2SO_4$)	*NO*	K_2SO_4
Monoammonium phosphate ($NH_4\ H_2PO_4$)	*NO*	$Mg(NO_3)_2$ $MgSO_4{\cdot}7H_2O$
Urea phosphate ($CO(NH_2)_2H_3PO_4$)	*NO*	$Mg(NO_3)_2$ $MgSO_4{\cdot}7H_2O$
Phosphoric acid (H_3PO_4)	*NO*	
Monopotassium phosphate (KH_2PO_4)	*NO*	$Mg(NO_3)_2$ $MgSO_4{\cdot}7H_2O$ K_2SO_4
Potassium sulfate (K_2SO_4)	*NO*	$(NH_4)_2SO_4$ $MgSO_4{\cdot}7H_2O$ KNO_3 KCl KH_2PO_4
Potassium chloride (KCl)	*YES*	K_2SO_4
Magnesium sulfate heptahydrate ($MgSO_4{\cdot}7H_2O$)	*NO*	$NH_4\ H_2\ PO_4$ $CO(NH_2)_2H_3$ PO_4 KH_2PO_4 K_2SO_4
Urea ($CO(NH_2)_2$)	*YES*	

cations in high concentrations such as Ca. The application of Fe and P in acid solutions leads to precipitates of Fe phosphates.

29.5 Quality of Water for Fertigation

The main salts in water are chlorides, sulfates, carbonates, and bicarbonates of Ca, Mg, Na, and K. Some waters may contain other ions (nitrates, phosphates, ammonium, etc.) and certain metals (Fe, Mn, Zn, Pb, etc.) that can be toxic (Table 29.3). Standard laboratory analyses of irrigation water include the major cations (Ca^{2+}, Mg^{2+}, Na^+, and K^+) and anions (Cl^-, SO_4^{2-}, CO_3^{2-}, HCO_3^-). Boron may also be determined because of its high toxicity even in small concentrations. Nitrate concentration (dominant N form in water) should also be measured to discount it from the crop N requirement.

The most common problem is the presence of bicarbonate, which combines with Ca and Mg and may precipitate depending on the pH. Waters high in Ca with alkaline pH will cause problems with more than 2 meq/L of bicarbonate. To correct these problems and keep pH in the desired 5.0–6.5 range, an acid is added, leaving 0.5 meq/L of bicarbonate not neutralized.

Another possible problem is related to P fertilizers. Insoluble Ca and Mg phosphates are generated in waters high in Ca or Mg when pH is high. These precipitates are deposited on the pipe walls and in the emitters, causing their clogging. The availability of P to the plants is also reduced. Acid P fertilizers such as monoammonium phosphate (MAP) or phosphoric acid will reduce the risk of precipitation of Ca and Mg phosphates.

In any case, dissolved fertilizers remaining in the emitters at the end of the fertigation can precipitate when water evaporates. To avoid this the duration of fertigation should be shorter than that of irrigation allowing flushing with water at the end of the irrigation. To dissolve the precipitates left and unclog the drippers, we may use the acidic reaction of some fertilizers and/or the injection of an acid solution that also removes bacteria and algae. After injecting the acid, the irrigation and the injection systems should be carefully washed with additional irrigation water.

Other quality issues in irrigation water may be the following:

(a) The presence of algae (irrigation ponds) or bacteria (groundwater, ponds) requires additional treatments, which may be performed with chlorine, copper sulfate, or potassium permanganate.

Table 29.3 Main ionic interactions to be considered in fertigation

Ion	Toxicity	Precipitates with	Impairs absorption of	Favors absorption of
Ca^{2+}	No	SO_4^{2-}, HCO_3^-, $H_2PO_4^-$		
Mg^{2+}	No	$H_2PO_4^-$	K^+[a]	
Na^+	Yes			
Cl^-	Yes		NO_3^-, $H_2PO_4^-$	
SO_4^{2-}	Yes	Ca^{2+}		Na^+

[a]This antagonistic effect is stronger with fertigation than with conventional fertilization since fertigation keeps higher Mg and K concentrations in the soil solution

(b) Ferruginous underground waters produce Fe or Mn rust deposits when they oxidize. They require first pre-treatment such as aeration or chelation and then filtration to retain precipitated oxides.

29.6 Calculation of Stock Solutions

In fertigation systems with proportional dosing, a concentrated solution known as stock or mother solution is prepared in the irrigation head. Fertigation is programmed to dilute the solution with the irrigation water in the ratios of 1:100 up to 1:500 while controlling the pH and *EC*. This irrigation water with the added fertilizer will reach the emitters after filtering. This solution reacts with the substrate and results in the final nutrient solution absorbed by the roots.

The electrical conductivity (*EC*, dS/m) may be calculated approximately as a function of the concentration of cations (*CC*, in meq/L) or anions or as a function of the salt concentration (C_S, also named total dissolved solids, *TDS*, in g/L):

$$EC = \frac{CC}{10} = \frac{C_s}{0.64} \tag{29.1}$$

For the calculation of the stock solution, we may face different situations:

(a) We know the total amount of N, P, and K to add to the total amount of irrigation. Therefore, we deduce the concentration of the nutrient and then convert it to a quantity of fertilizer to be added using the concentrations indicated in Table 29.1. The maximum solubility (e.g., 80% of this) should not be exceeded, particularly if temperature oscillations are expected. In the final fertilizer solution, the stock solution is diluted M times, so the amount of fertilizer to add to the stock solution (kg fertilizer/m^3) will be:

$$M \cdot \frac{\text{nutrient requirement}\left(\dfrac{\text{kg nutrient}}{\text{ha}}\right)}{\text{irrigation}\left(\dfrac{\text{m}^3}{\text{ha}}\right)\cdot\text{concentration}\left(\dfrac{\text{kg nutrient}}{\text{kg fertilizer}}\right)} \tag{29.2}$$

(b) We know the ideal concentration of each nutrient (Ne, Pe, Ke) in meq/L, and we want to determine the amount of fertilizers to be added to the tank, considering that the stock solution will be diluted M times. We have two possible options:

(b.1) No acid correction is needed. In the simplest case, we have soft water with less than 0.5 meq bicarbonate/L so no pH correction is required. In hydroponics, dissolved bicarbonate could be the C source for autotrophic nitrifying microorganisms; thus, nitrification is enhanced by a low NH_4^+/NO_3^- ratio.

We start from the P fertilizer requirement, as it is often the element of lower concentration. We will apply P as monoammonium phosphate (MAP) or monopotassium phosphate (MPP) to cover the needs. The remaining needs of N and K will be completed with potassium nitrate, ammonium nitrate, and/or potassium sulfate.

Example 29.1

The ideal solution for a given crop is 4–1-2 meq/L. The stock solution is diluted 200 times.

With MAP:

P: 1 meq P/L •115 mg MAP meq P^{-1} • 10^{-3} g mg^{-1} •10^3 L m^{-3} = 115 g MAP m^{-3}.

This amount contains also 1 meq/L of NH_4^+, which is discounted from the required N concentration, so we still need 3 meq N/L which may be achieved with 1.5 mmol/L of ammonium nitrate, AN (each mol provides 2 equivalents of N).

$$1.5\,\text{mmol AN/L} \bullet 80\,\text{mg AN mmol AN}^{-1} \bullet 10^{-3}\,\text{g mg}^{-1} \bullet 10^{3}\,\text{L m}^{-3} = 120\,\text{g AN m}^{-3}$$

Finally we satisfy the K requirement using potassium sulfate (PS):

$$2\,\text{meq PS/L} \bullet 87.2\,\text{mg PS meq PS}^{-1} \bullet 10^{-3}\,\text{g mg}^{-1} \bullet 10^{3}\,\text{L m}^{-3} = 174.4\,\text{g PS m}^{-3}$$

The concentrations in the stock solution will be obtained by multiplying the concentrations above by the dilution factor (200):

MAP	23 kg m^{-3}
NO_3NH_4	24 kg m^{-3}
SO_4K_2	34.9 kg m^{-3}

We should check that the concentrations in the stock solution do not exceed the solubility of the selected fertilizers (Table 29.1).

Other possible stock solutions could be:

MKP	27.2 kg m^{-3}
NO_3K	20.2 kg m^{-3}
NO_3NH_4	24.0 kg m^{-3}

MKP	27.2 kg m^{-3}
SO_4K_2	17.4 kg m^{-3}
NO_3NH_4	32.0 kg m^{-3}

(b.2) Water with more than 0.5 meq HCO_3^-/L: The pH has to be corrected. Under these conditions, dissolved bicarbonate is not restrictive for nitrification, so the ratio NH_4^+/NO_3^- is not important.

Acid is used to neutralize bicarbonate leaving only 0.5 meq/L. Then the procedure is similar to that explained in the previous case.

Example 29.2

Ideal solution 4–1-2 meq/L. Water with 3.5 meq/L of HCO_3^-. Dilution 200 times. Correction with phosphoric acid 55% (density 1.38 g cm^{-3}).

To neutralize 3.0 meq/L of HCO_3^-, we need 3.0 meq/L of protons that can be supplied by 1 mmol/L of pure PO_4H_3.

1 mmol PO_4H_3/L• 98 mg PO_4H_3 mmol $PO_4H_3^{-1}$ •10^{-3} g mg^{-1} •10^3 L m^{-3} = 120 g PO_4H_3 m^{-3}.

120 g PO_4H_3 m^{-3} • 1 g solution/0.55 g PO_4H_3 • 1 cm^3 solution/1.38 g solution = 158 cm^3 m^{-3} (phosphoric acid 55%).

We have also covered the need of P (1 meq/L).

We will cover now the need for K using potassium sulfate (PS):

2 meq K/L • 87.2 mg PS meq K^{-1} • 10^{-3} g mg^{-1} •10^3 L m^{-3} = 174.4 g PS m^{-3}

To supply 4 meq/L of N with ammonium nitrate, as each mol gives 2 equivalents of N, we will apply 2.0 mmol AN/L:

2.0 mmol AN/L • 80 mg AN mmol AN^{-1} • 10^{-3} g mg^{-1} •10^3 L m^{-3} = 160 g AN m^{-3}

Then we apply the dilution factor (200) and arrive at the following stock solution:

Phosphoric acid 55%	31.6 L m^{-3}
SO_4K_2	34.9 kg m^{-3}
NO_3NH_4	32.0 kg m^{-3}

Example 29.3

Ideal solution 4–1-2 meq/L. Water with 3.5 meq/L of HCO_3^-. Dilution 200 times. Correction with nitric acid 57% (density 1.35 g cm^{-3}).

To neutralize 3.0 meq/L of HCO_3^-, we need 3.0 meq/L of protons that can be supplied by 3 mmol/L of pure NO_3H.

3 mmol /L • 63 mg $mmol^{-1}$ • 10^{-3} g mg^{-1} •10^3 L m^{-3} = 189 g m^{-3} pure acid

189 g NO_3H m^{-3} • 1 g solution/0.57 g NO_3H • 1 cm^3 solution/1.35 g solution = 245.6 cm^3 m^{-3} (nitric acid 57%).

which contains also 3 meq/L NO_3; thus we need a further addition of 1 meq/L of N to complete the required 4 meq N/L.

We apply P as MAP:

1 meq P/L • 115 mg MAP meq P^{-1} • 10^{-3} g mg^{-1} • 10^3 L m^{-3} = 115 g MAP m^{-3}

which contains also 1 meq/L NH_4^+, therefore satisfying the whole needs of N.

Finally, we apply K as potassium sulfate:

2 meq K /L • 87.2 mg PS meq K^{-1} • 10^{-3} g mg^{-1} • 10^3 L m^{-3} = 174.4 g PS m^{-3}

(continued)

Example 29.3 (continued)

We apply the dilution factor (200) and arrive at the following stock solution:

NO_3H (57%)	49.1 L m^{-3}
MAP	23 kg m^{-3}
SO_4K_2	34.9 kg m^{-3}

There is software available for the calculation of stock solutions. For instance, the Nutrient Solution Calculator developed by L. Incrocci (U. Pisa) allows calculating the stock solution when the recipe is known.

29.7 Fertigation Control

The *EC* in the emitters can be estimated from water analysis and the amount of applied fertilizers. In any case, *EC* and pH can be measured in emitters to check the accuracy of the calculations. In systems that allow measuring drainage volume and the characteristics (pH, *EC*) of the input and output solutions, we can check if the fertigation program is correct and amend it if necessary. This would also serve for automation of the fertigation program.

First, we set the target leaching fraction (LF_t) as a function of the nutrient solution *EC*. The observed LF should be similar to LF_t. Otherwise, the irrigation volume should be adjusted.

Low nitrate concentration in drainage may indicate that N is limiting, so its concentration should be increased in the nutrient solution.

A higher value of *EC* and/or chlorine in the leachate than in the applied solution indicates an accumulation of salts in the root zone. If the difference between the *EC* of drainage and irrigation water is greater than 0.4–0.5 dS/m, and/or if the chlorine concentration in the drainage solution is higher than that of the incoming solution and above 50 mg/L, an irrigation without fertilizers should be applied to leach salts.

The optimum pH of the irrigation solution is 6–6.5 and can be adjusted by acid injection. The drainage water pH should not exceed 8.5. Otherwise, the NH_4^+/NO_3^- ratio of the nutrient solution should be increased up to 0.25.

29.8 Calculation of Complete Nutrient Solutions

In the case of hydroponics, we need complete solutions including micronutrients. The macronutrients to be added are determined taking into account the composition of the irrigation water and the composition of the ideal solution. A widely used reference nutrient solution is the one proposed by Hoagland and Arnon. The calculation procedure is shown in Example 29.4. Table 29.4 shows the composition of recommended solutions for different species.

Table 29.4 Some examples of recommended concentrations (meq/L) of macronutrients in the nutrient solution for different species

	NO_3^-	NH_4^+	$H_2PO_4^-$	K^+	Ca^{2+}	Mg^{2+}	SO_4^-
Tomato and pepper (hydroponics)	15		2	9	10	3	5
Tomato, pepper on soil)	8.0–12.0	0.9–1.4	1–1.5	4.0–6.0	4.8–7.0		
Melon (on substrate)	6.5–11.5	0.7–1.3	1.2	4.0–7.5	3.5–6.5		
Melon (on soil)[a]	9	0.8	–	7	4.5		
Strawberry[a]	7	3.5	1	4.5			
Bean	9		1	3.3	6.6	2	2
Cucumber	10.5	1	1	5	7.5	2	2
Lettuce, endive	19	1.2	2	9.0–11	9.0–10	2.0–3.0	2.25
Olive	1.4–2.75	0.6–1.25	1	2.0–4.0			2
Citrus	4–5.5	0.5	0.5	1–1.5	2		
Grapevine	2.5–5	0.5–1	1	3.0–6.0			

Adapted from Cadahia C. (2005). Fertirrigación. Cultivos hortícolas, frutales y ornamentales. Mundi-Prensa, Madrid, Spain

[a]Supplemented with basal fertilizer for P

Example 29.4

Example of preparation of the Hoagland-Arnon solution.

First, we prepare a table that shows in each row the composition of water (meq/L), the desired (ideal) concentrations, the required addition of each ion, and the resulting solution. The negative value for addition of bicarbonate indicates the need to apply 2.0 meq/L of a nutrient (e.g., N) as acid.

	NO_3^-	$H_2PO_4^-$	SO_4^{2-}	HCO_3^-	Cl^-	NH_4^+	K^+	Ca^{2+}	Mg^{2+}	Na^+
Water	0	0	2	2.5	1	0	0	2	2	1.5
Ideal	14	1	4	0	0	1	6	8	4	0
Addition	14	1	2	-2	0	1	6	6	2	0
Solution	14	1	4	0.5	1	1	6	8	4	1.5

The procedure for filling the second table is as follows:

– Add H^+ as HNO_3: in this case, we assign 2 to the cell where NO_3^- and H^+ meet.
– Add 1 unit of $H_2PO_4^-$ as KH_2PO_4: we are also adding 1 unit of K.
– Fill the row of NO_3^- in the order Ca^{2+} (add 6), NH_4^+ (add 1), and K^+ (add 5).
– Complete K^+ using SO_4K_2 (not required in this case).
– Add Mg2$^+$ as SO_4Mg.

	NH_4^+	K^+	Ca^{2+}	Mg^{2+}	H^+	Total
NO_3^-	1	5	6		2	14
$H_2PO_4^-$		1				1
SO_4^{2-}				2		2
Total	1	6	6	2	2	17

(continued)

Example 29.4 (continued)

Now, we convert each cell to mass of fertilizer as indicated in the third table. In this example, the resulting solution has a number of cations (or anions) of 20.5 meq/L; thus the expected *EC* will be around 2 dS/m.

Fertilizer	meq/L	g/mol	g m^{-3}
NO_3NH_4	1	80	80
NO_3K	5	101.1	505.5
$(NO_3)_2Ca{\cdot}4H_2O$	6	118	708
NO_3H	2	63	126
KH_2PO_4	1	136.1	136.1
$SO_4Mg{\cdot}7H_2O$	2	123.2	246.4

The need for applying micronutrients is increasing in proportion to crop yields but also because fertilizer products contain less micronutrients and manure applications have been reduced. The availability of micronutrients usually increases as the organic matter content of the soil or substrate increases and is reduced by irrigation with hard or alkaline water. In any case, we should prevent micronutrient excesses that may cause toxicity (Table 29.5). Metallic micronutrients (Fe, Mn, Cu, Zn, Ni)

Table 29.5 Allowable concentration of several elements in irrigation water

	Long term	Short term	
	mg/L	mg/L	Comments
Aluminum (Al)	5	20	May turn acid soils into unsuited for cropping. Precipitates with pH = 5.5–8.0 which eliminates toxicity
Arsenic (As)	0.1	2	Variable toxicity: 12 mg/L (Sudan grass)–0.05 mg/L (rice)
Beryllium (Be)	0.1	0.5	Variable toxicity: 5 mg/L (cabbage)–0.5 mg/L (bean)
Boron (B)	0.75	2	Toxic for sensitive species (e.g., citrus) above 1 mg/L. Grasses are tolerant of 2–10 mg/L
Cadmium (Cd)	0.01	0.05	Toxic for beans, beets, radish with 0.1 mg/L
Chromium (Cr)	0.1	1	Scarce information. Caution is recommended
Cobalt (Co)	0.05	5	Toxic for tomato with 0.1 mg/L. it is inactivated in neutral and alkaline soils
Copper (Cu)	0.2	5	Variable toxicity: 0.1–1.0 mg/L
Fluorine (F)	1	15	It is inactivated in neutral and alkaline soils
Iron (Fe)	5	20	Not toxic in well-aerated soils. Induces acidification and losses of P and Mo
Lead (Pb)	5	10	May inhibit cellular growth at high concentration
Lithium (Li)	2.5	2.5	Most crops are tolerant up to 5 mg/L except for citrus (limit 0.075 mg/L). Moves in the soil
Manganese (mg)	0.2	10	Variable toxicity in acid soils
Molybdenum (Mo)	0.01	0.05	Not toxic for plants in general. May be toxic for cattle when pastures grow on rich soils
Nickel (Ni)	0.2	2	Toxic for some species at 0.5–1.0 mg/L. Lower toxicity in neutral and alkaline soils
Selenium (Se)	0.02	0.02	Toxic for plants at low concentration. May be toxic for cattle when pastures grow on soils with low concentration
Vanadium (V)	0.1	1	Toxic for many species at low concentration
Zinc (Zn)	2	10	Toxic for many species. Toxicity is reduced when pH > 6 and in clay and organic soils

Table 29.6 Recommended concentrations (mg/L) of micronutrients in the nutrient solution

	Mn	Fe	B	Mo	Cu	Zn
Olive, grapevine, citrus	0.5–1	1–1.4	1–1.1	0.01–0.02	0.05–0.8	0.05–0.2
Tomato, pepper, eggplant	0.5–1	0.8–2	0.3–0.5	0.05	0.05–0.1	0.03–0.1
Strawberry, bean, cucumber	0.5	1	0.3–0.5	0.05–0.1	0.1–0.2	0.1–0.2
Lettuce, endive	0.3–0.5	2.2	0.32	0.05	0.05	0.3

Adapted from Cadahia C (2005). Fertirrigación. Cultivos hortícolas, frutales y ornamentales. Mundi-Prensa, Madrid, Spain

are usually present in soils and substrates as oxides and hydroxides of low solubility at high pH. Boron and molybdenum, whose concentrations are generally lower than those of metallic micronutrients, are more soluble and may be present in irrigation water or organic fertilizers. Chlorine is also a micronutrient but is rarely scarce and can be toxic at high concentrations.

Micronutrients are added as chelates or salts that can be applied individually or as ready-made solutions. For some species, optimal concentrations of micronutrients in the nutrient solution have been determined (Table 29.6). Some authors recommend providing all metallic micronutrients as chelates although some available soluble inorganic salts can be used (e.g., $CuSO_4$), but usually are less effective in providing available nutrients to plants due to oxidation in the soil, particularly in the case of Fe.

29.9 Examples of Fertigation Programs

Example 29.5

An orange grove has an annual N fertilizer requirement of 200 kg N/ha. The total amount of irrigation applied is 500 mm. We will calculate the amount of fertilizer to add to the stock solution (dilution x200) to meet those N needs.

We assume that we want to apply only N, so we rule out NP and NK fertilizers and restrict to urea and ammonium nitrate (AN). We could also apply other fertilizers containing sulfur, calcium, or magnesium, but they are discarded because of their low N concentration.

Irrigation water should have a concentration:

200 kg N/5000 m^3 = 0.04 kg N m^{-3} = 40 g N m^{-3}.

The two alternatives would be:

40 g N m^{-3} /(0.34 g N/g AN) = 117.6 g ammonium nitrate m^{-3}
40 g N m^{-3} /(0.46 g N/g urea) = 87 g urea m^{-3}.

The alternative stock solutions for a 200 dilution would have concentrations of:

117.6 g ammonium nitrate m^{-3} • 200 = 23.52 kg ammonium nitrate m^{-3}.
87 g urea m^{-3} • 200 = 17.4 kg urea m^{-3}.

Example 29.6
A citrus orchard requires 200 kg N/ha and 270 kg K/ha with a total irrigation application of 500 mm. We will calculate the stock solution (dilution x200) to meet those needs of N and K.

Our first choice is a fertilizer containing both K and N, potassium nitrate (PN). To supply 200 kg N/ha and 270 kg K/ha, as the concentrations of N and K are 13.4 and 39%, respectively, we should add:

270 kg K/ha /(0.39 kg K/kg PN) = 692 kg PN /ha
692 kg PN/5000 m^3 = 138.4 g PN/ m^3.

That contributes also:

692 kg PN/ha • 0.134 kg N/kg PN = 92.8 kg N/ha.

We still need to add 200–92.8 = 107 kg N/ha that is equivalent to 315 kg ammonium nitrate/ha or 233 kg urea/ha.

If we choose urea, the concentration in irrigation water will be:

233 kg urea/5000 m^3 = 46.6 g urea/m^3

And the stock solution will be:

27.68 kg potassium nitrate m^{-3} and 9.32 kg urea m^{-3}

Alternatively, we could have used simple fertilizers (urea and potassium sulfate) and the stock solution would be:

26.0 kg potassium sulfate m^{-3} and 17.4 kg urea m^{-3}.

Example 29.7
Calculate the minimum size of the fertigation tank for the previous example considering that the maximum irrigation requirement is 4.5 mm day^{-1} and that the fertilizer is added every day. We will consider only the option of using urea and potassium nitrate.

The required concentrations in irrigation water were calculated in Example 29.6:

138.4 g potassium nitrate/m^3
46.6 g urea/m^3.

Now by looking at Table 29.1, we see that the maximum concentration to be allowed in the stock solution would be:

Urea, 260 kg m^{-3}; potassium nitrate, 80 kg m^{-3}.

(continued)

Example 29.7 (continued)

The most limiting case is that of potassium nitrate which leads to a maximum dilution factor of:

80 kg m^{-3}/0.1384 kg m^{-3} = 578.

The stock solution should be:

Urea: 26.9 kg m^{-3}.
Potassium nitrate: 80 kg m^{-3}.

The amount of irrigation to be applied is 45 m^3 ha^{-1} day^{-1} which requires 77.85 L ha^{-1} day^{-1} of stock solution. This is the minimum volume required for the tank. For instance, in a 10-ha orchard, we would require a tank larger than 778 L.

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Soil Improvement and Reclamation

30

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Abstract

Proper soil health is crucial to ensure that cropping systems provide essential ecosystem services, including food and fiber production. When soil properties are not adequate for crop production and limit yields, we should improve soil conditions and in extreme cases reclaim affected fields. First, the causes behind the loss of soil health should be identified so specific treatments to improve the soil functionality can be implemented. This chapter reviews the main causes affecting soil degradation and proposes solutions to maintain and recover soil health. Low content of soil stable organic matter (SOM) is one of the main issues associated with cultivated soils and can lead to multiple problems including reduction of nutrient fertility, soil water holding capacity, and soil aggregate stability that may lead to cultivation restrictions. Strategies to maintain or build up SOM rely in a mass balance between losses and biomass inputs. Soil physical properties such as compaction, stoniness, or structural degradation require

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specific corrections relying on mechanical operations and/or management practices (i.e., tillage intensity, cover cropping). Reclamation of soils affected by chemical issues (salinity, sodicity, and acidity) is conducted by the application of amendments and/or leaching that relies on chemical equilibria revised in this chapter. Finally, the concept of regenerative agriculture is defined and exemplified by a case study.

30.1 Introduction

The critical resource in agricultural production is the soil. Therefore, we should preserve and improve, if needed, its biological, chemical, and physical properties. The actual conditions of many soils around the world are far from adequate for crop production and limit yields. For instance, more than 20% of soils are affected by salinity, while 40% show problems related to acidity.

In some cases, the problem is inherent to the soil (salinity due to parent material, stoniness), while in others it is the result of poor management. That is the case for salinization of irrigated areas, acidification due to N fertilizers, loss of soil organic matter, or soil compaction by tillage or machinery. Avoidance of these problems is considered in chapters about tillage (17), soil management (18), salinity (24), nitrogen fertilization (26), and cropping systems (36).

Extreme cases of soil degradation may occur as a result of severe pollution of soils by mining or industrial activities (Box 30.1).

We have several options to correct or mitigate these problems: chemical problems are dealt with amendments and/or leaching, while physical problems require mechanical operations and/or crops' use as biological tools. The lack of organic matter can only be addressed by increasing the input of dry matter to the rotation. Correction of one issue may help with another. For instance, increasing stable organic matter (SOM) will alleviate the risk of compaction and improve soil aeration.

Box 30.1. The Aznalcollar Disaster

On April 25, 1998, the failure of a dam containing acid water and toxic mud from mining occurred in Aznalcollar (Spain). It caused a spill that affected 3000 ha of agricultural land. After mechanical removal of the mud, the soil was still polluted with Cu, Zn, As, Cd, Tl, and Pb. Several experiments of phytoremediation (using crops to remove the pollutants) were performed to compare the uptake of these heavy metals by different species (barley, triticale, rapeseed, and Ethiopian mustard). The main drawback of this technique was the long period required to extract all the heavy metals (around 50 years) although the concentrations found were below the tolerance level for use as fodder.

The final solution was the purchase by the regional government of all the contaminated land that was then planted with trees and shrubs and kept as a natural park.

30.2 Soil Health

As mentioned in Chap. 2, soils are living entities providing essential ecosystem services including primary productivity. These services are the "soil functions" and the capacity of soils to perform them has been defined as "soil health" or "soil quality," depending on authors. The Intergovernmental Technical Panel on Soils (ITPS) defined soil health as "the ability of the soil to sustain the productivity, diversity, and environmental services of terrestrial ecosystems," i.e., to perform the so-called soil functions. This capacity is affected by human intervention and may be recovered, preserved, or promoted with adequate practices controlling soil degradation.

Soil health refers to soil properties that can be altered by management over the human time scale, so it reinforces the idea of soils as dynamic living systems, with diverse biological communities that perform crucial processes.

A healthy soil is able to perform the following functions:

- Provide food in quantity and quality, and other goods such as fiber and fuel; although focus has been frequently put on the productivity, soils can also affect food quality (e.g., micronutrients such as Fe or Zn in food, or the absence of contaminants).
- Contribute to water regulation and purification since water flows over and through soils affecting landscape hydrology; on the other hand, soils have adsorption capacity and may decrease pollutants in water, contributing to decrease the pollution of water bodies and ensuring water quality for animal and humans.
- Serve as a habitat for biodiversity, not only in terms of plants and animals but also for microorganisms that can contribute to relevant ecological services such as control of pest or diseases or are involved in the nutrient cycle.
- Capture carbon, as stabilized organic matter in soils, contributing to climate change mitigation.
- Nutrient cycling, i.e., closing the cycle of nutrients on the earth surface. This implies controlling the nutrient availability and losses essential for the recycling of nutrients at farm or regional scales.

Each of these functions is not related to a single soil property. As an example, water regulation and purification are affected by texture, structure, mineralogy, pH, etc. Biological properties affect strongly different soil functions, e.g., soil microorganisms that are involved in the hydrolysis of organic phosphorus will indirectly affect soil productivity by providing nutrients to plants or carbon storing through mineralization of organic matter.

30.3 Soil Organic Matter

Organic matter in the soil is the fraction of the solid phase that derives from the accumulation and transformation of organic residues. A portion of the C in organic matter corresponds to the microbial biomass (usually in the range of 1–5%), a major actor in the transformation of organic compounds in soil. Although a huge variety of organic compounds are present in soil, from a practical point of view, they can be classified as fresh organic matter (residues with little biological transformation), intermediate decay products, and stable organic matter (SOM) or "humus." Most of the well-known positive effects in soil properties are associated with SOM, such as its contribution to particle aggregation and cation exchange capacity.

Organic products applied to the fields are either fresh (crop residues, manures, slurries, etc.) or in an intermediate stabilization state in microbial-mediated transformation process (digestate, half-composted manures, etc.), so they go through an in-field decomposition process carried out by soil microorganisms and associated microfauna in a continuous loop. Decomposition is coupled to the mineralization of C compounds that produced both CO_2 that is emitted to the atmosphere and mineral salts that serve as nutrients to plants and microorganisms. Only a small fraction of the organic products is not mineralized by microorganisms and leaks to the SOM or humus, the recalcitrant pool that interacts with the mineral particles; thereafter this process is called humification. The cycle is named the soil organic matter turnover and is a key process to ensure soil functions and to maintain soil health (Fig. 30.1).

SOM reflects the balance between humification and losses. SOM is usually expressed on a mass basis (t SOM/ha) or as a percentage of the total soil mass, but it can be also expressed as carbon (C) to facilitate the connection with biogeological cycles. The amount of C content in the SOM is calculated by multiplying by 0.58. The C/N/P/S ratio of SOM is near 100/10/1/1 and may be used to estimate the nutrients released by mineralization.

In each field, the SOM balance leads to a steady state that depends on the soil type, environmental conditions, and management. Therefore, an optimum SOM level cannot be established due to the broad varieties of soils, environments, and cropping systems. As a reference, usual recommended values for Mediterranean loam or clayey soils are SOM >1.5% in rainfed cropland and > 2% in irrigated.

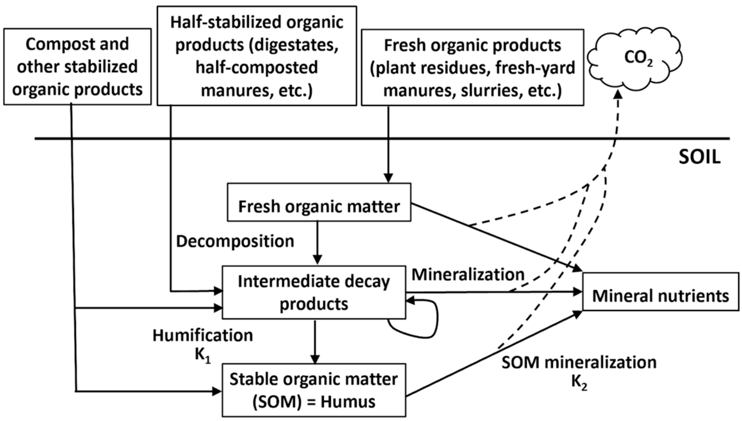

Fig. 30.1 Schematic representation showing the key aspects of the turnover of organic matter in the soil and added organic products

30.3.1 Soil Organic Matter Losses

Losses of SOM are mainly due to topsoil erosion and mineralization. In this chapter, we will focus on SOM mineralization, a slow but continuous process that can lead to soil degradation if it is not compensated by new organic matter inputs.

Mineralization is the oxidation of the organic C by soil microorganisms; therefore, it is enhanced in well-aerated soils. Additionally, clayey soils protect the SOM from decomposition by forming microaggregates, whereas in sandy soils the SOM molecules are more exposed to microbial activity. Therefore, mineralization is enhanced in sandy aerated soils and slowed down in clayey soils. Tillage aerates the soil and accelerates SOM mineralization, whereas reduced or no-tillage decelerates mineralization. Another soil characteristic that affects mineralization is the pH; near neutral or slightly basic soils (particularly if they contain high calcium carbonate) have a higher mineralization rate than acidic soils with low base saturation.

Humidity tends to increase SOM because it diminished oxygen availability, but on the other hand, it increases biomass production and C inputs into the soil. Flooded soils present low mineralization and decomposition rates and tend to have high SOM levels. The higher mineralization rates are found around water field capacity, as low water availability limits mineralization. Nevertheless, arid and semiarid soils usually have low SOM because the crop litter input is low.

SOM losses are enhanced by temperature as mineralization is driven by microorganisms, increasing from 0 to 35 °C. The combined effect of humidity and temperature is clearly observed in Europe, where SOM decreases from the cold and wet North to the warm and drier South. When water and temperature conditions favor microbial activity, the mineralization and decomposition rates are enhanced greatly; because of that in irrigated land of warm semiarid regions, SOM losses can be extremely high. In all soils, care should be taken to offset SOM losses by the incorporation of other external organic products if needed to ensure a humic equilibrium (SOM maintenance).

Mineralization is usually represented as a first-order process. In the simplest approach, only a SOM pool is considered, and it is associated with a mineralization rate (K_2), so the variation of SOM until time t is calculated as:

$$SOM_0 - SOM_t = SOM_0\left[1 - \exp\left(-K_2\, t\right)\right] \tag{30.1}$$

where SOM_0 is the amount of humus present at time (t) zero.

The K_2 rate depends on environmental conditions, soil type, and management (Table 30.1). Values like those of the table can be obtained by applying the equation proposed by Hénin-Dupuis based on the annual average temperature (T_{av}) and on the soil clay (sc, g/kg) and $CaCO_3$ content (cc, g/kg):

$$K_2 = \frac{0.003\,(1 + 0.2\left(T_{av} - 10\right)}{\left(1 + 0.005\,sc\right)\left(1 + 0.0015\;\,cc\right)} \tag{30.2}$$

Table 30.1 Annual soil stable organic matter mineralization rate (K_2) for different environmental conditions and soil types in conservation and conventional tillage systems

		Conservation tillage		Conventional tillage	
% clay	pH	Xeric and arid	Humid and ustic	Xeric and arid	Humid and ustic
5	7	0.016	0.02	0.018	0.024
5	5	0.008	0.01	0.009	0.012
5	8	0.0112	0.014	0.0126	0.0168
20	7	0.015	0.019	0.017	0.022
20	5	0.0075	0.0095	0.0085	0.011
20	8	0.0105	0.0133	0.0119	0.0154
35	7	0.01	0.015	0.014	0.018
35	5	0.005	0.0075	0.007	0.009
35	8	0.007	0.0105	0.0098	0.0126

Xeric and arid, rainfed in Mediterranean and semiarid climates with strong water limitation
Humid and ustic, rainfed in climates not water limited and irrigated in Mediterranean or semiarid climates

Example 30.1
Given the data below, calculate the SOM losses and balance of a clay-silty soil cropped with a wheat and barley rotation. Consider (i) that all the straw is incorporated in the soil and (ii) the straw is burned.

SOM content = 1.6%; K_2 = 0.014; tillage depth = 0.30 m; soil bulk density, 1.45 g cm^{-3}.

Grain yield, 3600 kg ha–1; straw, 3650 kg ha–1; root biomass = 25% of aboveground biomass; dry matter for roots and straw is 85%. The fraction of residue converted into SOM is 0.22 for the straw and 0.12 for the roots (see Sect. 30.3.2).

SOM content = 104 m2 0.30 m 1.45 t m–3 0.016 = 60.9 t ha–1.
SOM losses = 60.9 10^3 kg ha^{-1} (1- e$^{-0.014}$) = 847 kg ha^{-1} year^{-1}.

(i) Straw incorporated into the soil.

Root biomass = (3600 + 3650) 0.25 = 1812.5 kg ha^{-1}.
Annual SOM input = 3650 0.85 0.22 + 1812.5 0.85 0.12 = 867.4 kg ha^{-1} year^{-1}.
The SOM is in equilibrium.

(ii) Straw is burned.

Annual SOM input = 1812.5 0.85 0.12 = 184.9 kg ha^{-1} year^{-1}.
SOM will decrease until a new steady state is reached. High risk of soil degradation exists unless losses are offset by the application of external organic products (SOM maintenance).

More sophisticated SOM models such as *RothC* or *Century* distinguish various pools, each one with a specific mineralization rate. The active pool is very sensitive to management practices and turnovers within a week to a year. The slow pool reflects the effect of agricultural practices within a few years to decades, whereas

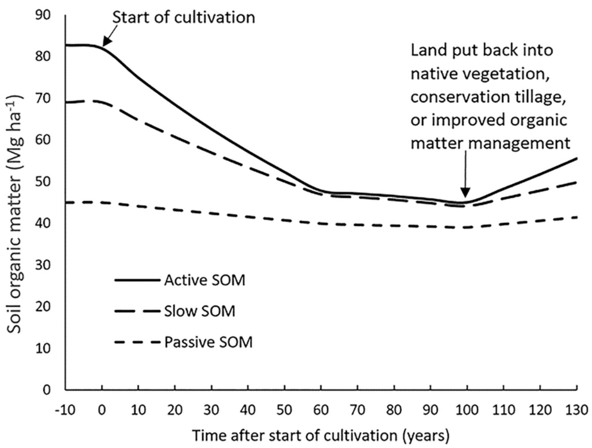

Fig. 30.2 Changes in various fractions of organic matter content (t/ha) in the upper 0.25 m of a representative soil from North American grasslands after bringing virgin land under cultivation. (Adapted from Brady & Weil, 2008)

the passive pool only shows changes in the long term (turnover ranging from decades to centuries). The grasslands of North America showed a SOM decrease after the start of cultivation in the nineteenth century. The return to native vegetation, the addition of organic amendments, or conservation tillage increased C sequestration in the various organic pools (Fig. 30.2).

30.3.2 Improving Soil Organic Matter

Soils with SOM content below recommended values have low fertility, retain less water, are prone to erosion, and are likely to present structural problems that impair their cultivation capacity. Because of that, in soils with low SOM, it is necessary to adopt practices that decrease losses (erosion control, conservation tillage) and/or increase the addition of organic products to build up SOM and ensure proper soil functioning.

Only a small fraction of the added organic products ends up building SOM, and this fraction is called the isohumic coefficient (K_1) (Table 30.2). The fraction depends mainly on the complexity of the molecular structure of the organic products, being larger when the lignin and polyphenol content increases or when the organic products are more stabilized. The biomass from grasses used as cover crops terminated in the vegetative state has a lower isohumic coefficient than the lignified straw produced at harvest. Similarly, fresh yard manure that contains easily decomposable molecules has a lower isohumic coefficient than a material produced after composting the same yard manure. The contribution to the SOM is not immediate but it is parallel to the decay of the organic product and so it can take several years.

The decomposition of the organic materials added is determined by the soil and environmental conditions mentioned in the previous section but also by the quality of the added products, characterized by the complexity of the molecular structure

Table 30.2 Typical dry matter (d.m.), isohumic coefficient (K_1), and C/N of organic products

Organic product	% d.m.	K_1	C/N
Litter from legume crops (at flowering)	20	0.1	18–22
Alfalfa hay	75	0.1	25
Grass cover crop (end of stem elongation)	20	0.1	25–30
Winter cereal straw	85	0.12	60–80
Maize fodder	85	0.12	50–60
Sawdust	–	–	400–600
Fresh yard manure	20	0.3	25–30
Half-stabilized manure (digestate, half-composted)	30	0.4	20–24
Compost (manure, mixed materials)	35	0.5	12–15
Digested sewage sludge	30	0.4	10–14

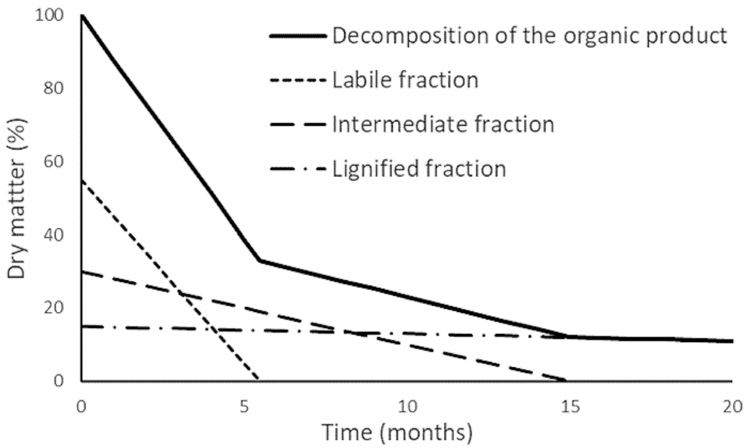

Fig. 30.3 Organic product decomposition as the result of the decay of its various fractions

and by the C/N ratio. In addition to the lignified fraction, organic products contain an easy-to-decompose labile fraction (soluble carbohydrates, amino sugars, etc.) and an intermediate (cellulose, starch). The decomposition of the organic product occurs altogether in a first-order process that is the addition of the decay of the various fractions (Fig. 30.3).

The decomposition can be delayed when high C/N organic products are added to the soil if sufficient N to support microbial growth is not available, either in the products or in the soil. Therefore, decomposition of high C/N products can be accelerated by mixing with other N-rich materials or even by adding synthetic fertilizers. When the C/N < 20–25, the microbial activity and so the decomposition are not N limited. The C/N ratio of SOM is between 8 and 12, being 10 the most common value, and organic products added to the soil will be stabilized by decomposition until they reach this range.

There are multiple tests to characterize the residue quality and to estimate K_1 but, in many cases, lookup tables are used as a first approach (Table 30.2). A limitation is that K_1 also depends on the soil properties affecting the stabilization of organic

Table 30.3 Recommended maximum manure and frequency applications for various soil types

Soil type	Maintenance SOM	Maintenance + buildup of SOM
Sandy	15–20 t/ha (every 2 years)	20–25 t/ha (every 2 years)
Loam	25–30 t/ha (every 3–4 years)	30–35 t/ha (every 3–4 years)
Clayey	30–40 t/ha (every 3–4 years)	40–50 t/ha (every 3–4 years)

matter, and so the clay content and mineralogy may affect the yield in humus that a given residue produces under particular edaphic conditions. This contributes to explain the relative wide range of values observed in different works and presented in the table.

Typical decomposition or decay rates for organic products in non-sandy soils are 0.5 in the first year, 0.3 in the second, and 0.1 in the third. In sandy soils or if the product has a low structural complexity, the decay rates are 0.6 in the first year and 0.3 in the second. Some recommendations on limits to the use of manure for increasing SOM are shown in Table 30.3.

Finally, some physical properties of organic products can affect the decay rate. The particle residue size determines the surface area exposed to the microorganisms for decomposition, and so small particles decay more rapidly than large ones. Chopping or other mechanical treatment of residues (i.e., branches or straw) can greatly accelerate the decomposition of organic materials. Incorporation of organic products into the soil facilitates access to bacteria and other soil microfauna, enhancing decomposition and decay rate.

Example 30.2

A rainfed farm applies a four-crop rotation in North Spain. The crops are barley, fodder rape, wheat, and fodder pea. The soil in the farm is loam and has a pH = 8.0 and SOM = 1.4%. The farm is under reduced tillage and a chisel plow is used to incorporate crop residues down to 0.25 m. The topsoil bulk density is 1.40 g cm^{-3} and K_2 = 1.05%.

Information about the crops (harvest index for cereals 0.5 and for fodder crops 0.9).

1. If the crop residues are the only organic input, is the SOM in equilibrium? What is the expected SOM in the long run?
2. Calculate the amount of digestate manure that should be applied to maintain the SOM balance in the field. Design an application program.
3. Calculate the amount of manure that should be applied to build up SOM to 1.8% and mitigate the structural problems present in this soil. Design an application program.
4. Plot a graph for the buildup program showing the time course of decomposition, SOM evolution, and CO2 emissions.

(continued)

Example 30.2 (continued)

1. SOM = (0.25 m × 10^4 m^2) 1.40 t m^{-3} 0.014 kg SOM kg^{-1} soil = 49 t ha^{-1}.
   SOM losses = 49 t ha^{-1} (1 − exp (− 0.0105 × 1 year) = 0.512 t ha^{-1} $year^{-1}$.

	Crop yield t ha^{-1}	Residues left in the field %	Moisture content %	Isohumic coefficient K_1
Barley	5.1	80	20	0.12
Fodder rape	28	100	85	0.11
Wheat	5.3	80	20	0.12
Fodder pea	30	100	85	0.08

In carbon (C) equivalent: SOC = 49 t ha−1 0.58 = 28.42 t C ha−1

SOC losses = 0.297 t C ha−1 year−1 (the C is lost as CO2).

Annual inputs from crop residues:

Barley: 5.1 t ha−1 0.80 0.80 dm fm−1 0.12 kg SOM kg−1 dm = 0.392 SOM t ha−1.
Fodder rape: 28 t ha−1 (0.1/0.9) 0.15 dm fm−1 0.2 kg SOM kg−1 dm = 0.093 SOM t ha−1.
Wheat:5.3 t ha−1 0.80 0.80 dm fm−1 0.12 kg SOM kg−1 dm = 0.407 SOM t ha−1.
Fodder pea: 30 t ha−1 (0.1/0.9) 0.15 dm fm−1 0.08 kg SOM kg−1 dm = 0.040 SOM t ha−1.

Annual SOM input from crop residues = 0.932 t ha^{-1}/4 years = 0.233 t ha^{-1} $year^{-1}$

SOM balance = Inputs −Outputs = 0.233–0.512 = – 0.279 t ha−1 year−1 = > Not in equilibrium.

The equilibrium after many years would be SOMeq:

0.233 t ha−1 year−1 = 2500 m3 1.40 t m−3 SOMeq (1−exp (−0.0105)) = > SOMeq = 0.64% = 22.3 t ha−1

2. To compensate the SOM balance, we applied digestate (moisture = 70%, K_1 = 0.4; Table 30.2).
   0.279 t ha^{-1} $year^{-1}$ 1/0.4 = 0.697 t dm ha^{-1} $year^{-1}$ = > 2.32 t digestate ha^{-1} $year^{-1}$.
   Application program for SOM maintenance: 9.3 t digestate ha^{-1} every 4 years

(continued)

Example 30.2 (continued)

3. To build up SOM from 1.4% (49 t ha^{-1}) to 1.8% (63 t ha^{-1}) (ΔSOM= 14 t ha^{-1}), we apply digestate (moisture = 70%, K_1 = 0.4; Table 30.2).

14 t ha^{-1} year^{-1} 1/0.4 = 35 t dm ha^{-1} year^{-1} = > 116.7 t digestate ha^{-1} year^{-1} SOM$_{1.8\%}$ losses = 63 t ha^{-1} (1 −exp (− 0.0105 × 1 year) = 0.658 t ha^{-1} year^{-1}. SOM$_{1.8\%}$ balance = 0.233–0.658 = − 0.425 = > 1.42 t dm ha^{-1} year^{-1} = > 3.54 t digestate ha^{-1} year^{-1}.

Adjusting to the recommendations in Table 30.3, the application program for the digestate is:

Year	Buildup (t ha^{-1})	Maintenance (t ha^{-1})	Total manure digestate (t ha^{-1})
0	29.2	9.3	38.5
4	29.2	10.5	39.7
8	29.2	11.8	41.0
12	29.2	13.0	42.2
16		14.2	14.2

In practice, the farmer will round up the digestate values and apply it before sowing wheat to profit from the nutrients released. If the digestate has 2.8 kg N t^{-1} and 1.1 kg P t^{-1}, the maximum annual application would be 119 kg N ha^{-1} and 46.4 kg P ha^{-1}. If other fresh organic materials richer in N or P are applied (Table 25.4), care should be taken to avoid trespassing environmental legislation thresholds (i.e., 170 kg N ha^{-1} in the European Union).

4. Assuming typical decay rates of 0.5 in the first year, 0.3 in the second, and 0.1 in the third, the results are shown in Fig. 30.4.

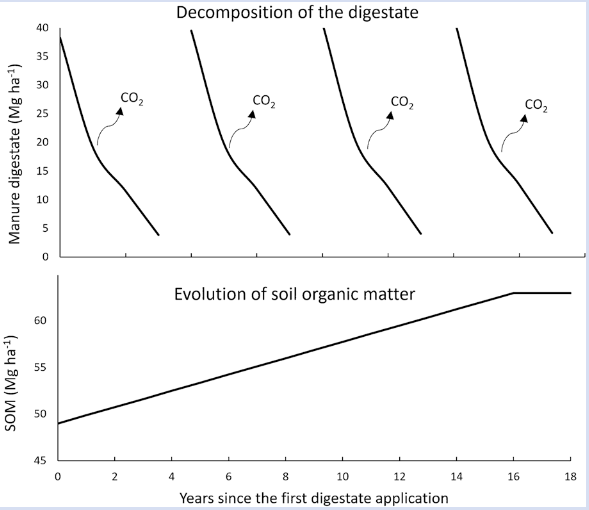

Fig. 30.4 Temporal manure digestate decomposition and buildup of soil organic matter (SOM) for Example 20.3

Table 30.4 Overview of key problems requiring improvement of soil physical properties

Problem	Possible reasons behind	Main soil properties involved	Possible actions for correction
Soil compaction	Over traffic Lack of soil structure Loss of topsoil	High bulk density, high penetration resistance, low organic matter content, low aggregate stability, high sodium content	Subsoiling, use of cover crops, controlled traffic, use of lighter machinery, use of low-pressure tires, conservation tillage, soil amendments
Lack of soil structure	Soil degradation Low SOM High sodium content		
Stoniness	None; it is a natural feature of our soil Loss of topsoil	High stone content	Remove stones

30.4 Improving Soil Physical Properties

Soil physical degradation is related to various relevant problems that require specific correction actions (Table 30.4). For instance, low SOM increases soil compaction and degrades soil structure. Because of this, the best course for improving soil physical conditions in the long term is to combine actions that improve permanently these key soil properties combined with others that might provide a short-term improvement, for instance, using cover crops and organic amendments systematically to increase SOM after subsoiling or deep plowing to improve a heavily compacted soil.

30.4.1 Soil Compaction

Soil compaction refers to a situation in which the soil is so consolidated that limits plant growth by restricting root growth. Soil compaction can be evaluated using two different soil properties (see Chap. 2.3):

(i) Soil bulk density defined as the mass of dry soil for a given volume. Bulk density is independent of the soil water content.
(ii) Penetration resistance defined as the force required to insert a cone of standard dimensions at a given depth into the soil. Penetration resistance increases as the soil dries.

Careful observations can help diagnose the problem, like detecting poor crop growth in all years, with all crop types showing the same spatial pattern in different years, eventually associated with wheel tracks, or digging the soil surface with a spade to detect dense layers and/or horizontal root growth. Soil compaction becomes an issue when it limits plant growth, i.e., some soils of relatively high bulk density do not present a compaction problem. This might be the case on soils under conservation tillage, which tend to have a higher bulk density than those plowed but present a more stable and optimized pore space and a better soil water content, which allows good root growth. Soil compaction might occur in specific soil layers or throughout the soil profile, as in over-trafficked areas. The former is the case of the plow pan, the layer of the soil that is consolidated by traffic and plowing operations but remains below the plow depth.

Soil compaction can be due mainly to three situations that may happen simultaneously. One is excessive or poorly managed traffic on the farm. Traffic of agricultural equipment, or grazing animals, needs to be reduced in intensity to the minimum required. The timing of traffic is also important, and no traffic or trampling should be allowed on wet soil since they result in over-consolidation of the soil profile which can reach up to 50 cm, a depth that can't be reached by common tillage operations and results in a plow layer of over consolidated soil in depth. A complement to controlled traffic is to limit the traffic always to the same tracks reducing the surface of the compacted area. This can be attempted with any kind of equipment but is facilitated by GPS. We may use lighter farm equipment or reduce the pressure on the soil (using the appropriate tire pressure or special low-pressure tires). In pastures, we may reduce the grazing density and avoid excessive concentration of animals by increasing the number of drinking and feeding areas. Compaction issues are exacerbated in soils with a poor structure and stability of the soil aggregates, which happen in soils with a low SOM and intensively tilled. A particular case is that of sodic soils in which a high sodium content results in a very poor soil structure and high compaction.

Soil compaction may occur even under proper traffic management, when extreme degradation of soil structure is caused by intensive tillage, leading to low SOM and poor aggregate stability. This lack of structure can also be the result of high sodium content in the soil, either naturally or due to irrigation. A third situation that can lead to extreme soil compaction is when accelerated erosion exposes a subsurface soil layer that is compacted, for instance, a poorly developed subsurface soil horizon or the parent rock from which the soil is formed (Fig. 30.5).

All the measures mentioned above (proper control of traffic and trampling; improvement of soil structure by reducing or eliminating tillage; using conservation agriculture techniques like no-till or cover crops; increasing soil organic matter content, again using conservation tillage and/or adding organic amendments) are techniques that should be incorporated to ameliorate or prevent soil compaction. However, when the soil is already compacted, the most effective, and immediate, way to alleviate compaction is through plowing. The depth and kind of equipment to perform this tillage depend on the depth that compaction reaches into the soil profile, as well as the soil (or parent material) type. So, surface compaction can be alleviated using a chisel plow, while a deep subsurface plow layer can only be alleviated by subsoiling. To reduce compaction of an exposed subsurface horizon, we may perform tillage to mix this layer with the remaining topsoil using a moldboard or a disk plow. All these tillage operations are energy-intensive and costly, so they need to be carried out when the soil is at the optimum soil moisture content (Chap. 17). They should be considered in the context of an integrated strategy, using the techniques mentioned at the start of this paragraph, to avoid repeating plowing.

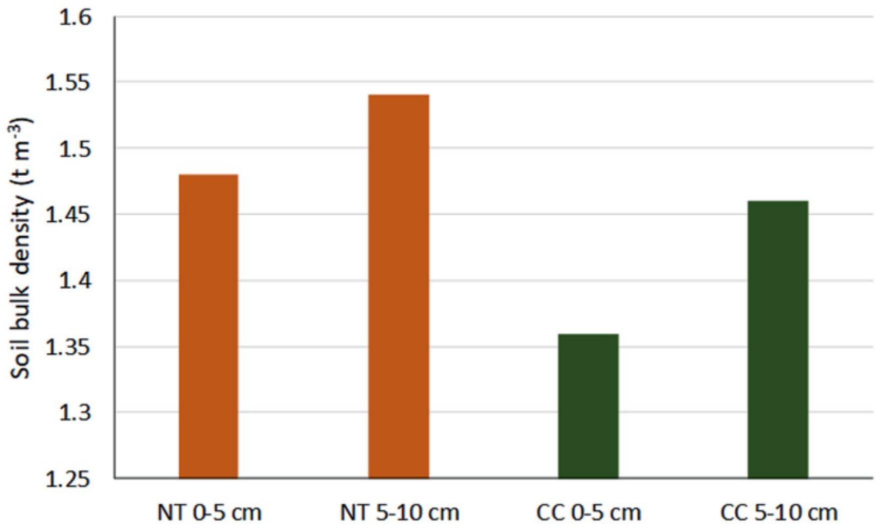

Fig. 30.5 Effect of a barley cover crop to decompact soil in an olive orchard alley (CC) at two different soil depths as compared to alleys with a bare soil (NT) after 5 years. (Adapted from Gómez et al. (2009). Soil Tillage Res 102: 5–13)

30.4.2 Stones

The presence of coarse material, above 2 mm in diameter (ranging from 2 to 200 mm), has an overall negative effect on some key soil properties like soil water holding capacity and can harm the quality of some crops, like potatoes, yams, or carrots. A high stone content also has a negative effect on the workability of different farming equipment, like that used for sowing, tillage, or harvest. Stony soils are common, occupying around 30% of agricultural area in Western Europe and more than 60% in the Mediterranean basin.

Although a stone mulch can have some benefits for reducing soil evaporation and increasing infiltration, the problems associated with stones in the soil compel the farmers to reduce their amount in the rooting depth using the following methods:

1. Stone gathering and removal from the field, with machines pulled by a tractor, leaving the stones in a pile or disposed of for further uses.
2. Stone crushing on-site using specialized machines.
3. Deep burial in which stones in the topsoil are buried by tillage, if they are small, or tipping them into a big hole.

Stone removal reduces the topsoil volume, while stone crushing has a higher cost because it works poorly on hard stones (e.g., non-weathered granite); stone burial is limited by the depth at which stones can be buried by machinery. In all cases, we should be aware that destoning might be necessary for the future when stones in the

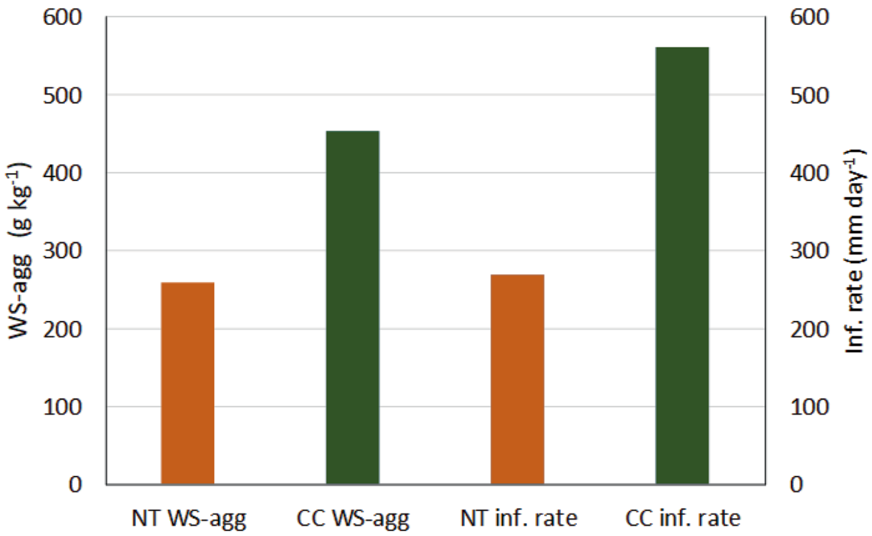

Fig. 30.6 Effect of a barley cover crop to improve infiltration rate (inf. rate) and soil aggregate stability in water (WS-agg) in an olive orchard alley (CC) at two different soil depths as compared to alleys with a bare soil (NT) after 5 years. (Adapted from Gómez et al. (2009). Soil Tillage Res 102: 5–13)

deeper layer resurface due to plowing or loss of topsoil by erosion. Destoning might also have a negative effect on the soil physical, chemical, and biological properties, in particular when crushing is used.

30.4.3 Other Techniques

The improvement of soil physical conditions increases water storage and enhances root growth. This can be achieved in the medium term following the same strategy outlined in Sect. 30.4.1 to prevent soil compaction. Sometimes we need to accelerate this process in extremely degraded soils to start their restoration process. For this, a successful strategy is to combine the incorporation of soil organic amendments with the sowing of herbaceous vegetation, which can be further incorporated into the soil as green manure or left for self-seeding (Fig. 30.6). This cycle can be repeated until the soil reaches a soil health status in which conventional techniques of conservation tillage can keep its physical properties.

30.5 Reclamation of Saline Soils

In general, a soil is classified as saline when its electrical conductivity in the saturation extract or saturated soil paste (EC_e) is greater than 4 dS/m. However, the tolerance of plants to salinity ranges widely. Yields decay in sensitive crops occurs at

$EC_e < 2$ dS/m (e.g., beans, maize, pepper, potatoes); meanwhile, tolerant crops have good performance even at $EC_e > 8$ dS/m (e.g., cotton, barley, sugar beet). Soluble salts most commonly present are the chlorides and sulfates of Na, Ca, and Mg. Sodium and chloride are the dominant ions, especially in highly saline soils, while Ca and Mg concentrations are usually enough to meet the crop needs. Many saline soils contain appreciable quantities of gypsum ($CaSO_4 \bullet 2H_2O$), while soluble carbonates are never present. The pH of the saturated soil paste is always lower than 8.2 and usually close to 7.

Saline soils usually have good physical properties as excess salts keep the clay in a flocculated state. Some saline soils, particularly heavy clays, tend to disperse when leached with low salt water.

Saline soils can be recognized by the spotty growth of crops (irregular plant size, barren spots) and often by the presence of white salt crust (salt efflorescence) on the surface. This is because there is always substantial spatial variability in the soil water properties that leads to wide spatial variations in soil salinity. If salinity is moderate and in the few cases it is uniform across the field, it may go undetected as it may not cause visible symptoms other than reduced growth rate, with the exception of a blue-green tinge in some cases. Symptoms of salinity stress may resemble those of water deficit without wilting due to gradual osmotic adjustment. Symptoms of specific toxicities, mainly ascribed to Cl or Na, (marginal or tip burn of leaves) are typical of woody plants.

The reclamation of saline soils is performed by salt leaching. The important question is the amount of water required and the best application strategy. Evacuation of drained water must be guaranteed, and if required to this end, a drainage network should be installed before salt leaching.

Theoretically, if the soil behaves as a perfect porous medium and assuming that there is no precipitation or dissolution of salts, the change in salts stored in the soil after applying an amount of water (*AW*) with EC_w is given by:

$$EC_{e\,\mathrm{final}} = EC_{e\,\mathrm{init}} \exp\left(\frac{-AW}{Z\left(\theta_{sat} - \theta_{\mathrm{init}}\right)}\right) + 0.5\,EC_w \left[1 - \exp\left(\frac{-AW}{Z\left(\theta_{sat} - \theta_{\mathrm{init}}\right)}\right)\right] \tag{30.3}$$

where Z is the soil depth being considered and subscripts *sat* and *init* refer to saturation and initial conditions, respectively. EC_e is the electrical conductivity in the saturated soil paste.

Example 30.3

The soil has initially EC_e = 10 dS m^{-1} with drains at 1 m depth. We apply 1000 mm with EC_w = 0.1 dS m^{-1} when the soil is at PWP (0.10 m^3 m^{-3}). Soil water content at saturation is 0.40 m^3 m^{-3}. Which EC_e will reach this soil?

$$EC_{e\,\mathrm{final}} = 10\exp\left(\frac{-1}{1\left(0.4 - 0.1\right)}\right) + 0.5\,EC_w\left[1 - \exp\left(\frac{-1}{1\left(0.4 - 0.1\right)}\right)\right] = 0.357 + 0.048 = 0.40\,dS/\mathrm{m}$$

Several empirical models have been proposed to estimate the volume of water required. Each soil differs in behavior, and the same amount of water has different leaching efficiencies in different soils, so field experiments are usually performed to determine the amount of water required. We have seen before (Example 24.3) that an amount of water equal to the depth of the soil would leach theoretically 96% of the salts. However, in practice, such an amount (equivalent to 1.5–2 times the pore volume) removes only around 70% of soluble salts.

Sprinkler irrigation is more efficient in salt leaching than surface irrigation. This is mainly due to preferential flow occurring under saturated conditions, leaving part of the soil without leaching. For the same reason, intermittent application of surface irrigation is more efficient (although slower) than continuous application. To calculate the depth of water required (I_w, mm) to reclaim a given soil depth Z (mm) to go from an initial EC ($EC_{e\,\mathrm{init}}$) to a final desired EC ($EC_{e\,\mathrm{final}}$), we may use the following equation:

$$\frac{I_w}{Z} = k_{\mathrm{leach}} \frac{EC_{e\,\mathrm{init}} - 0.5\,EC_w}{EC_{e\,\mathrm{final}} - 0.5\,EC_w} \tag{30.4}$$

where the parameter k_{leach} depends on soil properties (soil water content at saturation and texture) and the irrigation method. For continuous ponding $k_{\mathrm{leach}} = 0.45$ in peat soils, 0.30 in clay loams, and 0.1 in sandy loams. For intermittent ponding or sprinkler irrigation, $k_{\mathrm{leach}} = 0.10$.

Example 30.4

The soil has $EC_e = 10$ dS/m with drains at 1 m depth. We plan to reclaim the whole soil depth ($Z = 1000$ mm) to reach a final $EC_e = 2$ dS/m using sprinkler irrigation (so $k_{\mathrm{leach}} = 0.1$) and water with $EC_w = 1$ dS/m. Using Eq. 30.4:

$$\frac{I_w}{Z} = k_{\mathrm{leach}} \frac{EC_{e\,\mathrm{init}} - 0.5\,EC_w}{EC_{e\,\mathrm{final}} - 0.5\,EC_w} = 0.1\frac{10 - 0.5 \cdot 1}{2 - 0.5 \cdot 1} = 0.633$$

Therefore, the amount of irrigation to apply will be 633 mm.

In the case of saline-sodic soils, the addition of gypsum may help in improving water infiltration and thus accelerate both desalinization and desodification of the soil, especially in heavy textured soils, or when low electrolyte water is applied. The application of amendments should be tested by trials on an experimental scale for large-scale reclamation projects.

30.6 Reclamation of Sodic Soils

Sodic soils are those with a high content of exchangeable Na that adversely affects soil properties and the growth of most crops. As mentioned in Chap. 2, sodic soils are those with exchangeable sodium percentage (*ESP*) greater than 15. Sodium negatively affects soil physical properties by promoting colloid dispersion and clay swelling. In these soils, crops may be affected by Na toxicity. The pH in not saline-sodic soils, i.e., EC_e less than 4 dS/m, is usually above 8.5, and in extreme cases, it may be above 10.5. This can promote negative effects on plant nutrition, in particular micronutrient deficiencies such as Fe deficiency chlorosis, and microbial activity. The pH in saline-sodic soils, i.e., $EC_e > 4$ dS/m, is usually below 8.5, and salinity counteracts the dispersive effect of Na. Dispersed and dissolved organic matter in the soil solution of sodic soils may be deposited on the soil surface by evaporation, generating a dark surface that is why these soils have been termed black sodic soils.

The objective of reclaiming a sodic soil will be decreasing the amount of Na in the exchange complex by increasing the amount of Ca. This is achieved by amendment with Ca-rich products. After Na replacement by Ca, it is necessary to leach the soluble Na salts, which is difficult because of the low permeability of sodic soils. This may be improved by adding electrolytes (chemical amendments added to the irrigation water) and tillage.

Usual amendments for sodic soils include calcium chloride, calcium carbonate, or gypsum, the latter being the most frequently used. Sulfur can also be applied in calcareous soils since it oxidates to sulfuric acid that reacts with carbonates to form gypsum; the reclamation process is, however, slower since sulfur should be oxidized. Replacement is faster with soluble products, and thus calcium carbonate is the least recommendable product. Its use is not practical in calcareous sodic soils. Frequently, byproducts rich in gypsum have been used, like phosphogypsum from the phosphate fertilizer industry. The availability of gypsum has increased, as it is the byproduct of scrubbing sulfur dioxide gases from the emissions of coal-fired power plants.

Gypsum amendments are normally broadcast and then incorporated into the soil by disking or plowing. Fine ground gypsum is more quickly solubilized. When the problem is a surface crust, the gypsum needs are reduced. If the problem is in deeper layers, gypsum contributions should be much larger. Gypsum may also be applied dissolved in the irrigation water, which increases efficiency.

In general, the reclamation with gypsum is performed in several stages. The common practice is to make a first application of approximately 10 t/ha of gypsum in the first year with 1.5 m of water. In subsequent years (2 or 3), more applications of gypsum of 4 t/ha accompanied by some leaching may be performed.

Amendment rates for sodic soils are calculated based on the required reduction in *ESP*. This reduction is usually recommended down to $ESP = 10$ as the efficiency of amendments for replacing Na decreases sharply below that value. The equivalents of Ca (and thus of amendment) to be applied are the equivalents of Na to be replaced from exchange sites (on a soil mass basis). Thus, the amendment rate (Kg gypsum/ha) to be applied can be calculated as:

$$\text{Amendment rate} = 100 \cdot EM \cdot F_g\ \rho_b\ Z\,CEC\left(ESP_i - ESP_f\right) \quad (30.5)$$

where EM is the equivalent mass (86 for gypsum), ρ_b is soil bulk density (t/m^3), Z is soil depth (m) to be restored, CEC is the cation exchange capacity (cmol$_+$/kg), ESP_i and ESP_f are the initial and final values of ESP of the soil, respectively, and F_g is an efficiency factor that varies from 1.1 ($ESP_f = 0.15$) to 1.3 ($ESP_f = 0.05$) for gypsum.

This calculation can be applied to sodic soils. However, in saline-sodic soils, it is difficult to estimate accurately the exchangeable cations since chemical extractions to this end also dissolve soluble salts. Exchangeable cations are usually overestimated if specific analysis methods are not used. This is why USDA proposes a calculation based on the sodium adsorption ratio (SAR) of the saturation extract of the soil. Since numerical values of ESP and SAR are quite similar, this calculation can be done using the model above and replacing ESP by SAR, with the same final value of 10 as a recommendable value, such as in the example below.

Example 30.5

Soil bulk density is 1.3 t/m^3, and CEC is 40 cmol$_+$/kg. The initial SAR is 0.20 and we want a final value of 0.10. The amount of gypsum to recover the top 0.3 m layer of soil will be:

$$\begin{aligned}\text{Gypsum amount} &= 100 \cdot 86 \cdot F_g\ \rho_b\ Z\,CEC\left(SAR_i - SAR_f\right)\\ &= 8600 \cdot 1.2 \cdot 1.3 \cdot 0.3 \cdot 40 \cdot \left(0.2 - 0.10\right) = 16099\ \text{kg / ha}\end{aligned}$$

30.7 Reclamation of Acidic Soils

Acidic soils have a pH below 6.5 in water or saline (e.g., KCl) extracts. Soil pH is related to the base or acidity saturation of the exchange complex. In this regard, the percent of base saturation (PBS) decreases and the percent of acidic saturation (PAS) increases with decreased pH values. pH in saline extracts is lower than that in water since exchangeable acidity is released to the solution. This difference increases with increased exchangeable acidity in soil.

The reclamation of acidic soils with amendments (liming) aims at increasing the percentage of base saturation (and consequently to decrease the acidic saturation) to values that do not constrain plant growth. In this regard, sensitivity of plants to acidity ranges widely, with legumes in general being more affected by acidity than cereals. Some authors suggest a target PBS from 60 to 80% for most crops, which implies pH between 6 and 7. The main risk below pH 5.5 is Al toxicity. A pH of 6 ensures that all exchangeable Al is neutralized forming nontoxic compounds.

Products used as amendments for acidic soils should provide cation bases with positive effects on the soil. The most recommendable is Ca, although some amendments can provide Mg as well. This ensures the supply of these nutrients to crops and the amelioration of soil physical properties (see Chap. 2). Increasing *PBS* results in higher pH; also, reactions of the product in the soil should contribute to increasing the soil pH. Traditionally, products rich in calcium carbonate have been used. Mining products such as limestone, dolomitic limestone (essentially composed of calcium-magnesium carbonate), and marls (unconsolidated mixes of clay and calcium carbonate) are usual amendments for acidic soils. The products resulting from the combustion of limestone, i.e., calcium oxide or hydroxide, are more soluble but caustic and difficult to mix with soils when wet. Industrial byproducts such as sugar industry slag (rich in calcium carbonate) or basic slag (calcium silicate) from the steel industry may be used. Gypsum and phosphogypsum have been used as Ca sources for reducing aluminum toxicity in acidic soils; however, these products are not as effective as limestone in increasing pH.

Small-size particles are good for the application of poorly soluble products such as limestone and dolomite (or any carbonate-based amendment) since this increases the surface area in contact with soil. Thus, the quality of the amendment product and the time for achieving the objective depends on the particle size. This is less relevant in soluble products such as Ca oxides or hydroxides. Since the reaction of poorly soluble products is slow, they should be applied well in advance to sowing (3 months for limestone, 6 months for dolomites). The amendment should be mixed with the soil, down to 15–20 cm after broadcasting. Under no tillage, the surface application to reclaim a 15–20 cm soil depth may lead to high soil pH in the soil surface and, thus, nutrient deficiencies. However, there is a slow base movement and pH will increase in depth with time, something that may take months or even years.

The amendment (liming) rate can be calculated on an equivalent basis as the equivalents necessary to increase base saturation to a given value. This will lead to an increased soil pH. The negative charge of soil components such as oxides or organic matter increases with increased pH. Thus, the *CEC* of acidic soils increases when pH increases with liming. This is particularly relevant in highly weathered tropical soils rich in Fe and Al oxides. This is why some authors base the calculation on the estimate of *CEC* at a fixed pH value (buffering at pH 7) and propose the calculation of liming requirement as:

$$\text{Liming rate}\left(\frac{\text{kg}}{\text{ha}}\right) = 100 \cdot EM \cdot R^{-1} \cdot \rho_b \cdot Z \cdot f_L \cdot CEC\left(PBS_f - PBS_i\right) \quad (30.6)$$

where *EM* is the equivalent mass of the compound acting as amendment (e.g., 50 for calcium carbonate, 26 for CaO); *R* is the percent of active compound over product mass (e.g., sugar industry slag has R = 25 for calcium carbonate); ρ_b is soil bulk density (t/m^3); *Z* is the soil depth (m) to be restored; *CEC* is the cation exchange capacity (cmol$_+$/kg) determined at buffered pH 7 (ammonium acetate method); and PBS_i and PBS_f are the initial and final values of *PBS*. f_L is a liming factor to take into account that not all of the applied amendment replaces exchangeable acidity from the exchange sites. This efficiency in replacing acidity decreases with increased initial soil pH (increased base saturation). It has been shown that f_L is around 1.05 for PBS_f < 50%. Thus, in this case, almost all the applied Ca replaces acidity in exchange sites. However, its value increases with increased PBS_f up to 1.25 when final base saturation is close to 100%. In this model, since *CEC* is determined at a fixed pH, the result does not vary with increasing pH after amendment; thus, the calculation of the amendment is really based on the increase in exchangeable bases content in soil.

Other models widely used are based on the decrease of initial exchangeable acidity determined at the initial soil pH. The classical Kamprath model recommends a liming rate on an equivalent basis from 1.5 to 2 the initial exchangeable acidity depending on the sensitivity of crops to acidity. The Cochrane model recommends liming rates from 1.5 to 2 times the decrease in exchangeable acidity (fixing a target saturation acidity). When the target is to reduce Al toxicity, these methods based on exchangeable acidity can be reasonably accurate. Other methods are based on a target soil pH, which needs to estimate soil buffer capacity with slow titrations and should be developed specifically for similar soils of the same geographical region. Since the main risk associated to low pH in tropical soils is Al toxicity, other models for estimating liming requirement are based on the exchangeable Al in soils. However, this approach may underestimate lime requirements when Al toxicity is the only objective but the most yield-limiting issue is soil acidity.

Besides the natural origin mentioned, leaching and management factors can lead to acidification of agricultural soils (see Chaps. 2 and 26). Thus, in soils where there is a trend toward acidification, these factors should be counterbalanced to avoid a decrease in pH and base saturation.

Example 30.6

Extractable bases in a soil with a pH of 5.2 are ($cmol_+$/kg): Ca 4, Mg 1.5, K 0.3, and Na 0.2; *CEC* determined by the ammonium buffered method at pH 7 is 15 $cmol_+$/kg. Bulk density is 1.4 t/m^3. Calculate the amount of limestone with a richness of 90% in calcium carbonate necessary for reclaiming the soil down to 20 cm. The equivalent mass (*EM*) of calcium carbonate is 50.

We may assume a target *PBS* = 70%. For this target, f_L = 1.2 may be assumed.

Current *PBS* = (4 + 1.5 + 0.3 + 0.2)/15 = 40%.

$$\text{Liming rate}\left(\frac{\text{kg}}{\text{ha}}\right) = 100 \cdot EM \cdot R^{-1} \cdot \rho_b \cdot Z \cdot LF \cdot CEC\left(PBS_f - PBS_i\right)$$

$$= 100 \cdot 50 \cdot \left(\frac{1}{0.9}\right) \cdot 1.4 \cdot 1.2 \cdot 15 \cdot \left(70 - 40\right) = 3956 \approx 4000\,\text{kg / ha}$$

30.8 Regenerative Agriculture

Regenerative agriculture is an approach to farming that focuses on maintaining or regenerating the soil functions to provide and support multiple services, including food production and other ecosystem services. The scientific bases are the principles of soil conservation and reclamation, and the strategies to attain soil quality are increasing SOM and biodiversity, improving soil health, and restoring physical and chemical soil properties where they have been degraded. In recent years, an agroecosystem approach has been added by including a social and economic dimension for sustainable food production.

It is complicated to benchmark the ideal environmental performance of an agricultural system, as the human modification of ecosystems to produce food or other products always impairs its natural conditions. Nevertheless, properly designing and managing agricultural systems can keep a sustainable productivity level while providing other environmental services. For instance, soil erosion can be boosted with cultivation compared to a natural system if farming is performed under geomorphological and environmental conditions that favor erodibility. Nevertheless, soil conservation strategies can greatly mitigate erosion and regenerate soil functionality. On the same line, strategies to mitigate the biodiversity loss associated with cultivation, such as crop rotations, intercropping, or alley cropping, greatly enhance belowground diversity and can make a big difference in the agroecosystem sustainability.

An example of regenerative agriculture is the recovery of soil functionality in irrigated land by the introduction of cover crops. Irrigation in semiarid areas increases and stabilizes productivity, but it also enhances rapid SOM mineralization that can lead to soil structure degradation and to increased erosion and nutrient losses. In the Mediterranean region, it is common to find soils with low SOM that have become degraded due to intensive arable cropping and low biomass returns. That was the case of a farm in Aranjuez (Central Spain) where reduced tillage improved the soil quality. An additional improvement was attained by replacing the traditional winter fallow with cover crops. Cover cropping enhanced C and N sequestration, soil aggregate stability, and water infiltration (Fig. 30.7), leading to less dependence on mineral fertilizers and mitigating nitrate leaching. The main reasons for the improvement were the additional biomass incorporated into the systems and the root effect of the cover crops. Restoration of soil functionality is a low process, but, in this case, improvements were already attained 4 years after introducing barley as a cover crop.

Aboveground diversification and belowground diversification are crucial strategies of regenerative agriculture and are usually associated with an increase in biomass productivity and organic matter addition to the soil. In the farm in Aranjuez, the introduction of cover crops enhanced the diversification of soil microorganisms, particularly observed in an increase in mycorrhiza activity and hyphae length. Interseeding the cover crops in the cash crops at the end of spring allowed increasing diversity in the annual rotations and enhanced biomass production and soil protection (Fig. 30.8). Further, the early interseeding opens the opportunity for

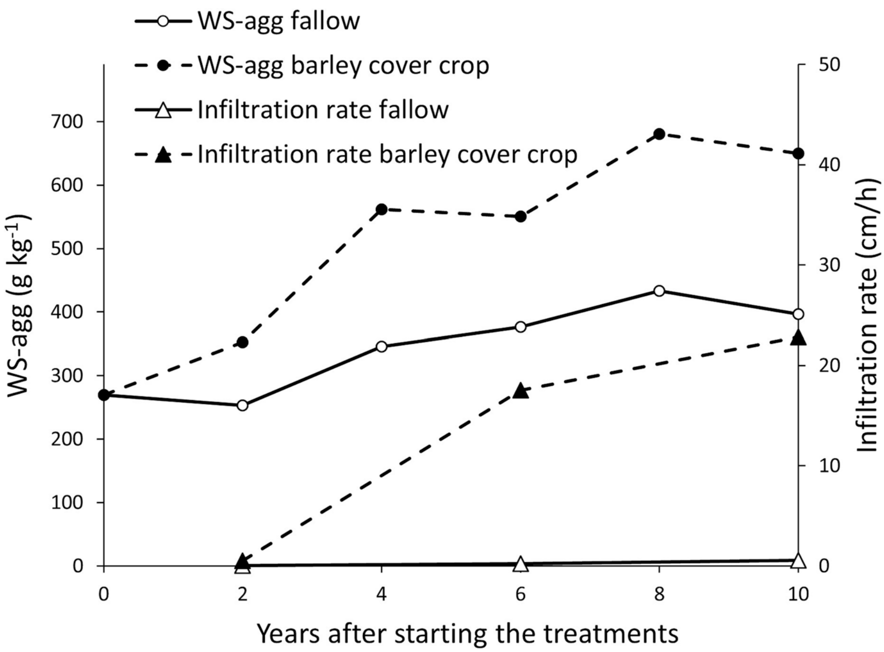

Fig. 30.7 Time course of soil aggregate stability in waer (WS-agg) and infiltration rate after 10 years of reducing tillage to a minimum and replacing the fallow by a winter barley cover crop. (Adapted from Garcia-Gonzalez et al. (2018). Geoderma 322: 81–88)

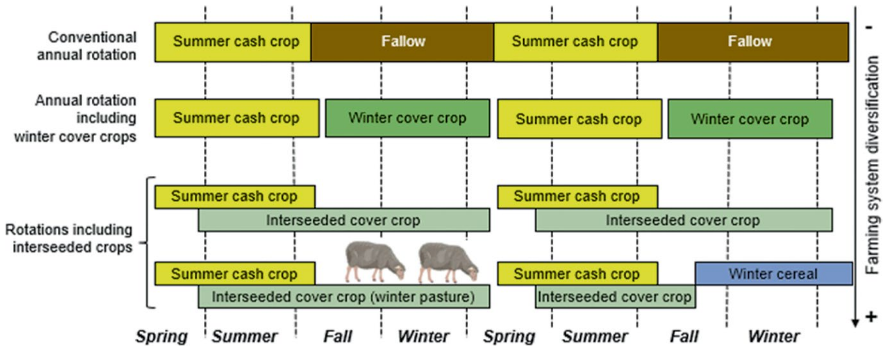

Fig. 30.8 Schematic representation of farming systems with increasing level of diversification from the top to the bottom. (Adapted from Alonso-Ayuso et al. (2020). Field Crops Res 249: 107762)

terminating the cover crop in late fall and sowing a winter cash crop that could benefit from the N released during the mineralization of cover crop residues. In addition, cover crops could be integrated into crop-livestock systems, if grazed by sheep or cattle during the fall/winter period, enhancing diversification in the Mediterranean inland. Transition to more diversified farming systems is challenging, and there is not a unique recipe, but incorporating scientific knowledge into local practices following the principles of regenerative agriculture is a solid foundation for success.

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Manipulating the Crop Environment

31

Francisco J. Villalobos, Luca Testi, Luciano Mateos, and José Paulo De Melo-Abreu

Abstract

Windbreaks are structures that reduce wind speed and may affect turbulence in the protected zone. The maximum efficiency is obtained with windbreaks of medium porosity that reduce wind speed up to a distance 20–25 times their height. Windbreaks promote larger temperature oscillations, which may increase frost risk and dew deposition.

Soil temperature can be modified by changing its exposure to radiation, artificial heating, or mulching. Mulches can be natural (e.g., crop residues) or artificial, most notably plastic films. The crop canopy may be cooled down with sprinkler irrigation when *VPD* is high. Additional environmental control may be performed with row covers and greenhouses that create a warmer wind-protected environment and are increasingly popular in horticultural production.

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31.1 Introduction

There are limited possibilities for modifying the aerial environment of crops grown outdoors. In this chapter, we discuss these possibilities starting with protecting crops from wind and then proceeding with environmental manipulations to modify soil and crop temperatures.

The main factor that can be manipulated is wind which may be modified by placing physical structures (inert or living) on the edges of fields. The structures may form walls, called windbreaks, whose main objective is to reduce wind speed. The term shelterbelt refers to several rows of trees and shrubs. The structures may be scattered isolated trees which affect wind flow in the area and also have a protective effect by intercepting rainfall. This association of crops and protective trees is termed agroforestry. In such systems, the trees may yield timber and/or fruit which directly contribute to farm income, besides protecting the crops.

Planting windbreaks has been a common practice in agricultural systems of regions with strong winds. An example would be the protective windbreaks against the mistral wind in the Rhone Valley in southern France. In the Great Plains of the United States, windbreaks appeared in the 1930s to protect the soil from wind erosion after a long drought (*Dust Bowl*). Today, they are used only in regions where wind poses substantial risks to agricultural production. Because they use valuable land, windbreaks are mostly used in horticulture (fruit tree production).

In contrast to their beneficial protective effects, windbreaks also have negative effects. First, they occupy part of the arable land and shade the cropped areas close to the windbreaks. If they are living structures, they may compete for water and nutrients and serve as shelter for some pests. Despite these drawbacks, most studies have shown an overall positive effect of windbreaks on crop yields in windy areas.

31.2 Effects of Wind on Crops

The effects of wind on crops and soils are diverse:

– Growth: Plant movement due to wind can reduce crop growth rate and increase plant's mechanical resistance (shorter and thicker stems, increased root/shoot ratio). This phenomenon, *thigmomorphogenesis*, does not require a continuous stimulus but may be triggered by infrequent movements.
– Mechanical damage: The wind's force can tear leaves or strip them from the plant. In dense canopies, abrasion may result from the rubbing of plant leaves and stems. Mechanical damage may be caused by the impact of soil particles carried by wind.
– Crop lodging: This is caused by strong winds after wetting the canopy by rainfall or irrigation, which increases the load on the plant and the bending moment and decreases the stability of the root plate. The result is that the stems bend or break at some point near the ground surface and the crop lays on the ground (see 31.3).

- Crop evaporation is proportional to wind speed when crops are well watered. Therefore, crop ET is reduced in protected areas.
- Dry and hot winds may cause grain shriveling in cereals during grain filling.
- Salinization in coastal areas may occur due to wind drift from the sea.
- Wind affects the variation of surface temperature. Therefore, the risk of frost may increase in protected areas (see Chap. 32).

31.3 Wind Forces on Plants, Lodging, and Windthrow

A body immersed in a flow of air is subjected to numerous forces. The total drag on the body is the sum of two forces in the direction of the flow: (i) *friction drag*, caused by air viscosity and resulting in momentum transfer through the boundary layer, and (ii) *form drag*, caused by the deceleration of the fluid and dependent on the body shape and orientation. These forces increase with the square of the velocity. The calculation of total drag force requires an empirical coefficient, known as the drag coefficient, which contains not only the complex dependencies of object shape and orientation but also the effects of air viscosity and compressibility. The latter effect, however, is negligible for naturally occurring wind speeds.

Plants are composed of multiple surfaces and are flexible. Streamlining of plant parts affects total drag, so the drag coefficient decreases with wind speed. Higher turbulence increases momentum transfer, thus increasing drag on plants. In wind tunnel experiments, turbulence is typically low so laminar flow, and thus smaller drag, is expected.

High wind speeds may exert disruptive forces on isolated plants or their populations. Lodging of crops is the permanent displacement of some plants from their vertical position, which is responsible for yield losses, increased harvest costs, and quality deterioration. Stem lodging occurs when the lower section of the stem breaks or bends, and root lodging occurs by either rupture of the roots that support the plants or fracture or turn of the piece of soil around the base of the stem (root plate).

Rice (Tani, 1963; Bulletin of the National Institute of Agricultural Science, Tokyo A 10, 99), in laboratory experiments, measured a critical turning moment for stem lodging of 0.2 N m on the base of the stems. However, the moment was only 0.057 N m (i.e., 29%) in the field. The difference is related to field experiments (i) not accounting for the actual wind speed during gusts, and/or (ii) having resonance due to periods of oscillation of plants and eddies at the top of the canopy, and/or (iii) having sanitary or nutritional problems.

Ennos (1991. J. Exp. Bot. 42:1607–1613), in laboratory experiments with bread wheat, determined that the critical turning moments was about 0.2 N m, the same value found by Tani. Moreover, he concluded that roots would fail before stems would bend due to the 30% lower anchorage resistance of the roots compared with the resistance of the stems. The value of this finding is restricted to the mechanical properties of the soil used.

The reasoning for the windthrow of forest trees is similar to the lodging of plants in field crops. Some models have been constructed to predict these events (Baker et al., 1998; Berry et al., 2003), but their practical application is limited due to the system complexities. For example, the profile of wind speed inside the canopy is not uniform and is influenced by population density and the shape of the crowns. Turbulence description is even more challenging and is critical to determine the actual critical values of wind speed for lodging or windthrow.

Lodging of cereals may be reduced by:

– Increasing the strength of the stem base and anchorage system.
– Reducing N availability, especially in the spring.
– Lower planting density.
– Delayed sowing dates.

Soil mechanical properties and soil moisture affect soil shear strength and resistance to anchorage failure. Increases in clay content and compaction increase shear strength, while higher soil water content tends to reduce it.

31.4 Windbreaks

Windbreaks are structures established to reduce wind speed and change its direction. Hedges may be formed by plants (shrubs, trees, or annuals) or inert structures (hurdles, plastic mesh enclosure walls, etc.). Apart from reducing wind speed, plant windbreaks generate additional benefits such as providing shelter for wildlife, protecting the livestock from weather elements, and acting as a barrier for sound and smell. In addition, some agricultural operations are improved in protected areas like reduced pesticide drift and higher uniformity of sprinkler irrigation or pesticide spray application. A better environment for farmworkers is also created. In some areas, environmental authorities promote windbreaks with incentives to farmers to increase biodiversity and enrich the landscape. The increase in biodiversity (especially animals) is often beneficial as birds and insects often prey on pests helping to reduce their impact. In some cases, however, windbreaks may host pests, maintaining population stocks that will feed on the crops once they are established. The species composition of windbreaks should then be chosen following an ecological rationale in addition to the aerodynamic considerations addressed below.

Field windbreaks may be single rows of trees or shrubs or multiple-row shelterbelts. The latter provide better conditions for wildlife and may be formed by four to five rows of alternating trees and shrubs. Taller species should be placed in the center of the belt with shorter species on each side. Deciduous trees lose their protective capacity during winter. Tall annual crops may be used to protect shorter crops.

31.5 Wind and Turbulence in the Sheltered Zone

Windbreak structure—height, density, number of rows, species composition, length, orientation, and continuity—determines the effectiveness of a windbreak in reducing wind speed and altering the microclimate.

The effectiveness of the windbreak depends mainly on its width, height, and porosity. Effectiveness is measured as the distance downwind, expressed as the number of shelter heights, through which the wind speed is reduced relative to that in the open.

On the windward side of a windbreak, wind speed is reduced upwind for a distance of two to five times the height of the windbreak (2H to 5H). On the leeward side, wind speed may be reduced up to 30H downwind of the barrier (Fig. 31.1).

Windbreak porosity is the ratio of the open fraction of the barrier to its total volume. Wind flows through the open portions of a windbreak; thus, the less porous a windbreak, the less wind passes through. Low pressure develops on the leeward side of very dense windbreaks, which pulls down air going over the barrier, generating additional turbulence and reducing protection downwind. As porosity increases, so does the flow passing through the barrier; thus, turbulence is not enhanced, and the effectiveness increases, although the magnitude of wind speed reductions is not as great.

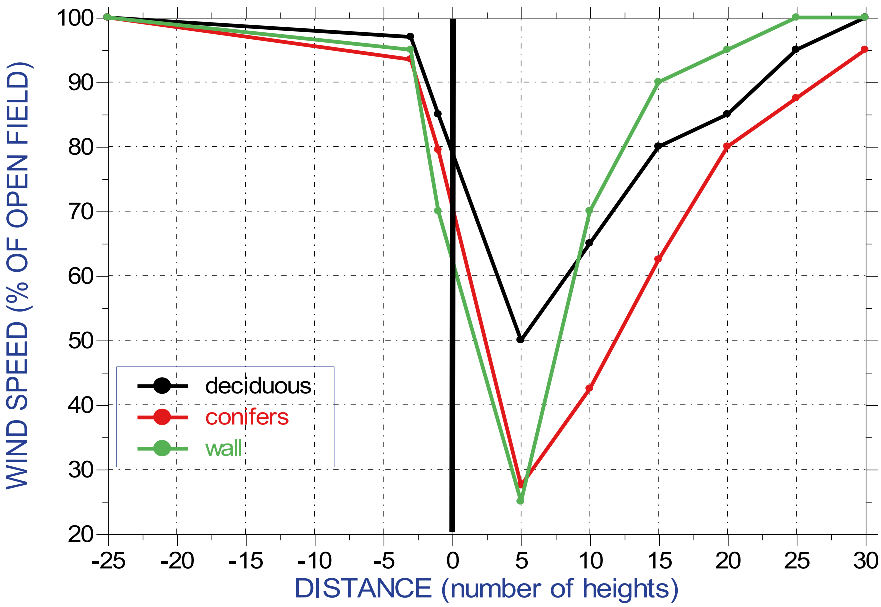

Fig. 31.1 Wind speed variation (as a percent of its value in the open) as a function of distance from the windbreak, expressed as the number of heights. Negative and positive values represent the windward and leeward sides, respectively. The porosity is 70–75% for deciduous and 50–60% for conifers

Dense windbreaks (porosity below 25%) show effectiveness (E_w) of 10–15H. With permeability around 50%, the effectiveness increases to 20–25H (Fig. 31.1), without adding large-scale turbulence. These values of effectiveness vary however with other factors such as wind speed (E_w is proportional to wind speed), atmospheric stability (E_w is larger in unstable conditions), and wind direction (E_w is maximum when wind direction is normal to the barrier). Even when the wind blows parallel to the barriers, some effect on wind speed is observed. Windbreaks with intermediate porosity (40–60%) are usually the most effective.

31.6 Establishment and Maintenance of Windbreaks

Trees or shrubs to form windbreaks should grow rapidly and have strong erect stems able to withstand wind forces and a well-anchored root system. They should also be able to survive under the prevailing biotic stresses of the area (drought, cold). Among plant windbreaks, the most common species are conifers such as cypress (*Cupressus* spp.), spruce (*Picea* spp.), and pine (*Pinus* spp.). Other trees used are poplars (*Populus* spp.) and *Eucalyptus* spp. Each species and, within species, each variety have characteristics of adaptation to the environment that determine the most appropriate. There are also differences between species and varieties regarding competition with the crop, which come mainly from root systems that may be shallow or able to explore deep soil horizons.

The orientation of windbreaks depends on the design objectives. Farmsteads and feedlots usually need protection from cold winds and blowing snow during winter. Field crops and fruit trees usually need protection from hot, dry summer winds, or wind-blown soil particles, especially during critical growing periods. Windbreaks for soil erosion control should be normal to the prevailing winds when the soil is bare (winter and early spring).

Despite predominant wind directions during given periods, wind direction may vary from day to day or during the day, so the level of protection by the windbreak may be reduced. A set of multiple windbreaks forming parallel lines spaced 10–15H provides a larger protected area than a single windbreak. If protection from several wind directions is required, another set of parallel lines, normal to the first, should be established, resulting in a rectangular arrangement of protected fields.

Gaps in the windbreak may be needed to allow access to the fields. The uninterrupted length of a windbreak should exceed the height by at least 10:1. This is because gaps in a barrier become funnels that concentrate wind flow, leading to wind speeds in the protected area that may even exceed those in the open.

The plantation of a windbreak follows the same rules as other plantations although the distance between trees may be smaller (e.g., 3 m between rows, 2 m between trees in the row) and high survival and rapid growth are critical. Lost trees should be replaced as soon as possible. Supplemental irrigation during dry periods, protection against browsing by animals (by planting thorny plants or putting a barbed wire fence), and weed control are critical, particularly during the early years of the plantation.

As the trees grow, some pruning may be required to keep the required porosity, promote vertical growth, and eliminate branches damaged by wind or pests. Tree thinning may be required to enhance trunk diameter growth.

31.7 Microclimate Changes in the Protected Area

Solar radiation is reduced significantly in the area shaded by windbreaks. The effect is almost nil for distances beyond 1–2H. The effect is marginal for north- to south-oriented barriers as the shaded area is very small around noon when radiation is at its maximum. Further reduction by shading may occur early in the morning or late afternoon but is partly compensated by the reflection of radiation from the windbreak. The largest effect on radiation occurs in east- to west-oriented barriers, on the area to the north (in the North Hemisphere) of the windbreak, in special for high latitudes and winter periods.

The reduction of wind speed, and thus, in turbulence in the protected areas has several effects:

(a) Temperature: During the day, it favors soil heating (Chap. 6), which usually leads to warmer soil surface and air above. During the night, strong temperature inversions will develop leading possibly to lower minimum temperatures. This explains the increased frost risk in protected areas.
(b) Vapor pressure: It tends to increase close to the canopy during the day, when plants are transpiring, as mixing is reduced, particularly on calm days. At night, the higher vapor pressure and the lower temperature enhance dew deposition in protected areas. The combination of higher vapor pressure or plants wet by dew with higher temperatures may increase the incidence of aerial diseases.
(c) *ET*: For well-watered crops, reduced wind speed means higher aerodynamic resistance (Chaps. 4 and 9) and, therefore, reduced *ET*. This effect may be offset partly by lower canopy resistance in some species. However, the improved environment in the protected area may increase crop growth and hasten soil water depletion. In rainfed crops subjected to water stress late in the growing cycle, the overall effect may be a reduction in the Harvest Index in protected areas. However, well-watered crops show the same or higher yield with reduced *ET*, which means a higher Water Use Efficiency.
(d) Chill factor: Heat losses of livestock, wildlife, and structures (farmsteads, greenhouses, etc.) due to windchill are reduced on the leeward side of a windbreak.

31.8 Scattered Windbreaks

The presence of scattered trees in the field reduces the average wind speed because of higher aerodynamic roughness. The reduction will be proportional to the fraction of the area covered by trees. The main difference between scattered trees and regular rows is the degree of interaction (including competition) between trees and crops which is higher when trees are scattered. In this case, the tree also protects crops and soil from direct rainfall impacts. The negative effects are:

– Increased competition for light (isolated trees intercept more radiation), water, and nutrients with the crop.
– Additional difficulties for cultural operations as trees become obstacles for the machinery.
– Higher cost of establishing isolated trees, especially when young trees have to be protected against wildlife or farm animals.

31.9 The Importance of Soil, Air, and Crop Temperatures

Soil and air temperatures influence numerous critical processes of the crop. Seed germination and plant emergence are extremely sensitive to the temperature of the soil. The time from sowing to emergence increases and seedling growth is slower when the soil is cold. Canopy temperature has an important effect on critical plant processes (development, growth, assimilation) and thus on crop productivity.

The root distribution is also affected by soil temperature. In some species, root growth is restricted to the upper layers when the soil is too cold, while a much deeper root distribution is observed at higher temperatures, which improves water and nutrient uptake. Other processes that respond to soil temperature are symbiotic nitrogen fixation, photosynthesis, water flow in the soil-plant system (water viscosity is high at low temperatures), organic matter mineralization, and soil respiration.

In summary, soil and air temperatures have varied effects on crops and their control may increase yields. Therefore, artificial soil and/or air heating is sometimes used in high-value crops. The alternatives for crops outdoors are limited but some may be very effective for manipulating soil temperature.

31.10 Slope and Aspect

The irradiance on a given surface increases as the incidence angle of solar rays decreases and is maximal when the radiation vector is normal to the surface. The effect of slope and orientation (aspect) of the surface will be proportional to the fraction of beam (direct) radiation reaching the surface, which lies between 0 (cloudy sky) and 0.85 (clear atmosphere with zero zenith angle). The slope and aspect of a plot are less important when the solar zenith angle is high or low, although for different reasons. The fraction of direct radiation decreases as the zenith angle increases due to the longer path of the atmosphere that sun rays cross to reach the Earth. Therefore, the slope and aspect of a surface will barely affect irradiance in high latitudes. On the other hand, the zenith angle is so small at low latitudes that orientation has little effect on irradiance. The same reasoning may be

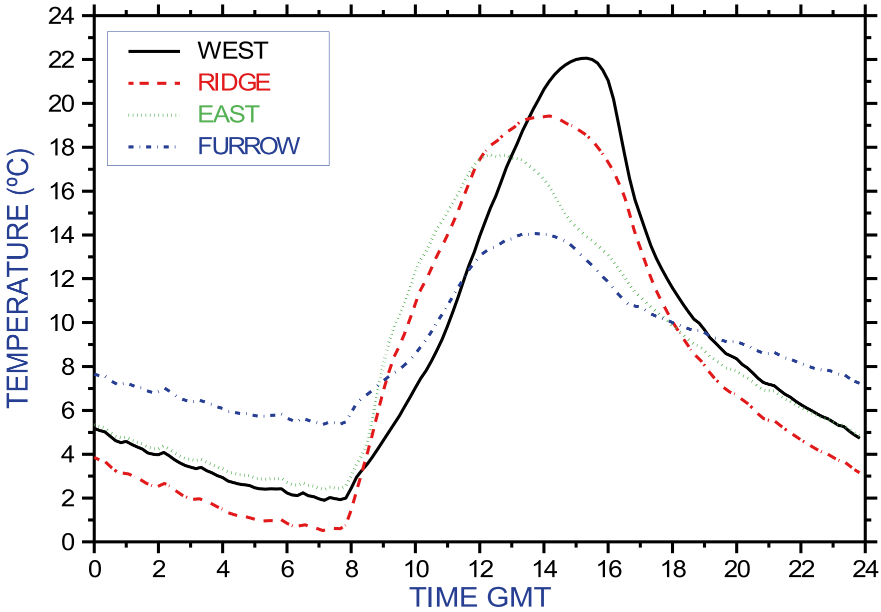

Fig. 31.2 Time course of soil temperature at 2.5 cm depth in a north to south ridged sandy loam soil in Cordoba, Spain

applied to seasonal changes: Slope and aspect are important in spring or autumn but less important in summer (low zenith angle) and winter (high fraction of diffuse radiation).

Figure 31.2 shows the temperature in different positions of a field with furrows in the north to south direction. The temperature at the furrow is lower than on the ridge. On the sloping sides, the temperature is typically higher than on the ridge, with the side facing east warmer in the morning and the side facing west warmer in the afternoon.

North-facing and south-facing slopes are colder and warmer, respectively, in the Northern Hemisphere.

31.11 Mulching

A mulch is a layer of material covering the soil and acting as a barrier to heat or water transport. Additional functions of mulches include soil protection against erosion and weed control. Some common mulches are weed residues, straw and other crop residues, inorganic mulches (plastic films, gravel, sand), and industrial by-products (bark, wood chips, etc.).

The effect of mulching on soil temperature is evaluated by considering first the possible change in net radiation. Black plastic will increase net radiation (reduced albedo) while straw will reduce it (high albedo). The second aspect to be considered

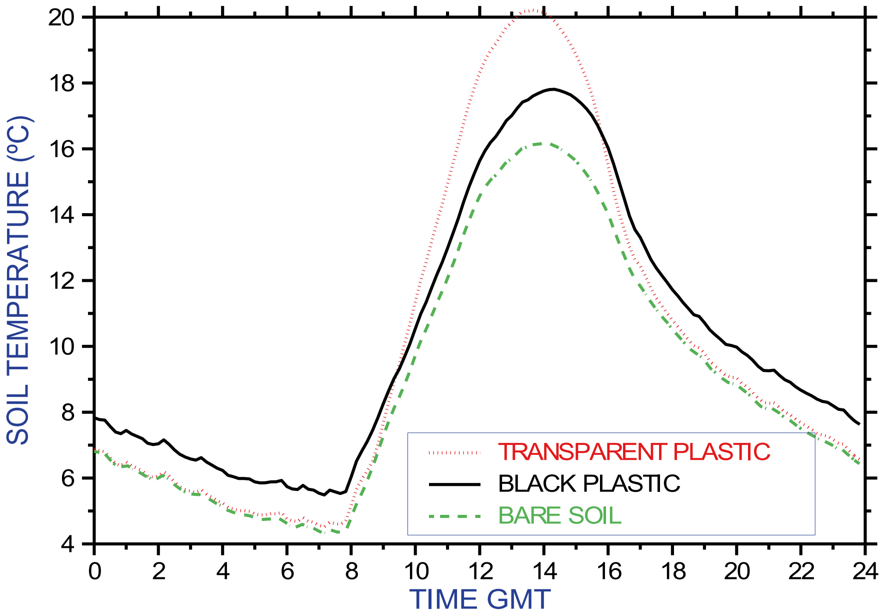

Fig. 31.3 Time course of soil temperature at 2.5 cm depth under black or transparent plastic films in a sandy loam soil in Cordoba, Spain

is water transport. Mulches may reduce water flow or even suppress it (plastic films). Therefore, more energy will be available for heating the air (straw) or the air and the soil. A transparent plastic will enhance soil heating much more than a black plastic (Fig. 31.3). The latter absorbs radiation but transmits and reflects little, so the black plastic is heated and may reach high temperatures. However, the air layer between the plastic and the soil surface limits heat conduction to the soil. The transparent plastic transmits most short-wave radiation but also long-wave radiation. Therefore, during the night, the soil under transparent plastic cools down like the control (bare soil) while the black plastic keeps the soil warmer due to the low long-wave transmissivity. Straw transmits little radiation, which reduces soil warming during the day and cooling at night.

Transparent plastic films are used widely in horticultural crops during the spring to increase soil temperature and, thus, speed up crop development for early production and reduce season length. Earlier harvest leads to better prices in many horticultural crops. In addition to the effect on temperature, soil water is conserved in the upper soil layer, which prevents the appearance of a surface crust and improves the conditions for germination, emergence, and early seedling growth.

Black plastic is often used in vegetable crops, but the main objective is weed control. Many weed seeds will remain dormant in the dark and those that do germinate will die soon due to lack of carbohydrates. Another advantage of a plastic cover (valid also for transparent films) is preventing the contact of fruits with the soil, thus avoiding diseases.

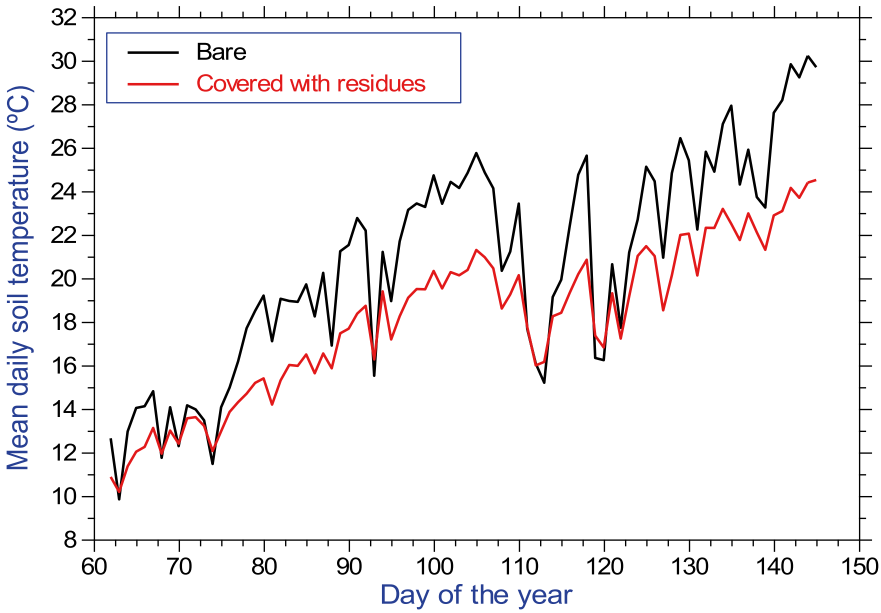

Fig. 31.4 Mean daily surface soil temperature for a sandy loam soil in Cordoba, Spain, in 2011 covered with straw or bare

Most mulches, and especially those of organic origin (straw, crop residues, cover crops) act as insulators, i.e., they damp the soil temperature waves and therefore will keep the soil cooler when applied in spring (Fig. 31.4) or warmer if applied in the summer. Mulched spring sown crops (e.g., direct sowing with residues) will thus show a slower development. The effect on the water balance depends on rainfall distribution: Frequent and light rains will wet the mulch and most water will evaporate directly from it. Heavier and isolated rainfalls will infiltrate better in mulched soil and soil evaporation will be reduced.

Inorganic mulches like sand or gravel have excellent properties as they do not reduce soil heating but are very effective in reducing soil evaporation and increasing infiltration.

31.12 Artificial Soil Heating

In some situations (nurseries, sports stadiums, high-value horticulture), the soil may be heated using electrical cables or pipes with hot water. The cost may be reduced when hot water is available as a by-product from cooling operations in industry or power plants.

31.13 Modifying Canopy Temperature

Windbreaks increase temperature oscillations in the protected area (see 31.5). An alternative for reducing canopy temperature of crops in the open is wetting the plants. A group of US researchers proposed using frequent irrigation to keep the canopy wet and thus bring canopy temperature closer to its optimum to increase productivity. The idea was abandoned because of the excessive water use, the higher risk of aerial diseases, and the reduction in crop nutrient uptake.

We can apply Eq. 21.3 to evaluate the difference between the canopy and air temperature, $T_c - T_a$, for different values of canopy resistance. The difference in canopy temperature between a dry and a wet ($r_c = 0$) canopy is:

$$T_c - T_c^w = \left[\frac{\Delta (R_n - G) + \rho C_p \, {}^{VPD}\!/_{r_a}}{\Delta + \gamma} \right] \frac{\gamma \; r_c}{\rho C_p \left[\Delta + \gamma \left(1 + {}^{r_c}\!/_{r_a} \right) \right]} \tag{31.1}$$

The cooling due to wetting the canopy is proportional to radiation, *VPD*, and canopy resistance. Note that the left term in Eq. 31.1 is the latent heat flux according to the Penman-Monteith equation for $r_c = 0$ (LE_w), i.e., the *LE* of the wet canopy. So the increase of evaporation when the canopy is wet is:

$$LE_w - LE = LE \; \frac{\gamma \, {}^{r_c}\!/_{r_a}}{\Delta + \gamma} \tag{31.2}$$

Example 31.1

An irrigated crop with r_c = 40 s/m and r_a = 40 s/m at midday in summer ($R_n - G$ = 600 W/m^2) in an arid area (air temperature 40 °C and relative humidity 30%). At 40 °C, $\rho \; C_p$ = 1140 J K^{-1} m^{-3}

e_s = 0.6108 exp[17.27 × 40 / (40 + 237.3)] = 7.37 kPa,
e_a = e_s × HR/100 = 2.21 kPa,
VPD = 7.37 − 2.21 = 5.16 kPa.
Δ = 4098 • 7.37 / (40 + 237.3)^2 = 0.39 kPa/K.

If the canopy is dry:

$$LE = \frac{\Delta (R_n - G) + \rho C_p \, {}^{VPD}\!/_{r_a}}{\Delta + \gamma \left(1 + {}^{r_c}\!/_{r_a} \right)} = \frac{0.39 \cdot 600 + 1140 \cdot {}^{5.16}\!/_{40}}{0.39 + 0.067 \left(1 + {}^{40}\!/_{40} \right)} = 727 \text{ W m}^{-2}$$

and canopy temperature is:

$$T_c = 40 + \frac{1}{0.39 + 0.067 \left(1 + {}^{40}\!/_{40} \right)} \left[\frac{0.067 \left(1 + {}^{40}\!/_{40} \right) 600 \cdot 40}{1140} - 5.16 \right] = 35.5°\text{C}$$

(continued)

Example 31.1 (continued)

If we wet the canopy, *LE* will be:

$$LE_w = \frac{\Delta(R_n - G) + \rho C_p \,{}^{VPD}\!/\!_{r_a}}{\Delta + \gamma} = \frac{0.39 \cdot 600 + 1140 \cdot {}^{5.16}\!/\!_{40}}{0.39 + 0.067} = 834\ \mathrm{W\,m^{-2}}$$

And the cooling effect is:

$$T_c - T_c^w = \frac{LE_w \gamma \ r_c}{\rho C_p \left[\Delta + \gamma\left(1 + {}^{r_c}\!/\!_{r_a}\right)\right]} = \frac{834 \cdot 0.067 \cdot \ 40}{1140\left[0.39 + 0.067\left(1 + {}^{40}\!/\!_{40}\right)\right]} = 3.7\ \mathrm{K}$$

So the temperature of the wet canopy would be 31.8 °C.

31.14 Greenhouses

The highest level of control of the aerial environment of plants is achieved in growth cabinets and growth chambers which are only used in research and breeding programs due to their high cost. The lowest level corresponds to windbreaks.

A second step in environmental control is achieved with mulches and row covers, i.e., pieces of clear plastic stretched over low hoops enclosing the rows of plants. Floating row covers are those supported by the plant itself. Shading nets and other covers are used in fruit trees as protection against hail and insects and to improve fruit quality. Nets of different colors that alter the light spectrum may improve certain fruit quality traits and disrupt insect flights.

The third level of aerial control of the crop environment is that of greenhouses which are structures covered with a transparent material. A wide range of designs differing in cost, level of control, and frame and cover materials is available. The simplest case is the plastic unheated greenhouse for horticulture production in mild-winter areas (e.g., Almeria in Southern Spain). The most sophisticated designs are metallic structures with glass or rigid plastic panels with artificial heating, supplementary lighting, and CO_2 fertilization (e.g., the greenhouse industry of the Netherlands). Greenhouse horticulture is increasingly using hydroponics instead of natural soils, a technology where plants are grown with or without mechanical support on an artificial medium (sand, gravel, rock wool, peat moss, etc.) and watered with a nutrient solution that is recycled through the system.

Glazing materials for greenhouses may be plastic films (e.g., polyethylene, PE), rigid plastic panels (e.g., polycarbonate), or glass. Glazing materials show high transmittance for *PAR* (above 80%), but they may be transparent to infrared (*IR*) like PE or not (PE with specific additives, glass, or any material covered by condensation). In the former case (*IR* transparent), radiative cooling at night is almost the same as in the open. This may be mitigated by using *IR* opaque curtains. During the day, the problem may be the opposite due to excessive heating of the air and plants inside the greenhouse during late spring or summer. In that case, it is possible to use shade cloth or whitewash to reduce irradiance and increase ventilation or use cooling systems.

In Sect. 10.6, we saw that evaporation inside unheated plastic greenhouses approaches equilibrium evaporation, i.e., it is mostly related to radiation inside the greenhouse. In this case, it is easy to deduce the sensible heat flux inside as the difference between net radiation and evaporation. This sensible heat flux will equal heat transport between the air inside and outside. For a given relative renovation rate (RR, h^{-1}) and mean greenhouse height (h_g, m), we can calculate the differences in temperature between the inside and the outside air as:

$$T_{\text{inside}} - T_{\text{outside}} = \frac{(1-k_L)\Delta + \gamma}{\Delta + \gamma} \frac{3600}{\rho C_p} \frac{k_{RN} R_{si}}{h_g\ RR} = \frac{C_T R_{si}}{h_g\ RR} \tag{31.3}$$

where γ is the psychrometric constant (0.067 kPa K^{-1}), Δ is the slope of the saturation vapor pressure function versus temperature (kPa K^{-1}; see Eq. 10.4), ρ is air density, C_p is specific heat of air at constant pressure (see 5.9), k_{RN} is the ratio net radiation/solar radiation inside the greenhouse, which may be taken as 0.7, and R_{si} is solar radiation inside the greenhouse (W m^{-2}). The coefficient k_L represents the fraction of evaporation as compared to equilibrium evaporation. For instance, if 75% of the greenhouse area is covered by well-watered vegetation, then $k_L = 0.75$ and C_T varies from 1.16 at 10 °C to 0.85 at 30 °C.

Example 31.2
A 3 m-high greenhouse of 200 m^2 area located at latitude 37°S is ventilated with an airflow of 3 m^3 s^{-1} (10,800 m^3 h^{-1}). Therefore, the relative renovation rate is 10,800/(200 · 3) = 18 h^{-1}. On June 21, solar declination is 23.45°, so the maximum solar radiation outside at noon on a clear day is 507 W m^{-2} (Chap. 3). The cover is polyethylene with a transmissivity of 0.7, so the estimated radiation inside is 355 W m^{-2}. The temperature outside is 20 °C and k_L is 0.75 so we can deduce $C_T = 0.99$. Therefore, the expected increase in temperature at that time is:

$$T_{\text{inside}} - T_{\text{outside}} = \frac{C_T R_{si}}{h_g\ RR} = \frac{0.99 \cdot 355}{3 \cdot 18} = 6.5\,\text{K}$$

So the temperature inside will be 26.5 °C.

This simple model is only a first approximation to characterize the micrometeorology of greenhouses as it ignores other processes that contribute to heat exchange (e.g., conduction through the cover) but is useful to illustrate the possibilities of climatic control in unheated greenhouses, namely, changing the radiation inside by putting shade cloth or whitewash painting on the cover or by manipulating ventilation via opening/closing vents or using fans. Apart from keeping the temperature within the optimal range for plant growth, ventilation is needed to prevent excessive air humidity inside the greenhouse as it favors fungal diseases. This is especially important at night when temperature approaches the dew point temperature so condensation occurs on plants and the inner surface of the cover.

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Frost Protection

32

José Paulo De Melo-Abreu, Luciano Mateos, and Francisco J. Villalobos

Abstract

Frosts affect agricultural production reducing yields and/or product quality. The best strategy to avoid frost damage is to use passive (preventive) methods, which imply a good choice of species, cultivars, planting dates, and locations, keeping the soil compacted, wet, and smooth, among other options. This requires the knowledge of the frequency distributions of minimum temperatures and the evaluation of the effect of low temperatures on crop performance (i.e., critical damage temperatures). However, the mechanisms of frost damage are rather complex and depend partly on plant hardiness, so damage predictions are very uncertain. When frost occurs, active (protective) methods minimize the damage by reducing longwave radiation loss (e.g., plastic covers), direct heating by burning fuel, air mixing (e.g., wind machines), and overhead irrigation for releasing the heat of fusion.

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32.1 Introduction

A frost is the occurrence of air temperature equal or lower than 0 °C at a height between 1.25 and 2 m, measured in an appropriate shelter. Most agricultural systems of temperate climates are affected by frost. The limitation to crop production due to frost is usually characterized by the mean frost-free period, which is the time from the last spring frost to the first in the fall. This period limits the season length of many species, which determines whether the crop may be grown successfully.

The frost risk increases as we move away from the equator, with a band between the two tropics where frost does not occur (except at high elevations). Areas with frost-free periods over 240 days are between 12 and 40° latitude and include the most important agricultural regions. In these regions, frost damage is often prevented on fruit and horticultural crops. Areas with frost-free periods of 180–240 days extend to 50°, although they may be found in higher latitudes due to the sea influence. When the frost-free period is less than 90 days, agriculture is limited and most food crops cannot be grown.

Frost is the weather hazard responsible for the greatest crop losses in the United States and, probably, the world. Among frost protection methods, the most useful are preventive, such as choosing the right species/cultivar and sowing date. Protective methods implemented in the night of frost are affordable only in high-value crops in horticulture and fruit production.

32.2 Effects of Frost on Crop Production

Frost damage depends on many factors such as the species, the cultivar, the degree of acclimation, the state of the plant tissues (which depends on the stage of development and irrigation and fertilization practices, among other factors), the height of the canopy, the type of pruning, the rate of temperature decrease, the duration of the frost, and the minimum temperature achieved. This complexity makes it difficult to predict frost damage. An additional problem is that the minimum temperature recorded at weather stations (according to standard rules) is not the same as the canopy temperature in a given field nearby (see 32.3).

The resistance of crops to cold is evaluated according to the lowest average minimum temperature at which they can survive. In tropical areas, plants are generally tender, and damage may result from exposure to low temperatures above the freezing point (chilling injury), sometimes as high as 12 °C. This is a problem in horticultural plants when unseasonal weather causes damage to chilling-sensitive species (most crops of tropical origin). As with frost, many physiological and environmental factors affect the magnitude of the injury; for instance, immature fruits are more sensitive than mature fruits. Contrary to frost, chilling injury symptoms may be reversed, at least partially, if exposure to low temperatures is brief.

Frost damage in plants occurs below 0 °C, at temperatures ranging from about −1 °C down to −196 °C. This offset is explained by two mechanisms: avoidance and/or tolerance of freezing. Plants avoid intercellular freezing either because the solutes outside the protoplast lower the freezing point of these aqueous solutions or because there is *supercooling* (the temperature of the liquid drops below its freezing point without becoming solid), due to the absence of freezing nuclei. Tolerance happens when, despite intercellular freezing and the resulting shrinking and dehydration of the protoplast, there is full recovery of the protoplast structure and function after thawing. Intracellular freezing, if it ever occurs under natural crop growing conditions, is always lethal for the cell. Freezing occurs in the intercellular spaces due to the lower concentration of solutes outside than inside the protoplasts. The decrease in water potential due to freezing and solute concentration induces loss of water by the protoplast, resulting in its shrinkage and the increase in its solute concentration.

In general, tissues are injured either by direct mechanical injury inflicted by the ice formed outside the cells or by the shrinkage and dehydration of the protoplast. In this case, denaturation of nuclear proteins may be the ultimate cause of injury.

Initially, *critical damage temperature* (T_{crit}) was defined as the maximum temperature that results in frost injury to a plant organ when exposed for more than 30 minutes. The term has been extended to specific levels of injury. For example, T_{10} for apple flowers refers to the T_{crit} that inflicts 10% loss of the total flowers, and T_{90} would correspond to 90% loss.

Cereals and fruit trees not of tropical origin show very low T_{crit} during winter rest. However, after bud burst, critical temperatures slowly approach their upper limit. During active growth, most plant organs have T_{crit} only a few degrees below 0 °C. Moreover, the difference T_{90}-T_{10} tends to decrease as plant phenological development progresses attaining a minimum that occurs, usually, around grain/fruit set (see Fig. 32.1). During the rest period and onset of growth, plants have a considerable capacity to keep low (or actively lower) T_{crit}, in response to the continued occurrence of low temperatures, in a process called *hardening* or *acclimation*. From flowering onward, hardening capacity is inexistent or reduced. On the other hand, after exposure to high temperatures, de-hardening may occur.

The nature of freeze damage varies with the plant/organ affected. Most injured vegetables present either a "burned" appearance or seem "soggy" or present changes in color or texture. Under rigorous winters, when the protective snow cover is insufficient, winter cereals may get leaf injury or even tillering node injury. After emergence, frost damage occurs usually at flowering or grain set. In temperate climates, deciduous fruit trees and grapevine are rarely affected by winter frosts. Only when temperatures are very low, in some extreme environments or when there is substantial de-hardening, there is frost damage to dormant buds or, even more rarely, to tree trunks. Flowers and small fruits of deciduous species are very tender and sensitive to frost. Sometimes, there is only a partial loss of seeds after pollination, which affects the growth of the fruits, particularly stone fruits, which have one or two seeds per fruit. When a small fruit experiences light freeze injury, a coarse russet tissue grows and covers a portion of the fruit, deteriorating fruit quality.

A detailed list of critical temperatures may be found in the review by Snyder and De Melo-Abreu (2005). Most vegetables and fruits have maximum freezing temperatures between −0.4 °C and − 2.7 °C, which represent the upper limit of critical

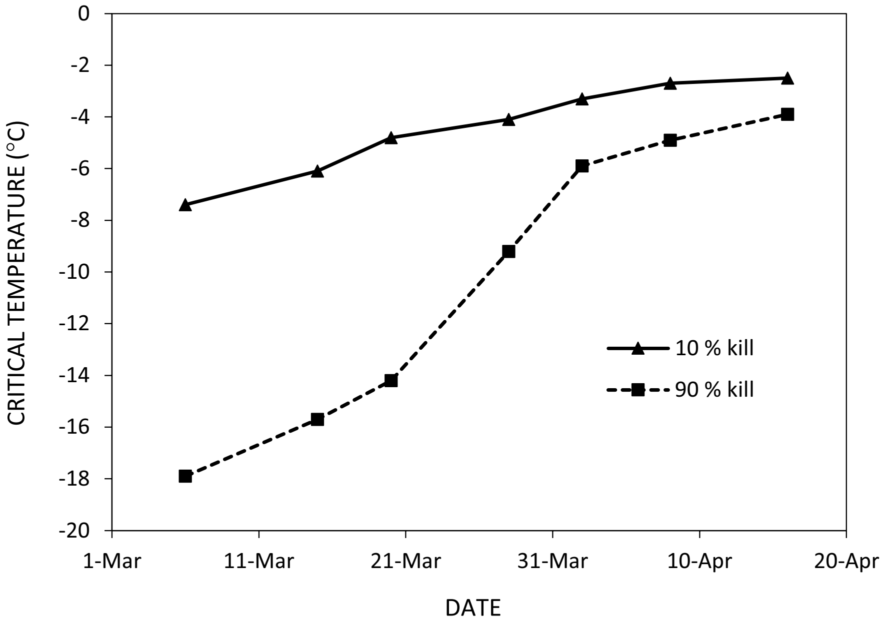

Fig. 32.1 Typical 10% and 90% bud kill temperatures for cherry trees corresponding to average dates observed at the Washington State U. Prosser Research and Extension Center. (Adapted from Proebsting and Mills (1978). J Amer Soc Hor Sci 103, 192–198)

temperature since the heat capacity of the structure and some (small) degree of supercooling may result in actual freezing temperatures that are somewhat lower. More juicy tissues tend to have higher critical temperatures.

A series of crops of tropical origin (tobacco, tomato, cucumber, peanut, rice, melon, and cotton) present T_{crit}, for the crop cycle, which decreases from 0 °C to −2 °C. Millet and corn have a T_{crit} around −2 °C to −3 °C at germination and grain filling, and one degree higher around flowering.

Table 32.1 shows critical temperatures at different stages of small grains, fodder crops, sugar beet, and olives. Table 32.2 shows the critical temperatures of fruit trees and grapevine.

32.3 Minimum Canopy Temperature

Air temperature is routinely measured in weather stations with shielded sensors at standard height (e.g., 1.5 m). However, the actual canopy temperature (T_c) will differ from that value (Chap. 5). The main factors determining the difference between air temperature at the weather station (T_{aw}) and T_c are net radiation, wind speed, air humidity, and aerodynamic roughness (Chap. 4). The calculation of this difference for the minimum temperature may be performed using a rather simple model as

Table 32.1 Critical temperatures in relation to stage of different crop species

Crop	Critical temperature		Stage
	Unhardened	Hardened	
Alfalfa	−6	−14	
Barley (winter)[a]		−17.3 to −12.9	Tillering
Barley (winter)[a]		−1 to −2	Flowering
Barley (winter)[a]		−2 to −4	Grain filling
Oats		−10.5 to −6.5	Tillering
Oats[a]		−8 to −9	Germination
Oats[a]		−1 to −2	Flowering
Oats[a]		−2 to −4	Grain filling
Olive	−12.4 to −4.1	−19.3 to −8.1	Rest
Potato[a]		−2 to −3	Germination
Potato[a]		−1 to −2	Flowering
Rye (winter)[a]		−19.5 to −25	Tillering
Ryegrass (Italian)		−8.4 to −7.4	3–4 leaf stage
Ryegrass (perennial)		−14 to −10.3	Mature
Soybean	−4.5		Seedlings
Soybean[a]	−1		Pod filling
Subterranean clover	−5.5	−7.8	Seedlings
Sugar beet[a]		−6 to −7	Germination
Sugar beet[a]		−2 to −3	Flowering
Sunflower[a]		−3.9	Bud formation
Sunflower[a]		−0.6 to 0	Flowering
Triticale		−17.5 to −9.2	Tillering
Wheat (spring)	−2	−5.5	Tillering
Wheat (winter)	−3	−18	Tillering
White clover	−7.7 to −4.9	−20.3 to −7.4	

Adapted from Snyder and De Melo-Abreu (2005)
[a]Under field conditions

Table 32.2 Critical temperature for deciduous fruit trees and grapevine

Crop	Stage	10% kill	90% kill
Apple	Silver tip	−11.9	−17.6
	Bloom	−2.4	−3.9
Peach	First swell	−7.4	−17.9
	Bloom	−2.8	−4.9
Pear	Scales separate	−8.6	−17.7
	Bloom	−2.9	−5.3
Grape	First swell	−10.6	−19.4
	Bud burst	−3.9	−8.9
	First leaf	−2.8	−6.1
	Fourth leaf	−2.2	−2.8

The 10% and 90% kill imply that 30 minutes at that temperature is expected to cause 10% and 90% kill of the plant part affected during that phenological stage. The values for bloom are the average from early to late bloom
Adapted from Proebsting and Mills (1978). J Amer Soc Hort Sci 103:192–198 and Snyder and De Melo-Abreu (2005)

during nighttime net radiation is only longwave, wind speed is low, and relative humidity is high. An example of model results is presented in Table 32.3 for crops with heights of 0.1 m (e.g., grass) and 1 m (e.g., cereal) when the air temperature is 0 °C at the weather station and wind speed is low. The difference T_{aw}-T_c is smaller for the taller crop when the sky is overcast and when humidity is high. In all cases, the canopy is colder than air at the weather station.

32.4 Frost Types

Radiation frosts occur on calm nights with a clear and dry atmosphere, which enhances longwave radiation losses (Chap. 3). The low wind speed determines a temperature inversion. Figure 32.2 shows an example of temperature profile changes during the night. When the wind blows, the temperature profile becomes more

Table 32.3 Canopy temperature in calm nights when air temperature at the weather station is 0 °C

	Short crop h = 0.1 m		Tall crop h = 1 m	
RH	Cloudy	Clear	Cloudy	Clear
70	−1.37	−4.05	−0.80	−2.53
100	−0.64	−2.41	−0.32	−1.25

Two conditions of cloudiness (completely overcast or clear) and two values of relative humidity (rather dry, 70% and saturated 100%) have been considered for crops of height 0.1 m and 1 m

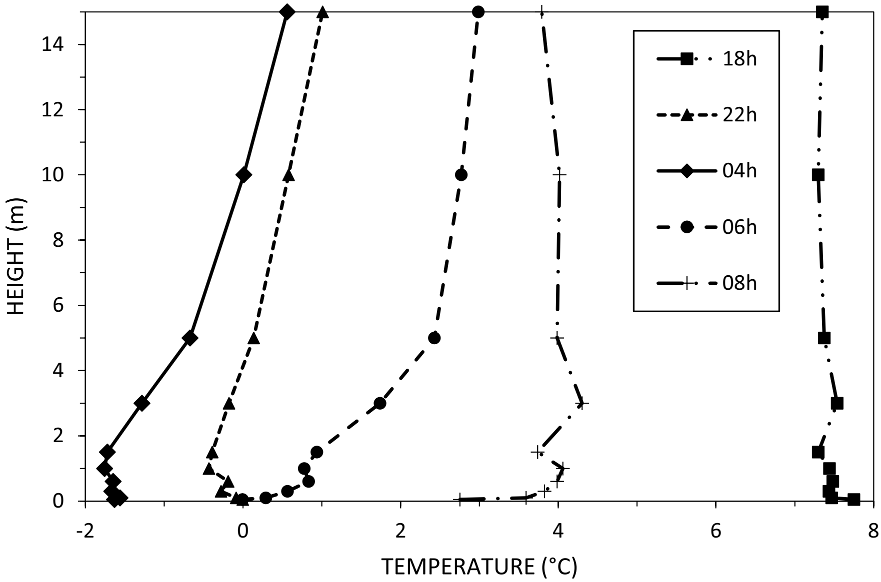

Fig. 32.2 Development of a temperature inversion over an apple orchard in Northern Portugal. (Adapted from Snyder & De Melo-Abreu, 2005)

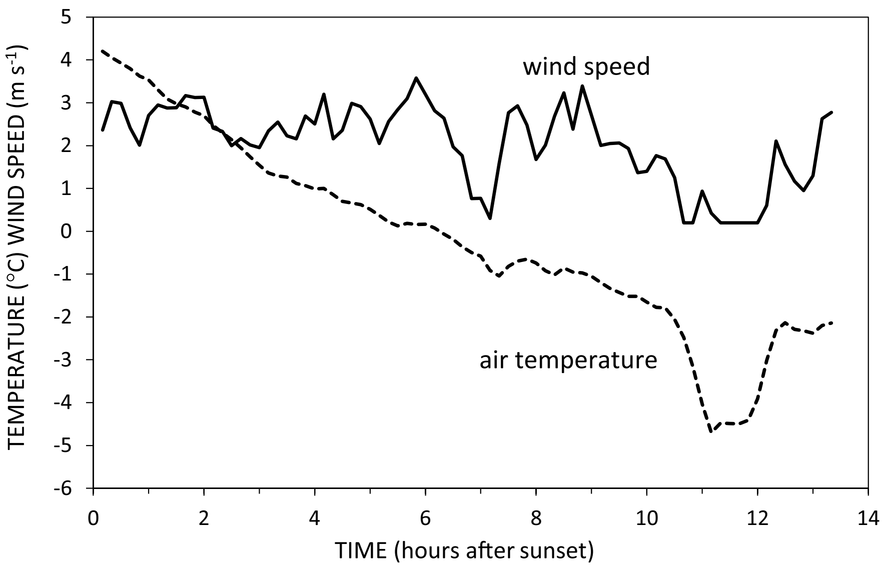

Fig. 32.3 Time course of temperature and wind speed over bare soil during the night. Espiel (Spain), February 3–4, 2012

uniform and the air temperature rises (Fig. 32.3). When the wind stops, the temperature drops again (Fig. 32.3).

Advection frosts occur as a result of large-scale transport of cold air masses. They occur on cloudy days or nights with moderate or strong wind coming in the wake of a cold front. Temperature inversions are not observed, at least in the first phase of such events. Later, after the wind weakens, an inversion may develop if surface cooling conditions occur.

Hoar frost occurs when ice crystals appear on the crop by deposition of water vapor or freezing of dew. Both processes release heat and therefore delay freezing of crop tissues. If the amount of ice is large, the term white frost is used. When water vapor concentration in the air is very low (dew point below the minimum temperature), there is no dew to freeze and no possibility of deposition and the tissues are affected without prior formation of ice, causing necrosis of the tissues ("black frost"). White frost indicates that damage may occur, but black frost is the visualization of the damage that has occurred.

32.5 Climatology of Frosts

The frost-free period is the time between the last frost (late winter or spring) and the date of the first autumn frost. This period is highly variable from year to year, so it is of limited value to assess the risk of frost damage, which should be based on the frequency distribution of frost dates. The dates of the first and the last frost are independent random variables. If they follow the normal distribution we can calculate the probability of frost during specific periods. For instance, the probability of spring frost after a given date is:

$$P(\text{frost after day } t) = P_y \cdot P\left[z > \frac{t - m_{LF}}{s_{LF}}\right] \tag{32.1}$$

where P_y is the fraction of years when frost occurs; m_{LF} and s_{LF} are the mean and the standard deviation of the date of the last frost, respectively; and z is the standard normal distribution which can be calculated using tables or the following approximate function:

$$P(z \le x) = 0.5\left(1 \pm \sqrt{1 - \exp\left(\frac{-2x^2}{\pi}\right)}\right) \tag{32.2}$$

where the positive root is used if $x > 0$ and the negative root when $x < 0$. Note that

$$P(z > x) = 1 - P(z \le x).$$

Similarly, the probability of autumn frost before a given date is:

$$P(\text{frost before } t) = P_y \cdot P\left[z < \frac{t - m_{FF}}{s_{FF}}\right] \tag{32.3}$$

where m_{FF} and s_{FF} are the mean and standard deviation for the date of the first frost. These statistics are only computed for years when frosts occur.

Example 32.1

The dates of the first and last frost (expressed as days from September 1) during 15 years are given in the table below for two locations (Gibraleon and Jerez del Marquesado) in Southern Spain. The minimum temperature observed each year is also shown.

	Gibraleon			Jerez del Marquesado		
	Date of frost		T_{min}	Date of frost		T_{min}
Year	First	Last	°C	First	Last	°C
2000			2	69	181	−2.9
2001			1.7	70	185	−5.7
2002	133	133	−0.6	94	217	−8.6
2003			0.7	88	223	−7.3
2004	119	168	−3.9	73	223	−15
2005	166	166	0	75	222	−10.2
2006	147	147	−0.6	98	219	−7
2007			1.2	77	212	−7.1
2008	131	132	−2.6	60	226	−6.1
2009	106	242	−1	45	247	−5.9

(continued)

Example 32.1 (continued)

	Gibraleon			Jerez del Marquesado		
	Date of frost		T_{min}	Date of frost		T_{min}
2010	156	156	−0.2	77	197	−5.4
2011	122	167	−3.1	104	229	−10.4
2012			0.8	88	243	−4.7
2013			1.1	76	208	−4.6
2014	123	129	0	96	207	−4.7
Average	133.7	160.1	−0.30	79.4	217.0	−7.04
Std. deviation	19.3	34.6	1.75	15.7	18.6	3.02

In Gibraleon, no frost occurred in 6 out of 15 years, so the mean and standard deviation are computed for the remaining 9 years and $P_y = 0.6$. The average dates for the first and last frost are day 134 (January 12) and 160 (February 10). The probability of frost after March 1 (day 182) is:

$$P(\text{frost after day}\,181) = P_y \cdot P\left[z > \frac{t - m_{LF}}{s_{LF}}\right] = 0.6 \cdot P\left[z > \frac{182 - 160}{34.5}\right]$$
$$= 0.6 \cdot P[z > 0.64] = 0.6(1 - P[z \le 0.64])$$
$$= 0.6 \cdot (1 - 0.74) = 0.156$$

The probability of frost before December 1 (day 92) is:

$$P(\text{frost before}\,92) = P_y \cdot P\left[z \le \frac{t - m_{FF}}{s_{FF}}\right] = 0.6 \cdot P\left[z \le \frac{92 - 133.7}{19.24}\right]$$
$$= 0.6 \cdot P[z \le -2.17] = 0.6 \cdot 0.012 = 0.007$$

In Jerez del Marquesado, the average dates for the first and last frost are day 79 (November 18) and 216 (April 4). The probability of frost after March 1 and before December 1 are 97 and 80%, respectively.

32.6 Risk of Extreme Cold Temperatures

Historically, farming has been pushed toward the environmental limits where risks of extreme events are higher. Many agricultural decisions have to be based on the probability of damaging events that can kill the plants or reduce yield substantially, thus making farming unsustainable. For frost risk analysis, we distinguish the probability $P(T < T_{crit})$ of temperature below a critical threshold in any year and the risk (R) which is the probability of the event occurring at least once over a design period (n_d). For example, the design period n_d is the expected duration of a tree orchard in years. Instead of risk, we may use certainty ($C = 1 - R$) which is the probability of the event not occurring over the design period. Assuming a Bernoulli distribution, the certainty (C) is related to the probability of having a temperature below T_{crit} in any given year:

$$C = \left[1 - P\left(T < T_{\text{crit}}\right)\right]^{n_d} \tag{32.4}$$

For example, if the probability of temperature below −10 °C in any given year is 0.003 (i.e., it happens 3 times in 1000 years), then the certainty for a 20-year project duration is 0.94, i.e., we are 94% certain that temperatures will never fall below −10 °C in 20 consecutive years.

The probability of an extreme event occurring in any given year should be calculated as the ratio of the observed extreme events over the years of record. As they are rare events, we would need a very long weather record (e.g., more than 1000 years) which is never available. Instead, for limited data sets, we calculate the parameters of the underlying statistical distribution. Haan recommended the *type I extreme value* (*Gumbel*) probability distribution:

$$P\left(T < T_{\text{crit}}\right) = 1 - \exp\left[-\exp\left(\frac{T_{\text{crit}} - \beta}{\alpha}\right)\right] \tag{32.5}$$

We need to know μ and σ, the average and standard deviation of the minimum temperatures recorded each year, respectively. The parameter β is the mode (most frequent value) of the distribution which is calculated as $\beta = \mu + 0.45\,\sigma$, while the other parameter $\alpha = \sigma/1.283$.

From the equations above, we may deduce how to calculate the certainty:

$$C = \left\{\exp\left[-\exp\left(\frac{T_{\text{crit}} - \beta}{\alpha}\right)\right]\right\}^{n_d} \tag{32.6}$$

Example 32.2

The annual minimum temperature in Jerez del Marquesado (Spain) has an average of −7.04 °C with standard deviation 3.02 °C (Example 32.1). Therefore, the parameters of the Gumbel distribution are $\alpha = \sigma/1.283 = 2.355$ °C and $\beta = \mu + 0.45\,\sigma = -5.68$ °C. If we plan to establish an orchard during 20 years and the critical temperature is −12 °C, the certainty will be:

$$C = \left\{\exp\left[-\exp\left(\frac{-12 - (-5.68)}{2.355}\right)\right]\right\}^{20} = 0.255$$

This value is very low as it indicates that the risk of failure of our orchard is 75%. In the other location (Gibraleon), the certainty is 0.998 which indicates a negligible risk for the orchard.

32.7 Frost Protection

Frost protection methods include those implemented before the frost night to avoid or minimize frost occurrence or damage (i.e., *passive*, *indirect*, or *preventive*), and methods implemented during the frost night (i.e., *active*, *direct*, *protective*). Often, the effect of passive methods, which are relatively cheap, adds up to the effect of the active methods. Therefore, passive methods should always be considered and, when suitable, implemented in conjunction with one or more active methods. A complete description of most existing methods and related computational tools is available in Snyder and De Melo-Abreu (2005). In Chap. 7, we saw that nocturnal cooling is proportional to longwave losses and depends on the thermal admittance (Eq. 7.2) which is the basis of some frost protection methods.

32.7.1 Passive Protection Methods

32.7.1.1 Site Selection

Section 7.4 described the physics of the cooling process in a specific location ignoring the horizontal movement of air. As the air cools, its density increases, and will tend to flow to areas of lower density, typically downward to valleys and depressions. The degree of accumulation of cold air or ventilation depends on the topography, the wind speed, and the temperature gradients.

Frost-sensitive crops should not be placed in locations where cold air accumulates due to orography (depressions) or artificial obstacles (fences, windbreaks).

The presence of large bodies of water (lakes, sea) in the direction where cold winds come from can reduce the risk of frost due to heat exchange between water and air.

If possible, the most critical areas should be detected using maps of minimum temperatures which could be obtained using remote thermal infrared imagery. As a rule of thumb, radiation frosts are more likely in the places where fog is more frequent.

32.7.1.2 Selection of Species, Cultivars, and Cultural Techniques

Crop species differ in their sensitivity to cold and frost, and genetic variability may exist within each species. Taking into account the climatology of frosts in the location and the critical temperatures for the crop alternatives to that location, we will choose the species and the cultivar to reduce the risk of frost damage.

Some cultural techniques may be beneficial when they explore the knowledge of the biometeorology of frost. In deciduous fruit trees, pruning is usually done in winter but, in locations prone to severe frost, late pruning is advisable from the viewpoint of frost damage prevention, since plants are more sensitive just after pruning and the probability of severe frosts decreases as the spring approaches. In the same regard, pruning promotes bud burst; hence, late pruning exposes new growth to less frequent and severe frosts. Training and pruning techniques raise the height of tender organs to avoid lower colder air layers during temperature inversions. Delayed budbreak has been achieved in pome fruits by periodic overhead irrigation in late winter that cools the buds and delays their development until past the frost period. Nitrogen fertilization and high water status tend to elevate the critical temperature. Hence, when there is a strong probability of frost in the upcoming days, it is not wise to N-fertilize or irrigate (but see next section).

Some bacteria, called Ice Nucleating Active (*INA*), may act as freezing nuclei and initiate the freezing process. These bacteria are often on the cover crops and weeds in the orchard and their removal may help prevent frost damage.

32.7.1.3 Soil Management

Minimum surface temperature may be increased by increasing the thermal admittance (irrigating, compacting the soil) or increasing the radiant energy reaching the soil during the daytime (avoid opaque mulches or cover crops). Daytime soil heating also depends on the partitioning between G and H (Chap. 6) so a smooth soil surface (high aerodynamic resistance) will improve soil heating compared to a rough soil surface. Therefore, tillage operations (reduce thermal admittance, increase surface roughness) are not desirable if frost is expected.

Irrigation increases soil thermal admittance, which reduces nocturnal cooling but also daytime heating as more energy is spent in evaporation from the soil surface (Chap. 6). The best situation would be wet soil covered with transparent plastic. If that is not possible, the best choice is irrigating some days in advance to let the upper soil layer dry and reduce soil evaporation while the rest of the profile is wet (high thermal admittance).

Soil heat flux is increased after removing cover crops or weeds in orchards. Their removal should be done with herbicides but not tillage which reduces bulk density and, thus, thermal admittance. Any tillage should be performed well before the sensitive frost period for the soil to settle and the residues to decompose.

32.7.2 Active Protection Methods

32.7.2.1 Increasing Radiation Interception

Radiation frosts occur when longwave radiation loss is high (absence of clouds, low air humidity). Thermal radiation may be intercepted partly by spraying water. The droplet diameter should be similar to the wavelength of thermal radiation (8–12 microns).

Artificial clouds of smoke produced by burning different materials (tires, wood, or fuel) have been used in the past but they are rarely used nowadays. The diameter of the smoke particles is too small to affect radiation absorption and any positive effect is due to the heat liberated by the combustion. Additionally, the energy cost is high, and the clouds easily drift away from the protected field, may be hazardous to traffic, and are a source of pollution.

Some materials, which are almost opaque to longwave radiation (e.g., thermal blankets), may be used to cover high-value crops.

32.7.2.2 Air Mixing

Inverted temperature profiles typical of nights with radiation frost may be homogenized by mixing air of different heights, thereby increasing the temperature at the canopy level. The effectiveness of air mixing will be proportional to the temperature gradient.

A good choice for air mixing is a conventional wind machine, which consists of a steel tower with a large rotating fan near the top. Fans, with blades of diameter between 3 and 6 m, are located about 10–11 m above ground and are oriented to blow at a slight downward angle (e.g., 7°) to improve mixing. Fans rotate around the tower at a frequency of one rotation per 4 or 5 min and propeller speeds are usually about 600 rpm. There are models of fans with two to four blades. The engine power should be about 20 kW per hectare. Hence, for a typical 4 or 5 ha of protection, the engine power should be about 80–100 kW.

The protection given by conventional wind machines is, under strong inversions, between 1.5 °C and 2.5 °C. Most of the beneficial effects result from air temperature increase at canopy level and the remaining comes from the reduction of the boundary layer resistance, which brings the temperature of the exposed organs of the plant closer to air temperature.

Mobile models of wind machines that, typically, have engines with less power have reduced protection areas. Helicopters have been widely used and are effective, but their availability and economics must be considered under local conditions.

32.7.2.3 Heating the Air or the Canopy

The loss of energy from a crop during frost may be compensated by burning fuel (solid, liquid, or gas) in heaters, which transfer energy by thermal radiation and convection. The energy loss from the crop is usually in the range of 20–40 W m^{-2}, while input from heaters is typically between 140 and 280 W m^{-2}, which indicates a very low efficiency. The best conditions for this method are no wind and a strong inversion.

The temperature of the air leaving the heater is very high so it will rise rapidly, mixing with the colder surrounding air, until it reaches the height where the air has the same temperature. Eventually, the mixed air will cool, become denser, and descend, which creates a circulation pattern within the inversion layer. When there is a strong inversion (i.e., a low ceiling), the heated air rises to a lower height and the volume influenced by the heaters is smaller so efficiency is higher. Efficiency is low when heaters are too big or hot as the warmed air can break through the top of the inversion layer.

32.7.2.4 Irrigation

Irrigation is very useful for protecting crops against frost and it relies mostly on the heat released by water cooling (4.18 10^{-3} MJ/K/kg) and freezing (0.334 MJ/kg), but some heat may be spent in evaporation. Water extracted from wells has a temperature close to the mean annual air temperature at the site so the contribution of water cooling is small compared to that of freezing. This is the basis of using sprinkler irrigation for frost protection, which usually requires lower application rates (usually 2–4 mm h^{-1}) than typical sprinkler systems to meet crop *ET*.

Water has to be applied continuously to the whole area to be protected, so there is always a thin layer of water over the ice that is formed, thus keeping the temperature at the freezing point (0 °C). Surface irrigation may also be used according to the same principles (heat of fusion and specific heat of water), but the heat is liberated to the air near the soil surface, and it may be insufficient to prevent frost damage.

Classical full coverage systems should have a rotation cycle shorter than 1 min; around 30 s tends to be better. The application rate depends on canopy growth and arrangement, minimum temperature attained in the worst-case scenario, wind speed, and air humidity. We developed a simple equation to calculate the sprinkler application rate (*SA*, mm h^{-1}) as a function of wind speed (u, m s^{-1}) and minimum air temperature (T_a,°C) (Snyder & De Melo-Abreu, 2005):

$$SA = \left(T_a - 1.447\,u^{-0.442}\right)\left(0.0645\,u^2 - 0.5788\,u - 0.4473\right) \tag{32.7}$$

This empirical model is valid for wind speeds in the 0.3–3 m s^{-1} interval. If the application rate is adequate, sprinkler irrigation may provide up to 7 °C of frost protection.

Overplant sprinklers, which only irrigate the area of the soil covered by the plants, need a lower application rate that is obtained by multiplying the value obtained by Eq. (32.7) by the fraction of ground cover.

The major restrictions of sprinkler irrigation for frost protection are the amount of water required and the adverse consequences of waterlogging (Chap. 15).

32.7.2.5 Avoiding Failure of Active Methods

First, the need and feasibility of frost protection should be evaluated and, if so, the most economical method should be selected. Two programs (*DEST* and *FrostEcon*) may support your decision (download at http://home.isa.utl.pt/~jpabreu/Downloads/).

Sometimes, project and/or installation problems occur when the requirements of the species/cultivar are ignored. For example, in the case of sprinkler irrigation, some plants or their parts break due to ice overload or root diseases may develop due to waterlogging.

However, most frost protection failures originate from inappropriate management. For example:

- Weather forecast failure at synoptic or local level.
- Inadequate monitoring system.
- Inadequate start and/or stop times.
- Low water quality (e.g., sprinkler irrigation).
- Installations poorly maintained or lacking backup systems.

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Control of Weeds and Other Biotic Factors

33

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Abstract

Weeds are plants whose presence is undesirable at a time and/or place because they compete with crops for resources, deteriorate the quality of the harvested product, and can hinder harvesting. The most important weed species include C4 perennials with vegetative propagation. Usually, weeds can produce many seeds that often present dormancy, which generates a soil seed bank that germinates over many years. This prevents weed eradication and forces us to use control techniques to keep tolerable weed populations. Weeds adapt in a few years to the cropping system, in special to control methods. Control techniques include herbicides and cultural practices such as tillage, mulching, mowing, and crop rotation. Crop management has an important effect on the incidence of pests. The irrigation method and frequency determine the germination of weeds and influence the infection by aerial or soil pathogens. Biological control is effective with invasive weeds and some insects. The ability of weeds to evolve in response to the selection pressure exerted by control measures forces us to establish long-term strategies (weed management) which should be based on detailed knowledge of the ecology of the weed species. Then different types of control should be alternated to improve the control efficiency.

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33.1 Introduction

Weed control has always been an important part of agricultural practices and is often considered part of agronomy. Traditionally, only manual weeding was specifically aimed to control weeds, but many practices, such as tillage, burning, and rotations, contributed in some way to this control. In 1944, when *2,4-D* was introduced as an herbicide, *Weed Science* appeared as a discipline within the techniques of Plant Protection, although much more tied to crop production techniques.

It is estimated that not more than 250 species have become important weeds for agricultural production.

In this chapter, we will review the main ecological characteristics of weeds and the methods of control except pesticides, presented in Chap. 34. For some specific control techniques, we will also mention their impact on other pests.

33.2 Characteristics of Weeds

A weed is a plant growing where it is not wanted, i.e., in the wrong time or location. This is a relative definition as seeds left from a crop after harvest may lead to weeds for the next crop. However, the most troublesome weed species usually show special characteristics that allow their dispersal and persistence in agricultural systems and increase their ability to compete with crop plants.

33.2.1 Dispersal of Weeds

Weeds use the general dispersal mechanisms of plants (wind, animals, water, gravity) but also present among their invasion strategies, *anthropochory*, the dispersal by human action. The commerce of agricultural products, seeds, and other materials has contributed to the dispersal and homogenization of weeds worldwide. The most damaging species are found in many environments and systems around the world. Table 33.1 shows the most important weed species on a global scale. Most of these species are C4 perennials.

The invasion of a new site is usually based on a small but continuous flow of propagules transported from short distances. However, the most effective dispersal strategy of a weed population is based on adaptations that ensure the return of weed seeds with the crop seed at the time of planting.

33.2.2 Persistence of Weeds

The persistence of weed populations is often guaranteed by many seeds that often exhibit dormancy mechanisms. These allow germination to spread over a long period (years) and ensure the population's survival.

Table 33.1 Top 10 worst weed species on a global scale

	Species	Common name	# crops	#countries	Cycle	Propagules
1	*Cyperus rotundus*	Purple nutsedge	52	92	Perennial	Rhizomes with tubers
2	*Cynodon dactylon*	Bermuda grass	40	80	Perennial	Rhizomes with stolons
3	*Echinochloa crus-galli*	Barnyard grass	36	80	Annual	Seed
4	*Echinochloa colona*	Junglerice	32	60	Annual	Seed
5	*Eleusine indica*	Indian goosegrass	46	60	Annual	Seed
6	*Sorghum halepense*	Johnson grass	30	53	Perennial	Rhizomes and seeds
7	*Imperata cylindrica*	Cogon grass	35	73	Perennial	Rhizomes
8	*Eichhornia crassipes* (C3)	Water hyacinth	1		Perennial	Stolons
9	*Portulaca oleracea*	Purslane	45	81	Annual	Seeds, nodes
10	*Chenopodium album* (C3)	Lambsquarters	40	47	Annual	Seed

The number of crops and countries where it is an important weed are also presented. All species are C4 except where C3 is indicated

The community of buried propagules (soil seed bank) consists of rhizomes, stolons, bulbs, and seeds of different species. The seeds entering the soil may be dormant or enter into secondary dormancy. The most important factors for germination or dormancy release are water, temperature, light, NO_3, O_2, and CO_2. The permanence of some form of dormancy in buried seeds is an adaptive advantage as it allows adjusting seed germination to ecological conditions favorable to the survival of seedlings. The loss of seed dormancy in the soil occurs especially if the water content and aeration are adequate. Germination is very sensitive to the quality of light (phytochrome system), especially that resulting from radiation interception by vegetation. Thus, by detecting the light quality, the seed not only receives information about the depth at which it is buried but can also detect the presence of a canopy above, which may limit the growth of the seedling. Apart from that, some species respond to short light pulses as those that the seed may experience during secondary tillage.

Other factors contributing to break seed dormancy are a low concentration of CO_2, a high concentration of nitrates, and temperature oscillations. The latter allows the seed to “detect” its depth in the soil because the temperature range decreases with depth (Chap. 6). A buried seed under a wide temperature variation is probably near the surface and likely to stay on a clear area without vegetation since the presence of the latter buffers the soil temperature variation.

On the other hand, weeds often show a great capacity for acclimation and adaptation, associated with annual cycles, reduced chromosome number, and self-pollination or vegetative propagation. The most important selective force acting on weeds in agricultural systems is human action including type, depth and timing of tillage, sowing date, timing and type of herbicide application, etc. There are selection pressures that select weed genotypes suitable to endure in the system due to adjusted mechanisms of dormancy and germination, and, more importantly, there are similarities to the crop in height, seed size, and maturity period to ensure the joint harvest with the crop. It is clear then that the main determinant of weed flora in a given area will be the main crops grown in addition to management practices.

In some cases, besides selective forces, the system provides genetic information that can contribute to the evolution of the weed (crossing between weeds and crop plants).

Unlike insects and fungal pathogens, weed populations do not suffer sudden changes in population density due to the damping exerted by the seed bank. Therefore, weeds are usually a chronic but not an epidemic problem, but the variability is large. Some species with high reproductive potential but low seed dormancy and low persistence in the soil, such as *Alopecurus myosuroides* (green foxtail), are typically aggressive opportunistic invaders but are also easily removable. By contrast, other species with low reproductive potential but strong dormancy in seeds, such as *Veronica hederifolia* (speedwell), tend to persist with steady populations. These differences in the population dynamics of different weed species have implications for their control that should try to eradicate populations of the first type with intense short-term measures while keeping reduced populations for the second type.

33.3 Classification of Weeds

According to their life cycle, weeds are classified as:

– Annual weeds: They complete their life cycle in 1 year. We may distinguish two groups:

   (i) Winter annuals that germinate in the fall and set seed in spring or summer. They are usually found in winter cereals. Examples: *Avena sterilis* (wild oat) and *Sinapis arvensis* (wild mustard).
   (ii) ii) Summer annuals that germinate in spring and set seed in autumn. Examples: *Amaranthus retroflexus* (redroot pigweed) and *Portulaca oleracea* (common purslane).

– Biannual weeds: They require 2 years to complete the cycle, devoting the first year to vegetative development and storage of carbohydrates (rosette stage in many species) and flowering in the second spring.

Example: Thistles.

– Perennial weeds have cycles of several years: In some cases, they show vegetative reproduction from organs (roots, stems, rhizomes, stolons, tubers, bulbs) that remain dormant until suitable conditions for sprouting occur.

Examples: *Cyperus rotundus* (purple nutsedge), *Cynodon dactylon* (Bermuda grass), and *Sorghum halepense* (Johnson grass).

Weeds can also be classified according to the habitat where they are usually found (crops, pastures, orchards or forests, surface waters, roadsides, and waste places).

33.4 Crop-Weed Interactions

Weeds always compete for resources (water, light, nutrients) and often show certain competitive advantages such as high density, earlier emergence, or high early vigor. Some morphological (taller plants, deeper roots) or physiological (C4 photosynthesis, allelopathy) mechanisms may also enhance weed growth when in competition with crop plants. Apart from yield losses due to competition, weeds have other negative effects such as hindering harvest or degrading crop quality by altering the color, smell, and taste or adding toxins.

In all cases, the level of competition and thus of yield loss will be directly proportional to the earliness of weed emergence relative to that of the crop, as discussed in Chap. 12. Therefore, it is difficult to establish general relationships between crop yield and weed density (D_{pw}). If we use the reciprocal yield law (Chap. 12), we may calculate yield (kg/ha) as:

$$Y = \frac{10\,HI\,D_p}{b_1 + b_2\,D_p + b_{2w}\,D_{pw}} \tag{33.1}$$

where b_1 and b_2 are empirical coefficients that determine the response of the crop to plant density. The factor 10 in Eq. 33.1 is used to convert g/m^2 to kg/ha. Now, we have added a term ($b_{2w}\,D_{pw}$) that incorporates the competition of the weed. If the crop and the weed are very similar in form and cycle, then the coefficients b_2 and b_{2w} should be the same.

Example 33.1

Let's calculate the yield of a cereal crop as a function of weed density. We'll assume that:

$b_1 = 0.01$ plant/g, $b_2 = b_{2w} = 0.001$ m^2/g, HI=0.4, and $D_p = 200$ plants/m^2.

According to Eq. 33.1, yield may be calculated as:

$$Y = \frac{10\,HI\,D_p}{b_1 + b_2\,D_p + b_{2w}\,D_{pw}} = \frac{800}{0.01 + 0.20 + 0.001\,D_{pw}}$$

Yields for weed densities of 0, 100, and 200 plants m^{-2} would be 3810, 2581, and 1951 kg/ha.

Many studies indicate that the 30–40 days after emergence are critical for determining yield losses due to weeds. If the crop is kept clean during this period, any later invasion will not cause yield reduction but may lead to other problems (e.g., harvest problems). On the other hand, if weeds are completely removed at the end of this period, yield reduction will be small.

33.5 Economic Threshold

An *economic threshold* or *action threshold* for a given pest is the pest density at which control should be applied. Otherwise, the pest will reach a higher density level (called *Economic Injury Level*, *EIL*) at which the cost of control equals the economic loss due to the yield reduction caused by the pest, quality loss, or harvesting difficulties. Note that if the action level is exceeded, there will be an economic loss. The action threshold may be equal to the *EIL* for weeds, but it may be much lower for insects if the population increases rapidly.

Using Eq. 33.1, we may calculate the yield loss (*YL*, kg/ha) for weeds as:

$$YL = \frac{10\, HI\, D_p}{b_1 + b_2\, D_p} - \frac{10\, HI\, D_p}{b_1 + b_2\, D_p + b_{2w}\, D_{pw}} \tag{33.2}$$

One important difference between weeds and other pests is that weeds have a negative effect for any density as they always use resources (water, nutrients). Other pests (e.g., insects) may not reduce yield when populations are low.

If the selling price of the harvest is P_Y (euro/kg) and the cost of weed control is C_H (euro/ha), then the economic threshold (taken as equal to *EIL*) corresponds to a yield loss of C_H/P_Y. Using Eq. 33.2, we may deduce the corresponding weed density:

$$D_{pwu} = \frac{10\, HI\, D_p\, C_H}{b_{2w} Y_x \left(P_Y\, Y_x - C_H \right)} \tag{33.3}$$

where Y_x is yield in the absence of weeds. We see that the economic threshold is directly proportional to planting density and the cost of weed control, while it is inversely proportional to weed competitive ability (b_{2w}), crop yield, and selling price.

Example 33.2

Using the data of Example 33.1, we may calculate the economic threshold if the grain price is 0.25 euro/kg and the cost of weed control is 150 euro/ha:

$$D_{pwu} = \frac{10 \cdot 0.4 \cdot 200 \cdot 150}{0.001 \cdot 3810 \left(0.25 \cdot 3810 - 150 \right)} = 39 \text{ plants m}^{-2}$$

In this case, control should not be performed unless weed density exceed 39 plants m^{-2}.

The economic threshold thus defined is valid in the short term as it affects only the current crop. Lower values of the economic threshold will result if one considers a longer perspective. For example, in organic farms in the Netherlands, the main problems of weeds in certain crops (e.g., onion) are due to seeds from weeds not controlled in the previous wheat crop. This implies the need for more intensive weed control during the wheat season at a higher cost than this crop would need.

Some species (e.g., *Chenopodium album*) are easy to control with hormonal herbicides but difficult to eradicate due to their long seed persistence. In these cases, we may use the short-term economic threshold. In other species difficult to control with herbicides and low seed persistence (e.g., *Avena sterilis*), it is better to apply intense control measures using a long-term economic threshold.

The effect of a given weed density on yield depends on many factors, in special the time of weed emergence relative to the crop. Furthermore, weeds can gradually emerge, which complicates the prediction of its competitive ability, given the spatial variability in weed distribution within a field. Thus, the empirical equations between yield and weed density have a limited validity, and economic thresholds deduced from them.

The application of economic thresholds is limited in practice as it requires knowing the effect of pest densities on crop yield. However, it serves to illustrate some important principles of pest control. First, low population levels of the pest do not reduce farmer's profits, i.e., complete suppression of the pest is not usually the best economic alternative unless we can ensure long-term eradication. Second, the tolerable population density depends on biological (competitive ability of weeds, damage capacity of insects, the response of plants to damage, etc.), economic (market value of crop, cost of control), and agronomic (e.g., planting density) factors.

33.6 Pest Control

Pest control aims at reducing populations of pests to acceptable levels. The complete elimination of weed plants and seeds is expensive and almost impossible due to the soil seed bank. Fumigants will control nematodes, soilborne fungi and bacteria, soil insects, and weeds (seeds and germinating seedlings) but are restricted by their high cost and toxicity. A less aggressive option to fumigation is soil solarization whereby a transparent plastic sheet is placed on the soil surface following irrigation in summer. The high temperatures (> 60 °C) and humidity will eliminate most soilborne pests down to about 30 cm.

As eradication of weeds is not possible, we will prevent the entry of new propagules into the field and reduce their population. Prevention is based on using seeds free of pest propagules and viruses and clean machinery while keeping the field margins free of dangerous weeds that may host other pests.

33.6.1 Mechanical Control

Tillage in general stimulates the germination of weed seeds in the soil. The main effects of tillage on emerged weed plants are due to the burial of the aerial part (reduced assimilation), mechanical wounding of shoots and roots, and uprooting of the weed that dies by desiccation. Tillage is effective against annual weeds but may increase infestation of creeping perennials by breakage and spreading of propagules (rhizomes, stolons) when the soil is wet. The effect of tillage depends on the type and depth, with deep moldboard being very effective in killing plants by burial but promoting the transfer of seeds from deep to surface layers. Vertical tillage will act mostly by mechanical wounding but has little effect on seed distribution.

In earlier times, the only measures available for weed control in growing crops were pulling, harrowing, and hoeing. Pulling is very effective against annuals and tap-rooted plants but may not be so if the plant can resprout from root segments. Therefore, its effectiveness depends on the ability to remove as much root system as possible, which is quite difficult in perennials.

Mowing reduces the growth of weeds and is very effective in preventing seed production. However, mowing alone selects creeping genotypes or species that escape control.

Burning stubble or crop residues has been used since ancient times to control weeds, insects, and pathogens but also for seedbed preparation. However, burning is restricted because of several disadvantages (wildfire risk, air pollution, loss of organic matter and nitrogen). High temperatures kill seedlings and may kill or reduce the viability of weed seeds, insects, and fungi close to the soil surface. This may also be achieved by solarization as discussed above. Another possibility is flaming weeds, which is more effective on weed seedlings.

Flooding prevents the germination of seeds and kills submerged plants. It is the basic weed control measure in continuous flooded rice crops.

Opaque mulching with black or gray plastic or other materials (gravel, sand, sawmill residues) will prevent seed germination and kill weeds by carbon starvation.

33.6.2 Other Control Techniques

Crop management affects weed populations in many complex ways. The crop rotation may reduce weed problems, for example, alternating winter and spring crops. Rotations are also very effective in reducing the incidence of soilborne diseases. The management of residues plays a major role in pest control as they serve as a reservoir for pest propagules.

Secondary tillage for seedbed preparation induces the germination of weeds that are then controlled using herbicide or shallow tillage before actual sowing. This system is called stale or false seedbed.

Irrigation management also affects pests. The germination of weeds will not occur in dry soil; thus, partial wetting or underground irrigation will reduce weed abundance. Some soilborne fungi are promoted by continuous wetting of the soil, so reducing the irrigation frequency may be an effective control practice. Wetting of plant shoots promotes the infection by aerial fungal diseases (e.g., rusts) but may help control other pests (e.g., mites).

The selection of adequate genotypes may help in improving the competitive ability of the crop. In the case of aerial diseases, the use of resistant genotypes is one of the major alternatives for control (see 33.7). Cultivars that are Genetically Modified Organisms (GMO) have been bred that include resistance to certain herbicides (e.g., soybean resistant to glyphosate), thus allowing the application of the specific herbicide to the field areas where weeds appear after the crop has been established. In other cases, bacteria (*Bacillus thuringiensis*) genes that produce a toxin have been inserted in cultivars of some major crops such as corn and cotton, and these cultivars produce the Bt toxin that kills *Lepidoptera* larvae feeding on the crop. In all cases, weed and insect control costs have been greatly reduced in the GMO cultivars.

Planting density also affects the incidence of pests. On the one hand, a high planting density may compensate for plant losses due to pests. On the other hand, crops with high *LAI* suffer a more humid microenvironment and stay wet for longer after wetting which favors aerial pathogens.

Biological control involves the introduction of organisms that are consumers, pests, or diseases of other pests. The agent should not affect the crop and should be able to adapt successfully in the area where it is introduced. The most famous example of biological control of weeds was that of *Opuntia stricta* in Australia which was controlled successfully using a moth (*Cactoblastis cactorum*). Insect control may be performed by *Coccinellidae* (ladybugs, ladybirds) which feed on aphids and scale insects.

Chemical control is one of the main alternatives for pest control and will be considered in detail in the next chapter.

33.7 Using Pest-Resistant Cultivars

One of the best alternatives for reducing the impact of insects and diseases is using resistant cultivars. We distinguish two types of resistance:

(a) Qualitative or vertical resistance is controlled by one or a few genes so we find distinct resistant and susceptible cultivars. The continuous use of the resistant cultivar may lead to a new race for which resistance is lost, forcing the development of a new resistant cultivar.
(b) Quantitative or horizontal resistance is controlled by many genes so there is a continuous variation in the level of resistance of different genotypes. This type of resistance holds for many races of the pathogen so it will last much longer than vertical resistance but is difficult to transfer between genotypes.

We can also distinguish between resistance if the pest does not infect the host plant, or the infection is very limited, and tolerance when infection occurs with low impact on yield.

Several alternatives may be used to reduce the selection pressure on the pathogen so the resistance holds longer:

(a) Alternating resistant and susceptible cultivars in the crop rotation.
(b) Sowing a mix of resistant and susceptible cultivars: Resistant plants act as physical barriers to the spread of the pathogen among susceptible plants. The same happens with multiple crops.
(c) Using a multiline which is an ensemble of cultivars with resistance to different pathogen races.
(d) Incorporating the resistance to different races in a single cultivar.

Options a and b are not attractive to farmers, while options c and d require huge efforts by breeding companies, so in the end, plant breeders keep track of new pathogenic races and breed for new cultivars in a never-ending fight against the adaptation of pathogens. This is called maintenance breeding and is essential for the sustainability of agriculture even though it is not a priority of agricultural research in many countries.

33.8 Weed Management

Weed management is a set of strategies aimed at controlling the weed populations in the long term (years) in a cropping system. It involves a more comprehensive and longer-term approach than weed control. This technology is based on better knowledge of the ecology of weed populations, their critical periods for the formation of propagules, and their interactions with cultural practices. With that knowledge, it is possible to design long-term strategies to keep weed populations at acceptable levels from the point of view of crop production. For example, models of germination of weeds may be used to adjust the dates of tillage, herbicide application, or crop planting before the emergence of the weeds.

Another important aspect of weed management is to develop long-term strategies necessary if we look at weeds as a phenomenon at the farm or even the agricultural system level. In this case, we should be concerned about the production and dispersal of propagules. For instance, the better the separation between crop and weed seeds in the combine, the better the weed dispersal in the field.

Strategies for long-term management must also consider the evolution of weeds which may be very fast (several years) in response to the strong selective pressure exerted by agricultural practices (including herbicides). One interesting choice is alternating control measures. An example would be the application of herbicides for several years leading to a reduction of genetic variability, which often leads to strict temperature requirements for germination. After several years, we may exploit the characteristics of the weed population using tillage at the right time or by changes in cultural practices (e.g., earlier sowing). In this second phase, the weed population is selected to broader forms with greater sensitivity to herbicides.

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34 Application of Herbicides and Other Biotic Control Agents

Francisco J. Villalobos and Elias Fereres

Abstract

The main characteristics of pesticides from an agronomic viewpoint are selectivity, mobility within the plant, and toxicity on nontarget plants, insects, and other fauna. Pesticide application should maximize the protective effect while preventing drift, which is increased with high wind speed, unstable conditions, and high evaporative demand. There is a general trend in pest control toward less persistent molecules with lower environmental impacts. Pesticide doses may be adjusted according to the actual canopy volume (*TRV* method) for trees and Leaf Area Index in annual crops.

34.1 Introduction

In this chapter, we discuss the chemicals applied to crops and the environmental factors to consider for their application. The main pesticides used in agriculture are herbicides, insecticides, and fungicides for controlling weeds, insects, and pathogen fungi, respectively. The term pesticide also includes other products that are not exactly control agents like defoliants, desiccants, and plant growth regulators (Table 34.1).

Pesticide use is almost as old as agriculture with elemental sulfur being the first known pesticide, employed by the Sumerians to control insects and mites about 4500 years ago.

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Table 34.1 Classification of pesticides according to the target organism

Pesticide type	Target
Algicide	Algae
Avicide	Birds
Bactericide	Bacteria
Fungicide	Fungi
Herbicide	Weeds
Insecticide	Insects
Miticide	Mites
Molluscicide	Snails, slugs
Nematicide	Nematodes
Piscicide	Fish
Rodenticide	Rodents
Plant growth regulators	
Desiccants	
Defoliants	

34.2 Pesticides

In general, a small amount of pesticide active ingredient (a.i.) should be applied uniformly over a large area. To improve distribution and application uniformity, the active ingredient is usually made up into a formulation, which combines the active ingredient with various inert carriers, and other ingredients to improve shelf life, enhance dispersal in water, and prevent clumping (solids). The type of formulation can affect the toxicity, the persistence, and the rate of release.

The concentration of active ingredient in a formulation may be expressed as % weight (*% w/w*) for solids. For liquids, there are several alternatives like % weight *(% w/w*), % volume (*% w/v),* or concentration (g/L).

Pesticides may be liquid (solutions or suspensions) or solid (powder or granules). They may be applied with spray bars or dispensers over the entire surface or localized over only a fraction.

It is common to use mixtures of pesticides to expand the range of action (control more species), save on applications, and in some cases, produce synergism, i.e., the action of a pesticide enhances the effect of another. Compatibility is the possibility of mixing two pesticides without reducing their efficiency.

According to their mobility in the plant, pesticides may be called systemic when absorbed and translocated inside the plant or contact, when only the plant organ in contact with the chemical is affected.

We may also classify pesticides according to their persistence (residual or nonresidual) or selectivity (selective versus nonselective) depending on the species affected.

34.3 Application of Pesticides

Most pesticides are sprayed as liquid formulations but other methods may also be used, like baits, fumigants, dusts, or in irrigation water. Spray methods may be classified according to the volume application rate (*VAR*, L/ha) (Table 34.2). Table 34.3 shows the possible formulations used in pesticide spraying.

Spray application is a relatively complex process that can be divided into a transport phase and another of interaction with the surface to be treated. A set of droplets, characterized by a diameter distribution and an initial velocity, is released from the nozzle at a given height. These droplets suffer a vertical force, resultant of the forces of gravity and friction, and a horizontal force (wind drift) that determines the trajectory and hence the contact point. During transport, droplets are subjected to direct evaporation so the diameter decreases. The fall speed decreases as does the diameter of the droplets. Tiny droplets may remain suspended in the air and fall very slowly, which increases horizontal displacement and thus drift.

The interaction phase occurs when the drops reach the surface. Large droplets tend to bounce or drain down to the ground. Small droplets will likely stick to the crop surfaces. Therefore, optimal droplet diameter is generally in the 150–250 micron range depending on the product type (Table 34.4). The density of impacts required also depends on the type of product. For example, nonsystemic fungicides

Table 34.2 Classification of spray methods according to the volume of spray applied

	Trees and shrubs	Annual crops
	Dose (L/ha)	
High volume	>1000	>700
Medium volume	500–1000	200–700
Low volume	200–500	50–200
Very low volume	50–200	5–50
Ultralow volume	<50	<5

Table 34.3 Main formulations used in pesticide sprays

Name	Description	Typical use
Soluble powder	Dissolves in water. Often >50% a.i.	I, H
Wettable powder	> 50% a.i. forms a suspension in water	I, F, H
Dry flowable	Mixture of a.i. + inert material. Forms suspension in water	I, F, H
Emulsifiable concentrate	Contains a.i., petroleum solvent, and emulsifiers	I, F, H
Flowable	Particles suspended in liquid carrier. Forms suspension in mix	I, F, H
Gel	Semiliquid emulsifiable concentrate	H, I
Microencapsulated	A.i. with plastic coating. Mixed with water and sprayed	I, pheromones
Solution	A.i. comes dissolved in liquid. Forms a solution in spray mix	H
ULV or sprayable concentrate	Very high concentration of a.i. used as it is or slightly diluted	I in greenhouses

I insecticides, *H* herbicides, *F* fungicides

Table 34.4 Desired parameters for spraying pesticides

		Required droplet diameter	Impact density	Spray volume for *LAI*=1	Main concern
Pesticide	Type	μm	cm^{-2}	L/ha	
Herbicide	Contact	300	60	106	Drift
Herbicide	Systemic	700	20	449	Drift
Fungicides	Contact	150	60	27	Areas wetted
Fungicides	Systemic	250	20	20	
Insecticides	Contact	200	60	63	Impact number
Insecticides	Systemic	350	20	56	
Fertilizers		>1500			

The spray volume for *LAI*=1 has been calculated for nearly optimal conditions (10% loss by drift and 10% not intercepted by the canopy)

and preventive contact insecticides for very mobile pests require full coverage of plant organs and therefore a very high density of impacts. In the case of insecticides that are toxic by ingestion with highly mobile insects, the required density will be much lower.

34.4 Drift

Drift is a side effect of ground and aerial pesticide applications. It is the uncontrolled airborne movement of spray droplets, vapors or dust particles, away from the intended point of application, reducing the actual dose applied. Drift can cause injury to nontarget plants and animals and contaminate nontarget sites, in special, surface waters, sensitive crops, warehouses, populated areas, and flowering crops with bees present.

Any pesticide application may produce drift. The actual amount will depend on the pesticide formulation, the application method, the volume used, and the weather conditions during application. Pesticide drift is usually greater when the application height is large (e.g., by aircraft), so it is recommended not to exceed 1.2 m (above the crop) for ground applications. Drift is also important with light particles (e.g., dusts, low volatility oils) or small droplets. For sprays, droplet size increases with nozzle diameter and decreases with pressure. Droplets with diameters lower than 100 microns favor drift so the 150–200 micron range is recommended. Thickeners reduce the frequency of small droplets.

Fumigants and highly volatile formulations may produce vapors that easily drift. Volatilization is proportional to evaporative demand and inversely proportional to drop size. Water-based sprays will volatilize more quickly than oil-based sprays. However, oil-based sprays can drift farther because they are lighter, especially at high temperatures.

The best conditions to minimize drift are low evaporative demand (temperature below 32–35 °C), low wind (1–2 m/s) with consistent direction, and a neutral temperature profile. These conditions are more likely before mid morning and late in the afternoon. Unstable conditions favor the rise of droplets and therefore the horizontal displacement. Under stable conditions (temperature inversion), a highly concentrated cloud may form and move outside the target area. This is highly risky for herbicides but might be acceptable for insecticides or fungicides. Spraying pesticides, in special herbicides, should be avoided for calm (wind speed below 1 m/s) and windy conditions (above 2.5–3 m/s). Note that atmospheric instability adds thermal turbulence to mechanical turbulence due to wind, so for any given wind speed, the conditions for spraying get worse as instability increases.

Pesticide applications should be avoided when rain is expected in the short term. Wind direction should be considered to analyze the risk of drift arriving at sensitive areas. Untreated buffer zones should be established if needed.

34.5 Persistence of Pesticides

The persistence of pesticides determines the duration of the protective effect and the safety period between application and harvest. The persistence of an herbicide also may preclude planting a sensitive species in the same field.

The degradation of pesticides is caused by:

- Microbial decomposition, enhanced by environmental conditions that favor microbial activity.
- Chemical decomposition by oxidation, reduction, or hydrolysis.
- Photolysis, i.e., chemical degradation due to light absorption.

Pesticides can be immobilized in the soil (adsorption by soil colloids), mostly by organic colloids. Therefore, soils with high organic matter or clay soils will require larger doses of herbicides.

Pesticides can be lost by leaching or volatilization. Leaching depends on its solubility and its adsorption to colloids. The more volatile products should be incorporated into the soil to avoid volatilization. Residual herbicides (e.g., Atrazine) accumulate in groundwater after leaching, which led to restrictions in some countries (e.g., Atrazine use was discontinued in the EU in 2004).

34.6 Herbicides

34.6.1 General Characteristics

Herbicides are phytotoxic products. They may be classified as total or selective when they affect all or just some species. In terms of time of application, we may distinguish preplant, preemergent, and postemergent (in relation to the crop), and in terms of mobility, we have systemic and contact herbicides.

The dose of herbicide depends on its phytotoxicity to the weeds and the crop and weed density.

Herbicides may be absorbed by roots, leaves, or stems. Leaf absorption is increased by adding wetting agents. The absorption of polar herbicides is more effective by the roots than by the leaves. Herbicides interfere with plant metabolic processes (photosynthesis, respiration, and metabolism of nucleic acids and proteins). Visual symptoms of herbicide damage include reduced growth, malformation of leaves, and plant wilting.

The translocation of systemic herbicides can follow two paths. If it is absorbed by roots, the herbicide passes to the xylem and moves with sap flow. If it is absorbed by leaves, it moves via symplast to the phloem and then moves to the growing tissues.

34.6.2 Selectivity of Herbicides

The selectivity of an herbicide reflects its ability to control weeds without significant damage to the crop. The selectivity depends on several factors:

(a) Plant: Sensitivity is higher in young and fast-growing plants. The highest sensitivity in seedlings is due to their thinner cuticle. The morphology of the plant may be responsible for the selectivity. It may be due, for example, to differences between the crop and the weed in the root system or the location of sensitive organs such as the apical meristem.
(b) Climate: The selectivity of foliar-absorbed herbicides is reduced at high temperatures. However, in these conditions, the rate of metabolism of the herbicide in the plant is higher which helps reduce its negative effects. In conditions of high humidity and/or high soil water content, the leaf cuticles have a higher degree of hydration that facilitates herbicide leaf absorption and can increase the potential damage to the crop.
(c) Soil: Texture and organic content determine the degree of fixation of the herbicide to soil colloids and hence the concentration of the active ingredient in the root zone.

The high sensitivity of seedlings is the basis of the technique of split dosing which involves making several small-dose postemergence applications when weeds are emerging so that the crop hardly suffers their effects while weed seedlings are killed. The main groups of herbicides and their characteristics are presented in Table 34.5.

34.7 Insecticides

Insecticides are agents that control insects by killing them or preventing their destructive behaviors. Insecticides may be natural or artificial and are applied in different formulations and delivery systems (sprays, baits, slow-release diffusion,

Table 34.5 Classification of herbicides according to their main characteristics

Inhibition of	Chemical group	Activity	Translocation	Persistence	Toxicity
Photosystem II	Triazines (atrazine), ureas (Diuron)	Soil, leaf	Apoplast	M–H	L
Photosystem I	Benzothiadiazoles (Bentazon)	Leaf	No	L	L
Membrane synthesis	Bipyridylium (Paraquat)	Leaf	No	Nil	H
Membrane disrupters	Diphenylether, dinitrophenols	Leaf	No	L	M
AA synthesis (selective)	Sulfonylureas	Leaf	Apoplast, symplast	M–H	L
AA synthesis (not selective)	AA derivatives (glyphosate)	Leaf	Symplast	L	L
Lipid synthesis[a]	FOP, cyclohexane derivatives	Leaf	Symplast	Nil	M
Growth regulators[b]	PCAs (2,4-D), pyridines	Soil, leaf	Apoplast, symplast	V	M
Cell division	Dinitroanilines (Trifluralin)	Soil	No	V	M
Protein synthesis	Amides, thiocarbamates	Soil	Little	L–H	M
Pigment synthesis	Pyridines	Soil	Apoplast	M–H	L

Some examples of the group are shown in parentheses
L low, *M* medium, *H* high, *V* variable
[a]Not affecting dicots
[b]Not affecting monocots

etc.). Some GMO genotypes incorporate bacterial genes coding for the synthesis of insecticidal proteins.

Table 34.6 shows a classification of insecticides.

By 1940, only some inorganic (e.g., sulfur) or botanical (e.g., pyrethrum) insecticides were available. Then the first synthetic organic insecticide, *DDT*, an organochlorine, appeared. After that, the history of insecticides has been a mixture of success (high levels of control at low cost, development of specific products with low persistence) and failure (e.g., organochlorines are toxic for animals, accumulate in the trophic chain, and had to be banned).

34.8 Fungicides and Control of Diseases

Plant diseases are best controlled by integrating several practices including sowing date, planting density, crop rotation, cultivar selection (using disease-tolerant or disease-resistant genotypes), fertilizer and irrigation programs, microclimate modification, and application of fungicides.

Knowledge of the disease cycle of the pathogen is important when developing disease forecasting systems or economic thresholds. Forecasting systems are based on temperature and relative humidity or leaf wetness. Thresholds-based programs involve periodical monitoring of symptoms (e.g., number of disease spots per leaf).

Table 34.6 Classification of insecticides according to their main characteristics

Type	Main effect on insect	Toxicity for other organisms	Main targets
Organochlorine	Nervous system	High	Broad spectrum
Organophosphate	Neuromuscular system	Very high	Broad spectrum
Organosulfur	Ovicidal	Very low	Mites
Carbamates	Nervous system	High, in special to fish	Broad spectrum
Formamidines	Nervous system	Medium	Organophosphate and carbamate-resistant pests
Organotins	ATP synthesis	High for aquatic life	Mites in trees
Pyrethroids	Nervous system	High for fish	Most agricultural insects
Nicotinoids	Nervous system	Low	Sucking insects, soil insects, whiteflies
Spinosyns	Nervous system	Low	Caterpillars, lepidopteran larvae, leaf miners, thrips
Pyrazoles	ATP synthesis	Low	Psylla, aphids, whiteflies, thrips
Pyridazinones	Mitochondrial electron transport	Medium for aquatic life	Mites
Quinazolines	Blocking chitin synthesis	Medium	Broad spectrum
Botanicals	Pyrethrum—nervous systems	Low	Lice
	Nicotine—nervous systems	Low	Aphids and caterpillars
	Rotenone—Respiration inhibitor	High to fish	Fish
	Limonene—nervous systems	Low	Fleas, lice, mites, ticks
	Neem—reduces feeding, disrupts molting	Low	Moth and butterfly larvae
Antibiotics	Blocking the GABA neurotransmitter	Toxic to fish and bees	Mites, leaf miners
Fumigants	Act as narcotics	Depends on compound	Depends on compound
Inorganics	Dependent upon type	Depends on compound	Depends on compound (e.g., S for mites)
Biorational	Attractants, growth regulators or endotoxins	Very low	Very specific
Benzoylureas	Insect growth regulators	May affect other invertebrates	Caterpillars, beetle larvae

Important aspects of the disease cycle include the number of generations per year of the pathogen and the time between infection and the appearance of symptoms (latent or incubation period) which may be a few hours for aerial diseases up to several weeks for soilborne pathogens.

Fungicides are products that kill or prevent the growth of fungi and their spores. They may be classified according to different criteria.

(a) Mobility in the plant.

Contact fungicides remain on the surface after application, not entering the plant and having no after-infection activity. Repeated applications are needed to protect new growth and to replace losses by rain or irrigation, or degraded by environmental factors.

Systemic fungicides are absorbed into the plant and move within it. They may offer some after-infection activity. Very few fungicides are truly systemic (the group of the phosphonates) but some are acropetal penetrant; they move upward in the xylem, protecting new growth. Other fungicides are localized penetrant, redistributing only within the treated leaf.

(b) Role in protection: We distinguish the following categories:
- Preventive fungicides offer a protective barrier that prevents infection.
- Early infection activity: The product enters the plant and stops the pathogen, acting until several days after infection. This type is also preventive and is most effective before infection.
- Eradication: A few products can stop disease development after symptoms appear. Even then, the damage caused by the disease often does not disappear.
- Anti-sporulant activity products prevent spore formation. The disease continues to develop, but spores are not produced, reducing the amount of inoculum to infect surrounding plants.

(c) Mode of action.

The mode of action is how a fungicide acts on a target fungus, i.e., the specific process in the metabolism that is affected (e.g., damaging cell membranes, inactivating critical enzymes). A single-site fungicide affects only one point in one metabolic pathway or a single critical enzyme or protein. These fungicides are less phytotoxic and tend to have systemic properties, but show a higher risk of pathogens developing resistance, as the mode of action is so specific that small genetic changes in fungi can overcome the effect of the fungicide. On the other hand, a multisite fungicide affects different metabolic sites within the fungus.

34.9 Calculation of the Volume Application Rate of Pesticides

The minimum volume of pesticide to apply or volume application rate (VAR, L ha^{-1}) may be calculated as a function of the desired impact density (N, impacts cm^{-2}) and the droplet diameter (d, μm) as:

$$VAR = f\left(LAI\right)\frac{10^{-7}\,\pi}{6}\frac{d^3\,N}{1-p_s-p_d} \tag{34.1}$$

where p_s and p_d are the probability of droplets not being intercepted by the canopy and the fraction of droplets lost as drift, respectively. The $f(LAI)$ function depends on the type of pesticide:

– Contact fungicides and insecticides $f(LAI) = 2\ LAI$.
– Systemic fungicides and insecticides $f(LAI) = LAI$.
– Herbicides $f(LAI) = 1$.

If the calculated value of $f(LAI)$ is lower than 1, $f(LAI) = 1$.

Example 34.1
We want to apply a contact fungicide on a wheat crop with full ground cover and $LAI = 3$. The required impact density is 60 impacts cm^{-2} and our sprayer generates droplets of average diameter 150 μm. We will perform the application with good conditions (drift loss of 10%). With full ground cover, we can assume that almost all (90%) droplets will be intercepted by the canopy ($p_s = 0.1$). With a contact fungicide, we take $f(LAI) = 2\ LAI = 6$. Therefore:

$$VAR = f\left(LAI\right)\frac{10^{-7}\,\pi}{6}\frac{d^3\,N}{1-p_s-p_d} = 6\cdot\frac{10^{-7}\,\pi}{6}\frac{150^3\cdot 60}{1-0.1-0.1} = 80\,\mathrm{L\,ha^{-1}}$$

34.10 Calculation of Spray Volumes for Fruit Tree Orchards

The Tree-Row-Volume (*TRV*) system was developed for hedgerow apple orchards in the United States. Instead of using a standard volume application rate (*VAR* = 3741 L/ha = 400 gallon/ acre), the *VAR* was corrected in proportion to tree volume per unit area (*TRV*, m^3 ha^{-1}):

$$VAR\left(L\,ha^{-1}\right) = 0.0937\cdot TRV \tag{34.2}$$

where 0.0937 is the volume (in L) of spray necessary to wet 1 m^3 of crown (of low leaf area density). This value increases to 0.1337 L m^{-3} for dense trees. This same approach may be applied also to orchards where tree crowns do not overlap. However, the specific factor of spray volume per unit of canopy volume may change for high-density orchards or different leaf anatomy (e.g., for grapevines, 0.3 L m^{-3}).

If the recommended dose of pesticide is δ_p (kg active ingredient ha^{-1}) for a standard *VAR* of 3741 L/ha, then the actual dose of pesticide should be:

$$\text{Actual dose}\left(\text{kg a.i.}\,\text{ha}^{-1}\right) = \frac{0.0937\cdot TRV\cdot\delta_p}{3741} \tag{34.3}$$

Example 34.2
An apple orchard has tree spacing of 7 × 5 m. We want to apply a fungicide with a recommended dose of 2 kg a.i./ha. The horizontal radius of the trees is 2.0 m and the vertical radius is 1.5 m. The trees have a low leaf area density. The tree volume per unit area is:

$$TRV = \frac{\frac{4}{3}\pi \cdot 2 \cdot 2 \cdot 1.5}{7 \cdot 5} 10^4\ \mathrm{m^2 ha^{-1}} = 7181\,\mathrm{m^3 ha^{-1}}$$

For low leaf area density, the volume application rate is:

$$VAR = 0.0937 \cdot TRV = 0.0937 \cdot 7181 = 673\,\mathrm{L\,ha^{-1}}$$

and the actual dose is

$$\text{Actual dose} = \frac{0.0937 \cdot TRV \cdot \delta_p}{3741} = \frac{0.0937 \cdot 7181 \cdot 2}{3741} = 0.36\,\mathrm{kg\,a.i.ha^{-1}}$$

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Harvest and Conservation

35

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Abstract

Harvesting is the key operation in farming that culminates the season's efforts. It took a large fraction of labor used in agriculture until recently. Mechanical harvesting has decreased costs dramatically, contributing greatly to lower food prices. Determining the harvest time is normally a compromise between factors that increase profits (e.g., delaying it for greater biomass) and risks (e.g., lower product quality or persistent bad weather). There are yield losses during the harvest operation that must be prevented and postharvest losses related to storage conditions. Drying grain and storing it under low relative humidity (*RH*) minimizes fungal diseases that deteriorate the product. The water content of the seeds after harvest tends to an equilibrium value in storage that depends on the *RH* and air temperature. The equilibrium water content may be determined through *Moisture Release Isotherms*. Forage crops may be browsed by animals or cut and conserved as silage, haylage, or hay, with each process requiring drier plant materials before safe storage. Fruit harvest for the fresh market is still done by hand with special regard for quality. The harvest of fruits and vegetables for processing has been extensively mechanized, but determining its timing is based on a trade-off between quality factors and yield and marketing objectives.

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35.1 Introduction

Harvest is a key activity as it culminates all farming operations leading to the ultimate goal of agriculture, producing food and useful materials. The first agricultural practice in history was harvest. Long before actual crop husbandry began, humans were collecting seeds from some grass species as part of a diverse diet. These hunter-gatherers processed the seeds to produce ale and bread. A great advantage of seeds was the long-term storage for later use in contrast with the limited preservation time of meat from hunting. Furthermore, the low efficiency of collecting seeds from natural populations where useful plants are scattered probably fostered the idea of crops. Someone must have wondered: What if this field was filled every year only with the plant that I want? What if all the plants ripened at the same time, with larger seeds that would not shed before I collected them? Thus, harvesting the edible parts of plants in natural environments probably was pivotal to the invention of agriculture.

The great advances in crop productivity of recent decades have often been associated with a reduction in harvesting costs through mechanization. In many cases, harvest costs limit the economic viability of crops. Traditionally, harvesting was based only on human labor with the partial support of beasts of burden for gathering and transport. The availability of labor for harvest often limited the area of arable land. For instance, hand harvesting 1 ha of wheat required about 180 man-hours of work (15 days of 12-h days) while current mechanized harvesting requires only 0.4 man-hours. Therefore, if the time to harvest is between 30 and 60 days, one person could harvest 2–4 ha manually but as many as 750–1500 ha using a standard combine harvester.

One important decision for the farmer is when to harvest. Physiological maturity is defined as the time when the biomass of the harvested part reaches a maximum. However, the best conditions for harvesting (harvest maturity) will occur later because, in most cases, reducing further the water content of the product facilitates mechanical harvesting, reduces weight to be transported, and improves conditions for storage. In the case of fruits, the level of ripeness involving color, accumulation of secondary products, and taste has to be considered. In the case of many vegetables, the harvest date may not be associated with physiological maturity when special quality characteristics are the main concern.

The harvest method and associated operations also affect other components of the farming system. Normally, the harvested product represents only part of the biomass and the rest must be managed so that it contributes to the subsequent crop and does not interfere with subsequent farming operations. The management of crop residues has a major impact on the organic matter and nutrient balances of the soil and offers great opportunities for soil conservation. Harvesting can also have adverse effects on the agricultural system like the spread of pathogens, insects, and weeds and soil compaction due to the traffic of the heavy machinery used.

35.2 Harvest Operations

Harvest can affect the whole plant or only part of it. In this case, the harvested organ may be aerial or underground (Table 35.1). The crop residues may be also harvested and exported outside the field, either separately or still attached to useful parts, for further separation. In the best case, only the useful organs are exported while crop residues remain in the field.

Decisions about when and how to harvest depend on the final use of the product (Table 35.1). For example, vegetable and fruit products for fresh consumption are frequently gathered by hand in several passes as the crop ripens.

The operations involved in crop harvesting depend on the species and its use (Table 35.2). In most cases, the harvest consists of cutting part or the total aboveground part of the plant and separating the useful fraction (e.g., seeds) from the residues. These two processes may occur at about the same time (e.g., combine harvest of grains) or the cut plants may be left in the field for drying and then either combined or transported out of the field for threshing and winnowing. Before harvest, it may be necessary to prepare the crop (using defoliants or abscission promoters) and/or the soil (compaction, irrigation, etc.).

After harvesting, some postharvest operations may be performed in the field/farm or outside, like drying, cleaning, removing plant parts, sorting by size, etc.

Finally, the harvested product may go directly to the packing plant or the storage facility, which may require aeration and/or temperature control. For horticultural crops, a controlled atmosphere is frequently employed, with low oxygen and high carbon dioxide concentrations that slow down fruit ripening.

Table 35.1 Classification of products harvested in agriculture according to the final use or the harvested organ

Use		Harvested organs and products	
Food	Fresh	Shoot	Vegetative
	Transformation		Reproductive (flowers, fruits, seeds)
Fodder			Sap (e.g., maple)
Industrial products	Textile		Latex (e.g., rubber, opium)
	Chemical (oil, varnishes)		Resins (e.g., pine)
	Fuels	Subterranean	Roots (e.g., beet, carrot, cassava)
	Perfumery, cosmetics		Bulbs (e.g., onion)
	Pharmaceutical		Tubercules (e.g., potato)
Seeds, propagules			Rhizomes (e.g., ginger)

Table 35.2 Some basic operations in the harvest of different crops

Harvesting operations	Crops
Mowing	Forages, medicinal crops
Reaping, threshing, and winnowing	Cereals, pulses, oil crops
Combing and pulling	Fruits
Digging, sieving, and loading	Tubercules, roots
Cutting	Vegetables
Gathering	Fruits
Shaking, sweeping, loading	Nuts, olive

35.3 Yield Losses During Harvest

Not all crop biomass but only part (yield) is useful. The ratio yield/biomass was defined as the Harvest Index in Chap. 13. However, the harvested yield is always less than the actual yield (measured at physiological maturity) because of losses:

(a) Before harvest, due to:

- Respiration of the harvestable organ, which is proportional to the time in the field after maturity and to its water content and temperature.
- Loss of harvestable structures (dehiscence of pods, abscission of fruits, consumption by herbivores, fire, hail, etc.).

(b) During harvest:

- Not captured by the harvest system (e.g., parts below the cutter bar) or dropped by it.
- Deterioration of structures collected (broken grains, damaged fruits).
- Rejection due to low quality: Although not strictly a loss, part of the yield may be left uncollected because of poor quality or excessive harvest costs. For instance, a low grain yield may not compensate for the cost of mechanical harvesting.

(c) After harvest (during packaging, transport, or storage).

- Respiration of the harvested organ: dependent on water content and temperature.
- Consumption or deterioration caused by pests and diseases: dependent on the humidity and sanitary conditions of the storage facility and the product water content and temperature.
- Rejection due to postharvest quality criteria: The collected product (or a fraction of it) may not meet quality standards implying a loss or an additional cost for sorting and separating those products not meeting the standard.

Box 35.1 The Year Without a Summer

Weather conditions in 1816 turned extremely cold. It was the result of the volcanic eruption of Mount Tambora in Indonesia, which ejected an enormous amount of ash into the atmosphere, thereby reducing transmissivity and global radiation. It is estimated that the global average temperature decreased between 1.5 and 3 °C during the 3 years after the eruption. Heavy rainfall and cold temperatures during the summer in Western Europe delayed the development of many crops that did not reach maturity. Those that did could not be harvested in many cases, and when harvested, the grain was lost later during storage. At that time, subsistence agriculture was common and people in the cities lived from harvest to harvest depending on fragile agricultural systems that did not produce sufficient food. Food shortages were dramatic during 1816 and the two following years, not only in Europe but globally. In Asia, the monsoon patterns were disrupted causing not only famine but also epidemics that killed millions, and political unrest was at a high point in China.

35.4 Agricultural Operations Affected by Harvest

Harvesting normally requires the concentration of efforts by the farmer and its labor force thus restricting other simultaneous farm operations. The date and method of harvest of a crop determines the possible choices for the next crop in the rotation. The harvest method determines the amount and distribution of residues in the field, which determines the need for additional operations (burning, chopping, removal) and, thus, the time required for land preparation before sowing the next crop.

Irrigation may improve soil conditions before harvest (e.g., before digging tubers or roots). Irrigations may also be stopped to promote abscission (of leaves or fruits) and to prevent soil compaction due to traffic on wet soil during harvest.

Some tillage operations may be required before harvesting (e.g., surface soil compaction to facilitate sweeping of fallen fruits after tree shaking of nut trees). Pesticide treatments must be stopped sometime before harvest to comply with the safety periods. In other cases (e.g., cotton), defoliants are applied to facilitate mechanical harvesting.

35.5 Harvest of Grains and Seeds

While there is some leeway in harvest time, delaying harvest in winter cereals, while leading to drier grain, has negative effects by increasing:

- Dry matter losses and/or reduced grain quality.
- Seed losses by dehiscence.
- The risk of deterioration or destruction by lodging, hail, or fire.
- Concentration of *mycotoxins*, toxic chemicals produced by naturally occurring molds, and some plant pathogens like *Fusarium*. The most common type is *aflatoxins*, produced by molds of *Aspergillus flavus* and *A. parasiticus*. The probability of contamination with aflatoxins is higher when the harvest is delayed during wet weather or when the grain is harvested wet and drying is delayed. Water-stressed crops are more susceptible to infection. Aflatoxin contamination occurs not only in grains but also in other agricultural products such as sunflower seeds, nuts, cassava, cottonseeds, spices, pepper, and hay. Maize harvest can be delayed longer than winter cereals but only if weather conditions are dry, thereby reducing drying costs without risking aflatoxin contamination.

In many cases, harvest is performed before reaching the minimum water content required for safe storage and then the seed has to be dried out of the field. In species where pod shedding is an issue (e.g., rapeseed), or when time is limited, harvest is performed in two stages. The first is swathing, i.e., cutting the crop and leaving it to form windrows where it will dry for 5–10 days until the desired water content in seeds is achieved when the second stage to separate the seed from the pods (combining) is performed. Grain can be stored safely when clean, dry, healthy, and intact. Conditions improve if it is cold at the time of storage.

The water content of the grain affects (Table 35.3):

(a) The risk of physical damage during harvest.
(b) The incidence of insect pests and fungal diseases.
(c) The metabolic activity of the seed, which affects its rate of deterioration, the release of oxygen by respiration, and heat generation in the stock.

The water content of the seeds in storage tends to an equilibrium that depends on the relative humidity (*RH*) and air temperature. Equilibrium is achieved when the water potential is equal in the air and the seed (Ψ_{seed}, J/kg):

$$\Psi_{seed} = -\frac{RT}{M_w}\ln a_w \tag{35.1}$$

where $R = 8.3143$ J mol^{-1} K^{-1}, T is air temperature (K), $M_w = 0.018$ kg mol^{-1}, and a_w is the water activity, equivalent to the equilibrium *RH*/100. Therefore, for a given air temperature and *RH*, the grain will reach an Equilibrium Moisture Content (*EMC*). This relationship is called *moisture isotherm* (Fig. 35.1) and is applied not only to seeds but to any material. The main factor determining *EMC* is *RH*, while temperature plays a minor effect. For instance, cereal grains at 25 °C and 70% *RH* show *EMC* between 13% and 14% (wet basis) (−49 MPa). One of the main factors affecting the relationship between *EMC* and *RH* is the oil content: Seeds rich in oil will show a lower *EMC* for a given *RH*. This is seen when comparing seeds of wheat and sunflower (Fig. 35.1). Seed moisture may be expressed on a dry basis or wet basis:

$$EMC_d = 100\frac{\text{Mass water}}{\text{Mass dry seed}} \tag{35.2}$$

Table 35.3 Status of seeds of major crops as a function of water content

Water content g water/g	Water potential MPa	Seed status	Activity of biotic factors	Degradation under storage
>0.41	>−1.5	Physiological maturity		
0.30–0.40	−5 a − 1.5			
0.20–0.30	−11 a − 5	High respiration rate	High (bacteria, fungi)	Fast
0.13–0.20	−100 a − 11	High mechanical resistance (0.13–0.16), Fit for combine harvesting	High (insects, fungi)	Fast
0.10–0.13	−120 a − 100		High (insects)	Slow
<0.10	< −120		Low	Slow (may increase with high temperature)

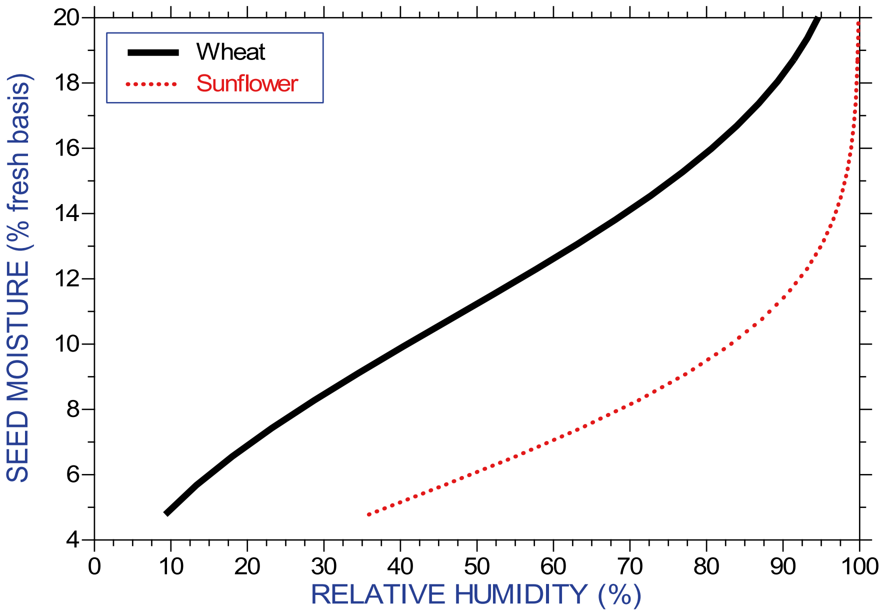

Fig. 35.1 Seed moisture isotherms for seeds of wheat and sunflower at 20 °C

$$EMC_w = 100\ \frac{\text{Mass water}}{\text{Mass wet seed}} \tag{35.3}$$

Therefore:

$$EMC_w = \frac{EMC_d}{100 + EMC_d} \tag{35.4}$$

Seeds are classified as orthodox, which can be dried without being damaged or recalcitrant when desiccation kills the seed. Most agricultural species have orthodox seeds while those of *Quercus* spp., oil palm, chestnut, and cacao are recalcitrant. The seed longevity in orthodox seeds decreases linearly with temperature and water potential from −350 (2–6% water) to −14 MPa (a_w from 0.1 to 0.9), regardless of species. Simple rules have been proposed for seed storage. For instance, the James' rule establishes that the sum of temperature (°C) and relative humidity (%) should be lower than 60. According to Harrington's rule, seed longevity decreases by one-half for every 1% increase in seed moisture content or every 6 °C increase in temperature.

To be on the safe side, the *RH* in the space between grains has to be lower than 67–70% so that spore germination of pathogens is prevented. Therefore, low *RH* prevents viability and respiration losses and attacks by pathogens and insects.

The grains may require conditioning (drying, cleaning) before safe storage. Postharvest losses of grains are significant, particularly in developing countries

Table 35.4 Water content of harvested organ at physiological maturity, harvest maturity, and recommended for long-term storage

Crop	Physiological maturity	Suitable for harvest	Recommended water content for harvest		Long-term storage
			No air drying	Air drying	
Winter cereals	35–40	<17–18	12		13.7–15.2
Maize	25–30	18–23			12.5–15.5
Rice	30–33	22–28			
Rapeseed	40	<15	8		8
Sunflower	30–40	9–10			7.0–8.3
Lentil		<13			
Soybean	50	14–20	14	18	12
Sorghum	25–30	12–25	14	20–25	12
Bean	38–44	30–40			
Pearl millet	30	<20			<13.5

where much of the production is conserved in the household. Although figures as high as 40% are frequently cited, the World Bank estimated that in 2010, postharvest losses were 15% of grain production in sub-Saharan Africa.

Table 35.4 presents values of seed water at physiological maturity and recommended for harvest and storage of different crops.

35.6 Harvest of Forage Crops

In pastures and some forage crops, harvest may be performed directly by grazing animals. In this case, it is important to adjust the density of animals to maximize productivity. Animals may also graze field crops during specific growth stages or the stubble after harvest. The former is the case of dual-purpose crops (cereals, rapeseed) that may be grazed during vegetative growth. As the meristems are not affected, crop growth will resume afterward, leading to seed production if the season is long enough.

Harvested forages are stored as silage (50–65% water content), haylage (30–50%), or hay (15–25%). The best nutritive quality in most forages is achieved around flowering. Delaying mowing after that time implies greater (and drier) biomass but lower quality. The other factor that determines mowing dates is the weather as conditions after mowing must be dry enough for successful drying.

For silage, the crop is cut, chopped, and taken to the silo where it is compacted to exclude air and then sealed with plastic to ensure anaerobic conditions. These are required for lactic bacteria to operate and reduce pH, thus ensuring long-term conservation. Some crops (maize, sorghum) may be taken to the silo just after cutting while others are left in the field drying for 1–2 days before silage starts. For haylage, the crop is left to dry longer in the field and then wrapped tightly in plastic-covered bales.

Hay production requires a longer drying period. It starts with mowing and sometimes conditioning, followed by tedding (mixing and upturning) and windrowing (piling the plant material in rows). Finally, when the material is dry (15–25% of water), baling is performed. The time to dry has to be minimized to reduce respiration losses. This time is proportional to forage biomass and inversely proportional to swath area and evaporative demand.

35.7 Harvest of Underground Organs

In this category, we include species that are harvested for their underground storage organs such as tubers (e.g., potato, yam), roots (sugar beet, turnip, cassava), and bulbs (onion, garlic).

Harvesting of underground organs should be performed around physiological maturity when little green area is left, although there are trade-offs between maturity and market targets; for instance, in some areas, potatoes may be harvested earlier than at maturity to fetch better prices even though some yield is sacrificed. Removal or killing of the shoot before harvest enhances periderm thickening of tubers which reduces the risk of peeling or bruising during harvest. Some root crops such as carrots are harvested when their size is adequate for the market.

The harvest process of underground organs includes cutting, digging, and lifting. The product may be transferred directly to a trailer after separating soil and plant residues or left in the field for drying.

As opposed to seeds, desiccation of harvested underground organs should be prevented under storage. As water loss is proportional to Vapor Pressure Deficit, it will be reduced by applying cool moist air.

35.8 Harvest of Fruits and Vegetables

Fruits for the fresh market are usually collected by hand when they reach the desired size and are approaching ripening. Quality considerations are critical in some crops such as wine grapes. Here, harvest is delayed until a certain sugar content is reached in the grapes, as determined by periodic monitoring, and/or the desired colors are achieved. In olive oil production, early harvest produces higher-quality oil as demanded by markets (more fruity) at the expense of lower oil content in the fruit and thus lower oil yields. An important difference between species is the increase in respiration and production of ethylene during ripening. Climacteric fruits (e.g., pear; Appendix) can ripen off the plant once they have reached physiological maturity, so they can be harvested at any time after reaching marketable size and ripened later or they may be harvested when fully ripe. Non-climacteric fruits (e.g., orange) complete ripening on the plant, so harvest must be delayed until then.

Fruits for processing (canning, dried, preserves, oil extraction, juice) may be mechanically harvested (e.g., using shakers) when ripe.

Harvest of nut trees occurs after physiological maturity considering two factors: the decreasing water content and the formation of an abscission zone to promote fruit detachment at harvest time. Delaying harvest leads to a significant fruit drop, causing a fraction of the fruits to be on the ground with increased costs. Nut harvesters are usually based on shaking the tree and collecting the fruits on inverted umbrellas or lateral boards before they are transferred to a trailer.

Appendix

Fraction of dry matter, gross energy per unit dry mass, and main composition of harvested products. Fresh fruits are also classified according to the capacity for ripening after detaching from the plant at physiological maturity (climacteric, C) or the lack of it (non-climacteric, NC).

Cereals and pseudocereals		Part harvested	DM	GE	Protein	Fat	Ash
			%	MJ/kg	% Over dry mass		
Barley (6 row)	*Hordeum vulgare*	Grain	86.5	18.4	14	3	3
Barley (2 row)	*Hordeum vulgare*	Grain	88.5	18.4	12	2.5	3
Maize	*Zea mays*	Grain	86	18.7	9.4	4.3	1.4
Millet-foxtail	*Setaria italica*	Grain	90.5	18.8	11.9	4.9	3.6
Millet-pearl	*Pennisetum glaucum*	Grain	89.5	18.8	12.4	4.9	2.7
Millet-Proso	*Panicum miliaceum*	Grain	90.5	19	14.2	5.5	3.7
Oats	*Avena sativa*	Grain	91	19.5	11	5.4	3
Rice (milled)	*Oryza sativa*	Grain	87.5	18	10.4	0.5	0.6
Rice	*Oryza sativa*	Grain	88	17.6	8.3	2.1	5.9
Rye	*Secale cereale*	Grain	87	18	10.3	1.4	2
Sorghum	*Sorghum bicolor*	Grain	88	18.8	10.8	3.4	2.1
Triticale	*X Triticosecale rimpaui*	Grain	89	18.1	11.7	1.5	2.1
Wheat- spelt	*Triticum spelta*	Grain	89	19	12.2	3.9	2
Wheat (bread)	*Triticum aestivum*	Grain	87.5	18.2	12.6	1.7	1.8
Wheat-durum	*Triticum durum*	Grain	87.5	18.5	16.5	2	2.1
Quinoa	*Chenopodium quinoa*	Seed	89	19.4	15.2	7.3	3
Buckwheat	*Fagopyrum esculentum*	Seed	89.7	19	18.5	4.9	4.2
Legumes							
Bean (dry harvest)	*Phaseolus* spp.	Seed	89	18.6	24.8	1.7	4.6
Chickpea (desi)	*Cicer arietinum*	Seed	89.5	19.6	22.1	5	3.3
Chickpea (kabuli)	*Cicer arietinum*	Seed	89.5	19.6	22.3	6.4	3.5
Cowpea	*Vigna unguiculata*	Seed	90	18.7	25.2	1.6	4.1
Faba bean	*Vicia faba*	Seed	90	18.7	29	1.4	3.9
Lentil	*Lens culinaris*	Seed	89	18.5	26.9	1.6	3.8
Pea (dry harvest)	*Pisum sativum*	Seed	90	18.3	23.9	1.2	3.5
Peanut	*Arachis hypogaea*	Pod	93	27.5	27	39	2.6
Soybean	*Glycine max*	Seed	87.5	23.6	39.6	21.3	5.8
Forages							
Alfalfa (hay)	*Medicago sativa*	Biomass	75	18.2	18.2	2.1	10.7
Clover (white, hay)	*Trifolium repens*	Biomass	75	17.4	22.7	2.2	12.3
Maize (silage)	*Zea mays*	Biomass	30	18.9	8.1	2.6	4.8

(continued)

Cereals and pseudocereals		Part harvested	DM	GE	Protein	Fat	Ash
			%	MJ/kg	% Over dry mass		
Sorghum (silage)	*Sorghum bicolor*	Biomass	26	18.1	6.7	2.6	8.8
Sugar, oil, and fiber crops							
Cotton	*Gossypium hirsutum*	Fiber+seed	91	23.8	21.8	19.7	4.4
Flax	*Linum usitatissimum*	Seed	93.5	27	22	34	
Rapeseed	*Brassica* spp.	Seed	91	28.8	20.9	46	4.3
Safflower	*Carthamus tinctorius*	Seed	92	26.1	15.6	32.2	2.4
Sugarcane	*Saccharum* spp.	Stalk	26	19	0.8	1.1	0.6
Sunflower (for oil)	*Helianthus annuus*	Seed	91.5	28.7	20	44	4
Sunflower (for seed)	*Helianthus annuus*	Seed	91.5	24	24	25	3
Tobacco Virginia	*Nicotiana tabacum*	Leaf	8		35		19
Horticultural crops							
Artichoke	*Cynara cardunculus*	Flowers	17	13.1	21.8	1	7.5
Asparagus (white)	*Asparagus officinalis*	Stems	7	12.5	32	1.8	8.5
Bean (green)	*Phaseolus vulgaris*	Pods	8.7	11.7	24.1	4.6	8.0
Beet	*Beta vulgaris*	Root	12	14.5	13	1.4	9
Broccoli	*Brassica oleracea*	Flower heads	11.8	12.4	36.4	5.1	5.1
Brussels sprout	*Brassica oleracea*	Leaf	13	12.8	24	2.1	9.8
Cabbage	*Brassica oleracea*	Leaf	9.9	10.2	12.1	1.0	7.1
Carrot	*Daucus carota*	Root	11	13.3	4.5	3.6	5.5
Cauliflower	*Brassica oleracea*	Head	8.9	14.4	28.1	4.5	7.9
Celery	*Apium graveolens*	Leaf	5	14.6	15	3.7	16.3
Chicory	*Cichorium intybus*	Leaf	8	12	21	3.8	16.3
Cucumber	*Cucumis sativus*	Fruit—NC	3.5	17.1	28.6	17.1	11.4
Eggplant	*Solanum melongena*	Fruit—NC	7	13.5	12.7	2.3	8.6
Endive	*Cichorium endivia*	Leaf	6	11.5	20.2	3.2	22.7
Faba bean (green)	*Vicia faba*	Fruit	27	13.4	29	2.7	4.1
Leek	*Allium porrum*	Bulb	17	15	8.8	1.8	6.2
Lettuce Iceberg	*Lactuca sativa*	Leaf	5	13.2	20.5	3.2	8.2
Lettuce Roman	*Lactuca sativa*	Leaf	3.9	12.3	30.8	2.6	10.3
Melon	*Cucumis melo*	Fruit—C	12	14.7	5.3	1.4	4
Muskmelon	*Cucumis melo*	Fruit—C	10	14.4	8.6	1.9	6.6
Parsley	*Petroselinum crispum*	Leaf	10	12.6	24.8	6.6	18.3
Pepper (green)	*Capsicum annuum*	Fruits	7.2	13.8	11.1	2.8	8.3
Pepper (red)	*Capsicum annuum*	Fruits	7.1	16.1	11.3	2.8	11.3
Pumpkin	*Cucurbita* spp.	Fruit—NC	9	13	11.9	1.2	9.5
Radish	*Raphanus sativus*	Root	6	13.2	13.6	2	11
Spinach	*Spinacia oleracea*	Leaf	6.5	10.6	40.0	9.2	30.8
Squash	*Cucurbita pepo*	Fruit—NC	14	13.8	7.4	0.7	5.9
Strawberry	*Fragaria x ananassa*	Fruit—NC	9	15.1	7.4	3.3	4.4
Tomato	*Lycopersicon esculentum*	Fruit—C	5.4	11.3	9.3	1.9	7.4
Watermelon	*Citrullus lanatus*	Fruit—NC	9	14.8	7.1	1.7	2.9
Fruit trees, vines, and shrubs							
Almond with shell	*Prunus amygdalus*	Fruit	93	21.4	11.4	22.4	5
Apple	*Malus sylvestris*	Fruit—C	13.8	15.6	4.3	3.6	1.4
Apricot	*Prunus armeniaca*	Fruit—C	14	14.8	10.3	2.9	5.5
Avocado	*Persea americana*	Fruit—C	27	25	7.5	55	5.9
Banana	*Musa paradisiaca*	Fruit—C	26	17.1	5.5	1.3	4.5
Cherimoya	*Annona cherimola*	Fruit—C	21	15.2	7.6	3.3	3.2
Cherry	*Prunus avium*	Fruit—NC	19	14.9	6	1.1	2.7

(continued)

Cereals and pseudocereals		Part harvested	DM	GE	Protein	Fat	Ash
			%	MJ/kg	% Over dry mass		
Coconut (copra)	*Cocos nucifera*	Fruit	92	32.1	8.6	66	2.5
Date palm	*Phoenix dactylifera*	Fruit—NC	77	14.7	2.3	0.2	2.2
Fig	*Ficus carica*	Fruit—C	21	14.8	3.6	1.4	3.1
Grape (table)	*Vitis vinifera*	Fruit—NC	17.3	15.2	4.0	1.2	2.9
Grape (wine)	*Vitis vinifera*	Fruit—NC	18.9	15.1	3.2	0.5	2.6
Grapefruit	*Citrus paradisi*	Fruit—NC	11	14.7	6.9	1.1	3.4
Hazelnut with shell	*Corylus avellana*	Fruit	91	24.5	13	33	1.9
Kiwi	*Actinidia* spp.	Fruit—C	17	13.3	6.7	3.1	3.6
Lemon	*Citrus Limon*	Fruit—NC	13	11	10	2.7	2.7
Mango	*Mangifera indica*	Fruit—C	18	15.2	5	2.3	3.2
Oil palm	*Elaeis guineensis*	Fruit bunch	58	23.5	7.8	47	3.6
Olive	*Olea europaea*	Fruit—NC	50	24	4.2	53	11
Orange	*Citrus sinensis*	Fruit—NC	18	14.6	7.2	1.7	3.4
Peach	*Prunus persica*	Fruit—C	12	14.6	8.1	2.2	3.8
Pear	*Pyrus communis*	Fruit—C	14.8	12.3	2.0	0.7	1.4
Persimmon	*Diospyros kaki*	Fruit—C	20	14.9	2.9	1	1.7
Pineapple	*Ananas comosus*	Fruit—NC	14	14.9	3.9	0.9	1.6
Plum	*Prunus domestica*	Fruit—C	15	15.1	5.5	2.2	2.9
Pomegranate	*Punica granatum*	Fruit—NC	25	15.7	7.6	5.3	2.4
Quince	*Cydonia oblonga*	Fruit—C	16	14.7	2.5	0.6	2.5
Walnut with shell	*Juglans regia*	Fruit	93	24.7	12.3	32.1	2.4
Roots, tubers, and bulbs							
Cassava	*Manihot esculenta*	Root	37.6	17.1	2.6	0.8	2.8
Garlic	*Allium sativum*	Bulb	39	15	15.4	1.2	3.6
Onion	*Allium cepa*	Bulb	10.9	13.8	9.2	0.9	3.7
Potato	*Solanum tuberosum*	Tuber	23.5	16.9	10.8	0.5	7
Sugar beet	*Beta vulgaris*	Root w/o crown	20	16.9	7.8	0.5	6.9
Sweet potato	*Ipomoea batatas*	Tuber	30	17.4	5.5	1.1	3.6
White yam	*Dioscorea rotundata*	Tuber	26.2	17.1	5.9	0.5	4.3
Yam (Chinese)	*Dioscorea opposita*	Tuber	18.6	17.3	8.7	0.5	4.2
Yam (yellow)	*Dioscorea cayenensis*	Tuber	16.6	17.3	6.2	0.4	3.2

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Cropping and Farming Systems

36

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Abstract

Cropping systems can be based on a single crop (monoculture) or many (polyculture), including intercrops and rotations. Intercrops are rarely used in Western agriculture although they offer several advantages (better use of resources, improved nutrient cycling) that are quantified by the Land Equivalent Ratio (*LER*). Agroforestry systems are a case of intercrop in which trees provide protection to the soil, improve the crop nutrient balance, and can generate additional useful products. Rotations involve crop diversification in time and have many advantages over monoculture (control of weeds, pests, and diseases, improved nutrition, risk diversification). Farming systems have interlinked components of inputs and outputs managed to achieve economic agricultural production to meet enterprise and/or household requirements. Cropping and farming systems can provide other ecosystem services beyond the production of food or other products.

36.1 Introduction

During the twentieth century, agriculture evolved from low-input agriculture to intensive systems with high inputs of energy, inorganic fertilizers, and pesticides. During the 1960s and 1970s, the Green Revolution exported successfully this type

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of agriculture to less developed countries, mainly in the tropics. Despite their success, these agricultural systems that seek maximum yield have raised doubts, so alternative and more sustainable systems have been proposed aimed at long-term yield stability with minimal environmental impact. A sustainable system must have some of the characteristics of a mature ecosystem (e.g., diversity) but considering that nutrients are exported with crop products and have to be returned as inputs (fertilizers) to maintain long-term soil fertility. A sustainable intensification is possible if natural resources and imported inputs are used efficiently while the soil and water quality are maintained or even improved. Understanding other farm ecosystem services and trade-offs at the farming system scale can help implement more sustainable cropping systems and design better policies to support targeted changes.

36.2 Types of Cropping Systems

The cropping system refers to the crops, their sequence, and the management practices on a given field. One type of cropping system is continuous monocropping (or monoculture) in which the field is cultivated with the same species every year. This is characteristic of large areas of North and South America (e.g., the US Corn Belt) and often is based on high inputs of energy and fertilizers. Sometimes, particularly in arid conditions, the crop is cultivated every other year leaving a long fallow period in between. On the other extreme, we find multiple (mixed) cropping systems that have in-common crop diversification in time and/or space. Multiple cropping is the oldest form of agriculture and remains a common practice in many tropical areas. In most developed countries, multiple cropping has disappeared and crop rotations, i.e., two or more crops grown sequentially in the same field, are more common. In this case, the diversification is only performed over time.

Multiple cropping variations are characterized by the number of crops per year and the degree of crop overlap. Double cropping or triple cropping means systems with two or three crops grown sequentially in a single year with no overlap in cycles. For example, in the Indo-Gangetic Plains, farmers may cultivate two crops of rice in 1 year, the main one during the monsoon season followed by another irrigated with a shorter cycle, or rice followed by wheat and then by berseem in 1 year. In this case, the production goal is not high yields for any crop but maximum yield per unit time (from kg/ha to kg/ha/day). Intercropping indicates that two or more crops are grown with partial or full overlap of their growing cycles. Relay cropping refers to the planting of a second crop before the first is harvested so the two crops fit a single season or year. When a crop is allowed to regrow after harvest from the crowns or roots, the term ratoon cropping is used. This is the case for cereals with this regrowth capacity (e.g., barley) or sugarcane.

Service crops can be included for improving sustainability with no economic or subsistence interest. For example, cover crops can be established to reduce runoff and protect the soil against erosion in periods of high rainfall when the crop is not present, to reduce the risk of nitrate leaching during fallow periods (catch crops), and to provide habitats for pollinating insects or as green manure to improve soil quality. Service crops usually fill the time windows between the main crops or occupy field borders.

36.3 Intercropping

Intercropping is the simultaneous cultivation of two or more crops in the same field to use resources more efficiently and space out labor demand. Intercropping encourages biodiversity in the paddock, which should increase stability. In Europe, intercropping is present in pastures (mixtures of clover and grasses), backyard vegetable gardens, and fruit orchards (alley cropping) but uncommon in field crops. The limited extent of intercropping can be explained, firstly, because the levels of soil fertility and the availability of inorganic fertilizers are high making it difficult to find a productive advantage. Secondly, intercropping hardly compensates for the additional management difficulties and higher costs. However, organic production regulation in Europe is expected to increase interest in intercropping, including grain production for feeding. This new interest should not mean returning to old systems but developing innovative technology-oriented new organic farming.

In developing countries in the tropics, intercropping is relatively common, generally combining a legume with a cereal. Legumes are intercropped in low fertile soils because of their N fixation ability. In Sahel, sorghum or millet is commonly sown with cowpea. The cereal grain is used for food, the straw as fodder, and the cowpea leaves and grain for fodder and food. In wetter environments, maize may be combined with high-value food legumes such as groundnuts or green gram. Other combinations of plant types that can use resources more efficiently are (i) deep- and shallow-rooted crops; (ii) tall and short crops, the last being able to grow in partial shade; (iii) climbing crop on a tall crop, for example, beans around maize; (iv) alley cropping; and (v) fast- and slow-growing crops so that the fast one is harvested before the slow one reaches maturity.

Intercropping systems must be carefully designed to limit competition for light, water, and nutrients. Intercropping also poses challenges to fulfill increased labor requirements or to mechanizing operations, particularly harvesting. The following elements should be considered to minimize competition and maximize complementarity during their cycles:

- The spatial arrangement:
  - Mixed cropping: The plants of the different species are distributed randomly in the field, for example, vetch-oat association as a forage crop.
  - Row intercropping: Two or more crops growing together with at least one crop planted in rows. Includes alley cropping and strip intercropping, with strips wide enough to facilitate the use of machines but close enough to interact. In this category, we find also relay intercropping, establishing a second crop into a standing crop before its harvest.

- Plant density: It should be reduced compared to single cropping but less in the main crop.

- Crop cycle/sowing date: Crops with different cycles or sowing dates would result in different peak demands of nutrients, water, and light so crop competition is reduced.
- Plant architecture: This is a key element when considering light competition and the possibility of using one crop as a support structure for other climbing crops.
- Proper management, i.e., adequate fertilization at optimal times, localized if there is spatial arrangement in rows, effective weed, and pest control and efficient harvesting with minimum damage to crops still growing.

The potential benefits from intercropping are the following:

- Reducing the risk from pests, extreme weather events, and price fluctuations. Apart from reducing risk by diversification, the population of natural biotic pest control agents (predators, parasites) is usually increased in intercropping.
- More efficient use of resources (light, water, and nutrients) in time and space due to the different resource requirements of the components. For example, a complex architecture cover can enhance the interception of light. The intensive use of resources by the intercrop also reduces their availability to weeds.
- Improved nutrient cycling: The combination of species with different temporal patterns of nutrient absorption reduces leaching. Moreover, crops with deep root systems absorb nutrients from deeper layers. Some of these nutrients then return to the soil surface after mineralization of the crop residues and can then be used by other crops with shallow root systems.

Intercropping advantages regarding pests and diseases are not clear in all cases. The number of parasites and predators increases with the number of plant species, but also the number of potentially harmful insect and fungi species may increase. The problem can be especially severe in the case of soil fungi. When the host plant is always present, the survival of pathogens is ensured. In the case of aerial diseases, a plant of a different species acts as a barrier to spore dispersal.

The Land Equivalent Ratio (*LER*) is used to quantify the effectiveness of intercropping systems. It is calculated as:

$$LER = \frac{Y_{I1}}{Y_{P1}} + \frac{Y_{I2}}{Y_{P2}} + \ldots + \frac{Y_{IK}}{Y_{PK}} = \sum_{1}^{K} \frac{Y_{Ii}}{Y_{Pi}} \tag{36.1}$$

where K is the number of crops and Y_{Ii} and Y_{Pi} are the yields as intercrop and pure stand, respectively, for crop i. There is an advantage in intercropping if *LER* is above 1, which typically occurs when the soil resources (water and/or nutrients) are limiting and the species differ in their pattern of root growth or when one species is a legume. There is a disadvantage in using intercropping if *LER* is below 1.

The advantage of intercropping depends on the relative abundance of the different components. For example, in Table 36.1, yield and *LER* of vetch (legume) and oats (cereal) mixtures in the region of Castilla-La Mancha (Spain) are shown. In this case, *LER* is only greater than 1 when the proportion of oats is 20% or lower, because oats in small proportions serve to support vetch growth as it is a creeping plant, so both species benefit. However, when the proportion of oats is high, this species has a competitive advantage because of its greater height as compared to vetch.

Table 36.1 Yield and Land Equivalent Ratio (*LER*) of vetch-oats intercrops in Castilla-La Mancha (Spain)

	Dry matter yield (t/ha)			
Percent of seeds vetch-oats	Vetch	Oats	Total	*LER*
100:0	3.1	0	3.1	–
90:10	3.2	1.0	4.2	1.19
80:20	2.9	1.8	4.2	1.13
70:30	2.2	1.8	4.0	0.97
60:40	1.7	2.6	4.2	0.95
0:100	0	6.6	6.6	–

Adapted from Caballero et al. 1995. Field Crops Res 41:135–140

Example 36.1
Maize and soybean were intercropped for silage in Canada. Intercrops were more cost-effective than pure stands although their success depended on seeding rate and spatial arrangement. The best performance was observed using 67% of the recommended planting density for pure stand in both crops. The resulting *LER* was 1.14. When mixed crops are intended for silage production, harvesting is not a problem as silage quality improves mixing complementing crops.

Example 36.2
In the United States, alternating strips of maize, soybean, and spring wheat in a ridge-till system were tested. The strip width was adapted to the equipment widths and herbicides were applied with a ground sprayer. The orientation of the strip was also a key to the system's success. The best combination was E-W-oriented strips of wheat-maize-soybean, with soybeans on the north side of maize. Wheat was harvested before maize plants could shade it. Maize rows next to the soybean strip profited from additional incident light.

Example 36.3
Backyard garden combinations. When radish and carrot seeds are sown together, radishes germinate, grow quickly, and are harvested when carrots are just getting established. Lettuce plants tolerate shade so they are suited to interplanting among larger vegetables. Young tomato plants may be planted among declining pea vines to replace them on the trellis. Intercropping two vegetables with different architecture and nutritional value such as beet-okra or pepper-onion is practiced in tropical Asia.

36.4 Agroforestry Systems

The practice of including trees in farming systems is an old form of intercropping still common in many parts of the world. Agroforestry systems are a good opportunity, especially in tropical areas, to increase sustainability.

Overall, an agroforestry system is more stable than other cropping systems. Trees protect the soil and the crop from the direct effect of wind and rain and improve the nutrient balance. If trees (e.g., *Acacia* spp.) or shrubs (e.g., *Leucaena* spp.) from the *Leguminosae* family are used, they contribute to nitrogen supply. Trees can also provide food (seeds) and firewood.

The need to conserve the soil in many agricultural systems worldwide will likely lead to a return to farming systems where trees and annual plants that act as protective covers from erosion are associated. In Europe, the *European Silvoarable Agroforestry For Europe* (SAFE) project has described many different alley cropping or agroforestry systems in the region. The equivalent *dehesa* in Spain and *montado* in Portugal is a good example of agroforestry in which oaks, pastures, crops, and livestock interact and complement each other. There are other examples of associated crops with little presence in developed countries. Cover crops are also common in orchards, particularly in areas prone to soil erosion.

In Kenya, fruit trees are intercropped with all types of herbaceous crops such as beans, peas, potatoes, maize, millet, and exotic and indigenous vegetables when they are still young as a way of attaining food security and income before the trees mature. Bananas may be intercropped with sweet potato and beans to reduce the incidence of weevils and nematodes and with *Grevillea robusta* for wood.

36.5 Crop Rotations

A crop rotation is a sequence of crops over time, repeated cyclically or not. The advantages of a crop rotation compared to monoculture are partly similar to those of intercropping:

- Better use of resources (water and nutrients) or improving fertility if legumes are included.
- Better control of weeds, pests, and diseases.
- Risk diversification.
- Better distribution of the means of production on the farm.

The choice of crop rotation is to be based primarily on economic factors. That being said, the species and their order in the rotation should consider the following aspects:

(a) Duration of the cycles and environmental requirements of the species.

There is considerable variability among species and within species in the crop cycle duration and adaptability to climatic conditions. For temperate areas, the following classification can be made regarding sowing dates periods of the different species:

– Autumn-winter planting:

Winter cereals: wheat, barley, rye, oats, triticale.
Grain legumes: broad bean, pea, chickpea, lentil.
Oilseeds: rapeseed, safflower, flax.

– Spring planting:

Grains: maize, sorghum, rice.
Oilseeds: soybean, sunflower.

Some species may belong to different categories depending on the climatic characteristics of the area. Sugar beet is sown in autumn in mild winter areas (e.g., south of Spain) and in the spring in colder areas like in most European countries. Winter cereals with low vernalization requirements may also be sown in early spring in cold areas or late autumn in the Mediterranean region.

This classification should not be taken strictly as the trend over the last 20 years has been to advance the date of sowing of spring crops. For instance, when sunflower was introduced in Spain in the 1960s, it was regarded as a spring crop planted in April or May, while today it is planted in many areas in February or March. Summer crops such as maize are sown in some areas of mild climates (California, Spain) 2 months earlier than 30 years ago. This is also due to the increased tolerance of this crop to suboptimal temperatures as it is being increasingly grown in the cool environments of the higher latitudes. The adoption of other cultural techniques like plastic mulching may allow an advance on the planting date of some species (e.g., cotton in the Guadalquivir Valley in Southern Spain).

(b) Time required for preparing the sowing of the following crop.

After harvesting a crop, a series of operations for soil preparation (residue management, primary tillage, seedbed preparation) can significantly delay the planting of the next crop. This time may be reduced by direct seeding the following crop (e.g., direct seeded wheat after rice harvest in South Asia).

(c) Ecological characteristics (e.g., rooting depth) and management of different crops.

Alternating crops planted in narrow (e.g., cereals) and wider rows (e.g., sunflower) has been recommended traditionally to control weed populations. For pest and disease control, repeating the same (or similar) crop in the same field should be avoided in consecutive years. Crop rotation is a good tool to reduce the incidence of pests and diseases, particularly soilborne pathogens, as the absence of the host plant causes a strong reduction in the inoculum in the soil. Some *Cruciferae* crops (and weeds) generate glucosinolates such as isothiocyanates, which have insecticide and fungicide effects, therefore providing a cleaning effect on the soil.

(d) Use and conservation of resources.

The cropping system should help to prevent losses of water and soil nutrients. The current situation in European agriculture can promote the adoption of more conservative cropping systems. Some crop management practices can be very useful although they are negative a priori. For example, in rainy areas where nitrogen is the limiting factor, keeping a clean fallow increases nitrate leaching. If weeds are left in the field, they will capture N in organic form and reduce soil water content, which reduces deep percolation and therefore N leaching. The same objective is achieved with catch crops that "capture" N in periods of high leaching risk.

The inclusion of long clean fallows (uncultivated land free of weeds) is justified only in areas with very low rainfall as leaving the soil bare increases the potential for soil erosion and N leaching. In principle, the rotation should keep the soil protected by a crop canopy or residues during the rainy period or when winds are strong.

The inclusion of legumes in the rotation improves N supply. The contribution is more important when the legume is incorporated into the soil as green manure which also helps increase the organic matter content. Deep root crops may use N left by shallow root crops.

The effects of some crops over others in a rotation are sometimes unclear as even the rotation of different cultivars of the same species is positive. This interaction is related to maintaining a large microbial soil biomass capable of rapid mineralization.

In summary, the primary concern for designing crop rotations is the farmer's profit, i.e., reducing costs and optimizing farm production means, but the design should be flexible enough to accommodate possible changes and suit the environmental and management (e.g., soil conservation) conditions.

36.6 Farming Systems

A farming system is a population of farms with similar resource bases, enterprise patterns, household livelihoods, and constraints. The following characteristics can be considered to classify a farming system, on one hand the available natural resource base, including water, land, grazing areas, and forest; climate; farm size and landscape; land tenure; mechanization and labor availability; and connection to transport networks; on the other hand the dominant farm activities, including annual, orchards and vegetable crops, livestock, processing and off-farm activities; and the technologies used often related to intensive production or to integrate different activities.

In subsistence farming systems, farmers produce food for themselves and their families and there is no profit, for example, rice production in Bangladesh or rainfed sorghum-cowpea in Sahel, whereas in commercial farming, farmers sell their crops and animals to make a profit as in most European farming systems. In general, intensive systems require high inputs of capital, labor, or technology to achieve high outputs or yields per hectare; the farms are usually small, like in protected horticulture in Almeria or pig production in Denmark. Extensive systems are, however, characterized by low use of inputs, large areas of land, and low outputs or yields per hectare, for example, wheat-sunflower production in the rainfed areas of Southern Spain. Arable systems are dedicated to growing crops, and pastoral systems to animal production, and in mixed systems, farmers grow crops and rear animals. Sedentary are the systems where the settlement is permanent and the landscape is farmed every year, whereas nomadic farmers move around looking for fresh pasture or new fields to cultivate. There are extensive subsistence systems, for example, nomadic pastoralism in Africa and Central Asia, or intensive subsistence systems, for example, rice-based farming systems in Sahel. Among the most complex are rainfed systems in humid tropics of high resource potential, characterized by a crop activity (typically cereals, cassava, banana, coffee, etc., at small scale or in plantations, and commercial horticulture), often mixed with livestock production.

A farming system represents a resource management strategy to achieve economic and sustainable agricultural production to meet some household requirements. Farming systems are not static as they have interlinked components of inputs and outputs through processes (Fig. 36.1). System management should give each crop its best chance of expressing its potential, and the spatial diversification of crops and farm activities results in more efficient use of resources as well as risk diversification. For this, an understanding of the system is required, firstly the inputs, processes, and outputs and then the influence of natural (soil, slope, rain, temperature, sunshine, etc.) and human inputs (labor, machinery, energy, political, etc.) on the processes and outputs. Their combined effects on the scale of production, methods of organization, and the products should be understood for optimizing the system, also in the mid and long term.

Understanding farm household decision-making is essential for targeting research, fostering innovation, and accelerating the adoption of innovations. How to manipulate natural inputs to use them optimally and avoid any waste? Could more inputs supporting diseases, weeds, and pests be reallocated to grain? Are diseases building up, and should a change in crop rotation be considered to control pests and diseases? Can spatial variation be profited for better adjustment of activities and diversification? Could the crop stubble be used to increase production of the next crops? Could water inputs be used more efficiently for producing grain? Is the management system environmentally sustainable or are soil and water resources being gradually downgraded or overused? Is current irrigation management progressively increasing soil salinity? Are the yield targets too high for the location? Would a lower yield target lead to a more efficient use of resources?

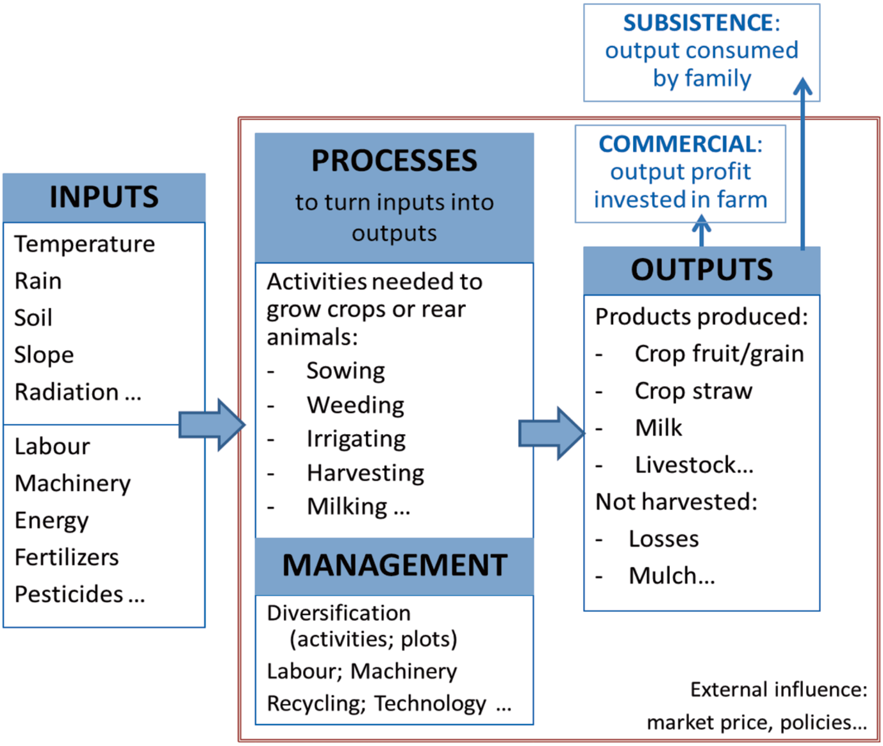

Fig. 36.1 Inputs, processes, and outputs in a farming system

36.7 Agricultural Ecosystem Services

The *ecosystem services* concept was proposed in the 1980s and developed conceptually in the late 1990s for improving the identification and valuation of benefits obtained by society, from functioning ecosystems. In the case of agriculture, ecosystem services go beyond producing food, fiber, oil, or wood (provisioning services) and include regulating services (e.g., water regulation and purification, air purification, climate regulation), cultural services (e.g., recreation, aesthetic values, tourism), or those needed to maintain the previous three, i.e., the supporting services (e.g., soil formation, nutrient cycling, or refugia of fauna).

The ecosystem services approach is generally used for designing outcomes-based policies that rely on more than just a financial cost-benefit analysis. However, giving value to ecosystem services is not straightforward as the connections between ecosystem processes and benefits to humans are complex. Knowledge is required of how decisions affect individuals and the community and the derived trade-offs. There are methodologies for valuing and assessing negative and positive effects at these scales. Valuations can combine values expressed in units (monetary, labor, time) or relative terms through indicators, for example, the number of beneficiaries, their preferences, the cost of maintaining access to the service or changing to alternatives. Additionally, individuals or groups can be confronted with hypothetical scenarios that affect an ecosystem and its services, vote on available options, and then infer the values of the services from these choices.

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Energy Consumption in Agriculture

37

Francisco J. Villalobos and Luca Testi

Abstract

Agriculture requires energy in different forms and for different purposes. The energy requirement may be decomposed into a direct (consumption of fuel or electricity at the farm) and an indirect component, associated with machinery manufacture and maintenance, equipment, and inputs (fertilizers, pesticides). Energy consumption of a given tillage operation depends on the tilled depth, soil type, and water content. Primary tillage and harvesting require much more energy than secondary operations. Pressurized irrigation systems require more energy than surface systems. However, the lower pressure and energy required in drip when compared to sprinkler irrigation is partly compensated by a lower indirect component for the latter. Additional energy may be spent on improving water quality. Fertilization is often the highest energy consumer for crop production due to the manufacturing of fertilizers, in special N. When compared to the other components, human labor requires a negligible amount of energy.

The energy efficiency of farming (energy captured per unit of energy consumed in all farming operations and materials) may be analyzed in terms of the inputs and outputs of energy. The latter, the captured energy in the harvested product can be estimated as the product of yield and its energy content.

Energy requirements of crop rotations may be performed using *CropEBal*, a free Windows application.

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37.1 Introduction

The great leap forward in agricultural productivity that occurred in the XX century was partly due to the increased energy consumption, mostly using fossil fuels. The use of machinery and synthetic fertilizers, and the development of new irrigated areas with pressurized methods (sprinkler, drip), explain the need for large energy inputs. In many cases, those are associated with CO_2 emissions, a major concern today.

We distinguish between direct (on-farm) and indirect (off-farm) energy consumption. Another possible distinction deals with the origin of the energy: renewable versus nonrenewable.

Despite the continuing increase in the use of renewable energy, agriculture still requires fuel as the only efficient alternative for machinery, thus the importance of reducing energy use per unit area and unit of product harvested. To do that, we need to understand the main factors affecting the amount of direct and indirect energy required by different operations or materials used in agriculture. This way, we may design and compare management alternatives. For instance, we need to know if moving from conventional to conservation tillage helps in reducing the energy requirement. We may also wonder if developing new irrigated areas is sustainable in terms of energy if we adopt a given irrigation method. In this chapter, we will analyze the different components of the energy requirement of agricultural production.

37.2 Energy Requirements of Farming

The energy balance of a field may be analyzed in terms of the energy requirements associated to the different agricultural practices and the final energy stored in crop products. Energy requirements may be direct (fuel used, energy spent in pumping water) or indirect (energy spent in production of inputs, machinery, or equipment). Each category may be also divided in a variable component (being proportional to input rate) and a fixed component (not dependent on input rate). Therefore:

$$E_{\text{req}} = E_{\text{dir fix}} + E_{\text{dir var}} + E_{\text{ind fix}} + E_{\text{ind var}} \quad (37.1)$$

Table 37.1 summarizes the types of energy inputs associated to different farm operations. For instance, the application of a pesticide requires a fixed direct input of energy to run the tractor, a fixed indirect input associated to tractor and machine manufacturing and maintenance, and a variable indirect input, the one of manufacturing pesticides that depends on the dose applied.

Table 37.2 shows some energy coefficients useful for calculating the energy requirements of the farm.

Table 37.1 Classification of types of energy requirements for agricultural operations

	Direct		Indirect	
Operation	Fixed	Variable	Fixed	Variable
Sowing	Fuel		Machine, tractor	Seed, pesticide, fertilizer
Tillage	Fuel		Tools, tractor	
Irrigation		Fuel or electric energy for pumping	Irrigation system	Desalination, transport
Pesticide application	Fuel		Machine, tractor	Pesticide
Harvest	Fuel		Machine	
Processing		Fuel or electric energy	Machine	

Table 37.2 Energy coefficients for different inputs used in crop production

Input	Observations	Energy coefficient	Units
Human labor	Increment over no activity	1	MJ/hour/person
Gasoline	Energy content	38	MJ/L
Diesel	Energy content	39	MJ/L
Ethanol	Energy content	22	MJ/L
Coal	Energy content	17–30	MJ/kg
Wood	Energy content	18–23	MJ/kg
Tractors	Manufacture and transport	87	MJ/kg
Implements	Manufacture and transport	70	MJ/kg
Pesticides	Manufacture and transport	358	MJ/kg
N fertilizer	Manufacture and transport	77	MJ/kg N
P fertilizer	Manufacture and transport	37	MJ/kg P
K fertilizer	Manufacture and transport	17	MJ/kg K
Anhydrous ammonia	Manufacture and transport	60	MJ/kg N
Ammonium nitrate	Manufacture and transport	85	MJ/kg N
Urea (solid)	Manufacture and transport	80	MJ/kg N
Drying grain		6.4–10	MJ/kg water
Transport	By truck	6.3	MJ/t/km
Water	Desalinizing seawater	9.0–13.0	MJ/m^3
Water	Desalinizing brackish water	3.6–10	MJ/m^3
Primary tillage	Total	1200	MJ/ha
Secondary tillage	Total	300	MJ/ha
Spray pesticide	Total (excluding pesticide)	90	MJ/ha
Spread fertilizer	Total (excluding fertilizer)	90	MJ/ha
Sowing	Total (excluding seeds)	340	MJ/ha
Harvest cereals and legumes	Total	1200	MJ/ha
Harvest tubers and roots	Total	2200	MJ/ha

37.3 Energy Requirements of Tillage

Primitive tillage was based only on human power with hand tools. It first evolved to the ard with draft animals and then to the plow until now, when tillage is carried out with powerful tractors that require external energy sources (fossil fuel).

Apart from the risk of compaction, tillage has been questioned because it increases soil erosion risk and for its large energy expenditure. These negative effects have fostered the adoption of reduced tillage systems (see Chap. 18). In the previous section, we discussed the classification of energy inputs in agricultural operations. In the case of tillage, only two components are relevant to calculate energy requirements per unit land area:

$$E_{\text{req}} = E_{\text{dir}} + E_{\text{ind}} = E_{\text{fuel}} + E_{\text{ind(tractor)}} + E_{\text{ind(machine)}} \tag{37.2}$$

The direct component is the energy in fuel consumed and the indirect component is that corresponding to manufacturing, maintenance, and repair of the machinery (tractor and implement or machine). The calculation of indirect energy requirements (MJ ha^{-1}) may be performed with the following equation:

$$E_{\text{ind(tractor)}} + E_{\text{ind(machine)}} = \frac{M_{\text{tractor}}\,EM_{\text{tractor}}}{L_{\text{tractor}}\,MFC} + \frac{M_{\text{machine}}\,EM_{\text{machine}}}{L_{\text{machine}}\,MFC} \tag{37.3}$$

where M is mass (kg), EM is the ratio of energy required and mass (MJ/kg), L is the useful life (hour), and MFC is the machine field capacity (ha/hour). Using average values of these parameters, we have calculated the indirect energy requirements of different operations shown in Table 37.3). Typical values of direct requirements are also presented for comparison. These data should be taken as an example. Actual direct requirements will be higher when tillage is performed under conditions departing from optimal (see Sect. 17.3). Actual indirect requirements may differ if the parameters M, EM, L or MFC change. The consumption of energy increases with the use of high-power tractor for small operations and with deeper tillage and depends on the shape of teeth or disks of implements.

Many studies on energy requirements of agricultural practices ignore the energy associated to human labor. Table 37.3 also shows the energy required for labor calculated as:

$$E_{\text{labor}} = \frac{EH}{MFC} \tag{37.4}$$

Table 37.3 Energy requirements of different agricultural operations calculated with Eqs. 37.3 and 37.4

	Indirect			Direct	Total	Labor	Total
	Tractor	Machine	Total				Inc. Labor
Operation	MJ/ha						
Plow	80	133	213	1000	1213	0.80	1214
Sprayer	13	5	18	68	86	0.13	86
Spreader	11	2	13	73	86	0.11	86
Sow rows	28	103	131	200	331	0.28	331
Roller	29	48	77	200	277	0.29	277
Disc harrow	69	20	90	264	354	0.69	355
Cultivator	20	27	47	220	267	0.20	267
No till drill	42	135	177	200	377	0.42	377
Combine	0	646	646	500	1146	0.51	1147

The value of EH, the energy required per human, has been taken as 1 MJ h^{-1}

where *EH* is the energy required per human (MJ h^{-1}) (see 37.6). The fraction of energy due to labor is negligible.

The relative importance of tillage in the energy requirements of farming is limited, as indicated in Example 37.1.

Example 37.1
A rainfed wheat farm produces 2500 kg grain/ha (dry matter basis) with a total energy requirement of 14,779 MJ ha^{-1} (1500 for tillage; 1900 for sowing, harvest, and other operations; 9613 for fertilizer; 1050 for seed; and 716 for pesticides). In this case, tillage is limited to one plowing and one pass of cultivator, so the fraction of energy used in tillage is only 10% of the total, thanks to the use of herbicides. Even with intensive tillage, its share of energy is small as compared to the energy inputs in fertilizers. Therefore, the adoption of reduced or no tillage should be primarily promoted for improving soil conditions rather than for saving energy.

37.4 Energy Requirements of Irrigation

The energy requirement (MJ ha^{-1} $year^{-1}$) for irrigation may be calculated as:

$$E_{\text{irrig}} = \rho_{\text{water}}\, g\, 10^{-6} \frac{I}{\mu_p\, \mu_m} \left(H_{\text{lift}} + 1.2\, H_{\text{op}} \right) + E_{\text{ind fix}} + E_{\text{ind var}} \tag{37.5}$$

where:
ρ_{water}: density of water (10^3 kg m^{-3}),
g: acceleration of gravity (9.81 m s^{-2}),
10^{-6} is used to convert from J to MJ
I: seasonal applied irrigation (m^3 ha^{-1}).
μ_p: pump efficiency (typically between 0.6 and 0.8),
μ_m: motor efficiency, which we may assume 0.4 for diesel and 0.9 for electric engines,
H_{lift}: the energy required to lift water from the water source (m). It is roughly equal to water table depth for groundwater and negligible for surface water sources.
H_{op}: operating pressure of the irrigation method (m). We may use typical values of 10–25 m for drip and 30–40 m for sprinklers. The coefficient 1.2 is based on the assumption that 20% additional energy is required to keep enough pressure in the whole network.
$E_{\text{ind fix}}$: energy spent in the manufacturing and installation of the irrigation system divided by its life span. We may use values of 7000–9000 MJ ha^{-1} $year^{-1}$for sprinkler and 13,000 MJha^{-1} $year^{-1}$ for drip irrigation. For surface irrigation, we should add here the energy required for land levelling and for shaping the ridges.

$E_{\text{ind var}}$: energy spent in desalination (if needed) and in delivering the water to the farm, which is proportional to the amount of irrigation applied:

$$E_{\text{ind}\,var} = c_w\, I \tag{37.6}$$

where c_w is the energy spent per volume unit of water. Therefore, we can calculate the energy requirement for irrigation as the sum of two terms, one variable and one fixed:

$$E_{\text{irrig}} = \left(\frac{H_{lift} + 1.2\, H_{\text{op}}}{102\, \mu_p\, \mu_m} + c_w \right) I + E_{\text{ind fix}} \tag{37.7}$$

Example 37.2
A farm is irrigated using good quality water from a canal. During extended droughts, the canal stops the supply, but water may be obtained from a nearby brackish lagoon after desalination. The farmer irrigates maize with 7000 m^3/ha/year, using a center pivot (H_{op} = 35 m, $E_{\text{ind fix}}$ = 8000 MJ/ha/year) using electric motors (μ_m = 0.9) and pumps with μ_p of 0.8. H_{lift} is negligible as the source is at ground level. Using Eq. 37.7, in normal years, desalinization is not needed (c_w = 0) so the energy spent in irrigation is 12,000 MJ/ha/year. During drought periods, the water comes from the desalination plant (c_w = 7 MJ/ m^3) and the total energy required is 61,000 MJ/ha/year, i.e., partial desalination multiplies the energy spent by 5. If the plant was processing seawater (c_w = 12 MJ/ m^3), the energy required would be 96,000 MJ/ha/year. Irrigation with desalinized water is not sustainable unless the desalination plant runs on renewable energy.

37.5 Energy Requirements of Fertilization

The energy requirement of fertilization (MJ ha^{-1} year^{-1}) is calculated as:

$$E_{\text{fert}} = n_f\, A + N_a\, c_N + P_a\, c_P + K_a\, c_K + E_{\text{ind}} \tag{37.8}$$

where

n_f: the number of applications of fertilizer,
A: the energy consumption as fuel in each application (MJ ha^{-1}).
N_a, P_a, K_a: amounts of N, P, and K (kg ha^{-1} year^{-1}) applied.
c_N, c_P, c_K: energy required for producing and transporting the fertilizers (MJ/kg N, MJ/kg P, MJ/kg K),

E_{ind}: energy spent in the manufacturing, repair, and maintenance of the fertilizer spreader or injector divided by its life span.

37.6 Energy Requirements of Human Labor

The energy spent in human labor is not easy to calculate. An average human being needs between 10 and 15 MJ day^{-1} of energy as food. In the first edition of this book, we adopted the concept of embedded energy for this calculation. However, although widely accepted, the embedded energy theory may not meet the principle of conservation of matter and energy. Therefore, we assume that energy associated to labor is equal to the increase of energy expenditure when humans perform hand labor as compared to energy expenditure for low activity. This increase may be around 4 MJ/day, so we have adopted a general value of 1 MJ/h labor (8 h/day with 50% efficiency in conversion from food). When agricultural activities are based mostly on labor, the total energy associated is small as compared to that of other inputs.

Example 37.3
The average needs of human labor for manual harvesting of wheat (yield of 6 t/ha) are around 500 hours/ha, while using just machinery, it is reduced to 2 h/ha. The energy requirements of manual harvest are therefore 500 MJ/ha. If we use a combine, the energy requirements would be the sum of a human component (2 h × 1 MJ h^{-1} person^{-1}) and a machine component (1146 MJ/ha, Table 37.3), which gives 1148 MJ/ha.

37.7 Farm Energy Outputs and Efficiency

The energy outputs of a farm may be computed according to different criteria. We usually consider only the energy contained in all materials exported from the farm, so the energy content of crop residues is ignored (unless they are sold for feed outside the farm) and so is the energy stored in soil organic matter. On the other hand, the energy content of a given material varies according to the use of the energy. We use values of gross energy which are close to the combustion energy of the material (Heating Value). Table 37.4 shows typical values of gross energy in crop products and crop residues. Apart from the composition of dry matter, an important factor in evaluating the energy content of biomass is its water content. The Heating Value (HV, MJ/kg fresh biomass) is calculated as:

$$\mathrm{HV} = (1 - w)\,\mathrm{HCB} - 2.45\,w \tag{37.9}$$

where w is the water content of biomass (g water/g fresh biomass) and HCB is the heat content of biomass (MJ/kg dry matter) (Table 37.4).

Table 37.4 Energy content in agricultural products and residues

		Energy content (MJ/kg DM)	
Crop	Use	Harvested product	Residues
Cereals	Grain	18–19	15.5–18.5
	Forage	18–19	
Legumes	Seed	19–20	18–19
	Forage	18–19	
Soybean	Seed	23.6	19
Cotton	Fiber + seed	23.8	19
Oil crops	Seed	26–29	18.3–18.8
Sugar beet	Root without crown	17	16.7
Tuber and root crops	Tubers, roots	17	18–20

Crop species have been grouped whenever possible: grain cereals (wheat, barley, rye, maize, millets, sorghum, rice, triticale), forage cereals (maize, sorghum), seed legumes (bean, cowpea, faba bean, lentil, pea, peanut, chickpea), forage legumes (clover, alfalfa), oil crops (safflower, rapeseed, sunflower, flax), tuber, and root crops (potato, cassava, yam, sweet potato)
The total energy output will be the product of yield and the energy content of the harvested product

Example 37.4
In the case shown in Example 37.1, wheat yield is 2500 kg grain/ha (dry matter) and the total energy requirements are 14,779 MJ/ha. If both grain and straw are exported, the output is 88,750 MJ/ha and the ratio output/input is 6.0. If only the grain is exported, the output/input ratio is 3.1. In both cases, the energy balance of farming is positive (more energy produced than consumed).

37.8 CropEBal

CropEBal is a Windows application to calculate the energy inputs of all agricultural operations and materials and the energy outputs from the farm. The calculations are based on the equations in this chapter and ASAE (2000). The program has been tested on computers running Windows 7, 8, 10, and 11. It includes a list of 149 crops.

The application is a standalone program. It is completely free and may be downloaded from https://www.uco.es/fitotecnia/cropebal.html.

The program first opens a form with a list of crops. The user may add as many crops to the rotation as needed. The selected crops are shown along with data on gross energy, protein, fat, ash, and percent of residues remaining in the field after harvest. The user has to supply the expected yield and the seed rate and mark if residues are burned.

Once the crop information is filled, the user has to indicate the soil type. If irrigation is performed, the user indicates the method, the source of water, and some data related to pumping. The second form allows the user to pick a sowing method and a set of tillage operations. The user may specify the depth and spacing between the tillage tools.

A third form allows selection operations related to fertilization, spraying, and harvest. The needs for additional labor, transport, or product drying are also contemplated.

Finally, the main results (required energy inputs for each operation type and material) and the energy captured in the product are presented in a text file.

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Remote Sensing

38

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Abstract

Remote sensing is obtaining information about an object without physical contact, typically carried out with sensors onboard satellites, aircraft, or land-based platforms. Today, several technologies can be integrated into these carriers to map and monitor different plant biophysical traits with high spatial and temporal resolution.

New sensors and information and communication technologies provide opportunities to refine agronomic management and advance agricultural research. Understanding the nature and limitations of the available technologies is essential for their correct use in applications such as precision agriculture. These techniques rely on identifying relationships between the sensor signals and plant traits such as biochemical composition, architecture, and water status. Depending on the type of sensor, we may use vegetation indices, physical models, or machine learning algorithms. A new paradigm in plant science called phenomics is emerging, combining information on plant genotypes and the environment with remote sensing.

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38.1 Introduction

Agriculture started around 10,000 years ago and since then, improvements in agricultural technology have contributed to increasing its productivity. Intensive agriculture in the second half of the twentieth century achieved high productivity from high inputs but also had some important environmental impacts.

The next step in agricultural technology is based on proximal or remote sensors and computers that allow a more precise and/or efficient application of inputs in the field. This is based on the improved knowledge of crop physiology and the advances in agronomy during the twentieth century. At this point, we see that agriculture evolved from low input/low control to high input/low control during the 1950–1960s and is now turning to optimal input based on high control. In this chapter, we review some of the technologies that improve crop production using remote sensing.

38.2 Basic Principles of Remote Sensing

Remote sensing is the acquisition of information about an object without physical contact. Although it has been generally related to the acquisition of images from satellite platforms, the term remote sensing is broader. It includes data collection from different platforms, from long distances (i.e., 36,000 km from the Earth using a satellite) or from just a few centimeters using a camera or an instrument close to the object (e.g., a leaf).

The remote sensing (RS) of objects is conducted through a physical carrier (electromagnetic radiation) that travels from the objects to the sensors through an intervening medium (the atmosphere). Depending on the nature of the radiation used, we can distinguish i) active RS, when a signal is emitted and received by the sensor, and ii) passive RS, which uses naturally occurring radiation (e.g., reflected from solar radiation).

Electromagnetic radiation is energy propagated through space between electric and magnetic fields. The electromagnetic spectrum is the extent of that energy ranging from cosmic rays, gamma rays, and X-rays to ultraviolet, visible, and infrared radiation, including microwave energy as a function of their wavelength (Fig. 38.1).

Our eyes detect radiation in the so-called "visible" spectral region, ranging between 400 and 700 nm in wavelength. Nevertheless, some sensors can detect and measure radiation below or above the 400–700 nm region. Remote sensing of objects is generally conducted with sensors working in wavelengths in the ultraviolet (UV) (below 400 nm), the visible region and then in the reflected infrared (beyond 800 nm), thermal infrared (3–14 μm), and microwaves above the visible. Above the visible region, some sensors detect reflected radiation while others detect emitted radiation used to measure the object's temperature.

The collection of reflected or emitted data by sensors needs to be conducted in the so-called "spectral bands." Each detector is sensitive to a different range and number of these specific spectral bands. The width in wavelength units and the number of these spectral bands enable the acquisition of data from objects in a

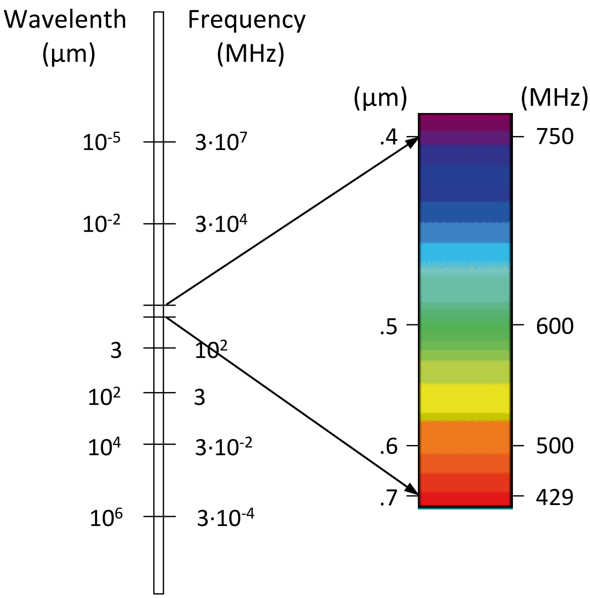

Fig. 38.1 The electromagnetic spectrum is classified as a function of wavelengths

multispectral way. Multispectral RS is the collection of reflected or emitted energy from an object in multiple electromagnetic spectral bands (Fig. 38.2). The more bands there are and the narrower these bands are, the more information is obtained from the object. When the detector can gather hundreds of bands contiguously throughout the electromagnetic spectrum, the technology used is called hyperspectral remote sensing or imaging spectroscopy.

38.3 Reflectance and Spectral Signatures

The reflected radiation measured by a sensor is a function of the total incoming radiation at that moment, i.e., the reflected radiation by an object will change as the sun changes. For this reason, RS methods rely on normalizing such reflected energy to the incoming radiation at the time of the measurement to calculate the spectral reflectance. Spectral reflectance is the ratio of radiation reflected by a surface to the radiation incident on the surface. Remote sensing methods are based on this reflectance as a function of wavelength, developing the so-called spectral signatures (Fig. 38.3). In Fig. 38.3, we can observe the reflectance measured from three objects: (i) green vegetation, (ii) dry vegetation, and (iii) soil. Reflectance changes with wavelength, which depends on the plant pigments absorbing and reflecting energy from the object under study, and other factors such as the leaf structure, soil background, and the vegetation canopy architecture. Analyzing these spectral signatures, it is possible to infer the status of the vegetation and soils by estimating the concentration of photosynthetic pigments (chlorophylls, carotenoids, xanthophylls), the density of vegetation layers (leaf area index, leaf area density), and other biochemical constituents such as the water and dry matter content of plants.

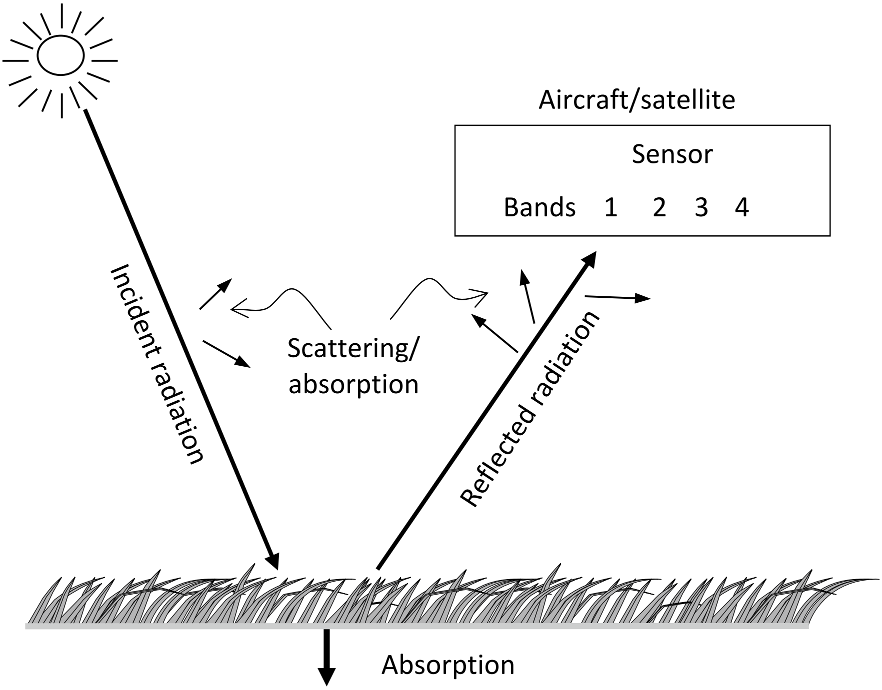

Fig. 38.2 Multispectral remote sensing

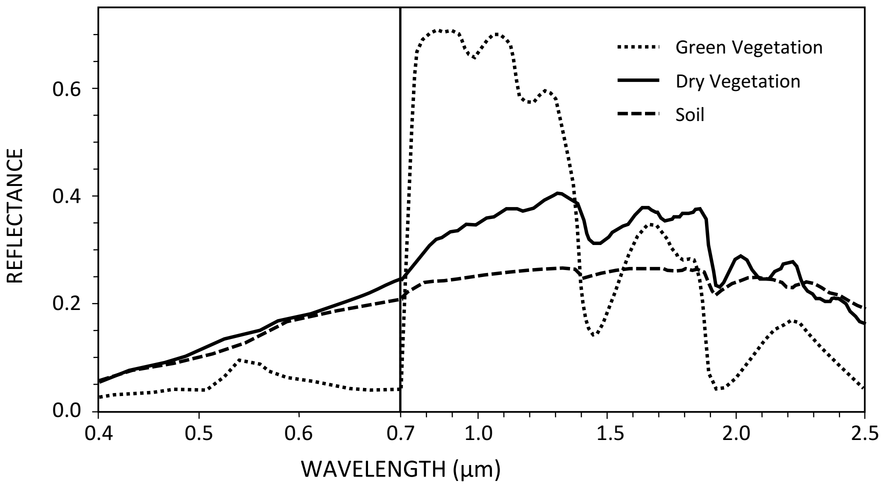

Fig. 38.3 Spectral signatures from green vegetation, dry vegetation, and soil

38.4 Remote Sensing Resolution

Four definitions of RS resolution are critical to understanding the data quality and image characteristics: spatial, spectral, radiometric, and temporal.

Spatial resolution is the size of each pixel recorded in an image, typically corresponding to square areas. The minimum detail discernible in an image depends on the sensor's spatial resolution and refers to the size of the smallest possible feature that can be detected. The spatial resolution of passive sensors depends primarily on the Instantaneous Field of View (IFOV) of the system, which is comprised of the detector and the lens. The area on the ground represented in the pixel is called the resolution cell and determines a sensor's maximum spatial resolution.

The spectral resolution is the wavelength width and the number of the different spectral bands recorded by the detector, which determine the spectral signatures used to assess the objects by remote sensing methods.

Radiometric resolution is the number of different intensities of radiation the sensor can distinguish. Typically, this ranges from 8 to 14 bits, corresponding to 256 levels of the grayscale and up to 16,384 intensities in each band. It also depends on the instrument noise.

Temporal resolution is the frequency of satellite or plane overpasses over the same place. The temporal resolution is relevant in time-series studies to understand seasonal changes.

38.5 Sensors and Platforms for Remote Sensing

The sensors are generally classified as optical or microwave sensors.

Optical sensors detect visible and infrared radiation (IR) in three subregions: near IR, intermediate IR, and thermal IR. Two types of radiation can be measured from optical sensors: (i) visible/near IR (reflected) and (ii) thermal IR (emitted).

In the visible and near IR region, the sensors detect radiation of sunlight reflected by the objects which is used to quantify land surface conditions such as the distribution of plants, forests and farm fields, rivers, lakes, urban areas, etc. This technique can only be used during the daytime under clear-sky conditions.

In the thermal IR region, the detected radiation is that emitted by the objects, typically used to monitor the temperature of the land's surface (see Chap. 3). It is not restricted to the daytime period but is affected by cloudiness.

Microwave sensors may be active or passive and are designed to measure radiation in the microwave spectral region, with wavelengths longer than the infrared. The observation is not affected by period (day or night) or weather as microwaves penetrate the clouds.

The platforms used for RS can be divided into the following classes:

(a) Proximal sensing platforms are used to acquire high spatial resolution imagery from towers, cherry pickers, trucks, and mobile platforms in the field.
(b) Airborne platforms (i.e., planes of different sizes and weights) are generally used for acquiring imagery at typical altitudes between 300 m and a few kilometers over the ground. They can be divided into piloted and unpiloted aerial vehicles.

    (b.1) Piloted vehicles are the traditional platforms for aerial photography and remote sensing using heavy cameras working in the visible, near IR and thermal regions. Access to these sensors is limited as they have a high cost of operation, so they are generally used for research purposes and less often for operational applications. Sensors in these platforms are very expensive, but they obtain high-quality imagery for validating remote sensing models and methods.
    (b.2) Unpiloted aerial vehicles (also called as UAV, UAS), also known as Remotely Piloted Aircraft (RPAS) or "drones," are the result of transferring this technology from the military to civil applications. These drones are small planes that can fly autonomously over desired areas at low altitudes, therefore acquiring high-resolution imagery using miniature sensors carried onboard. Wingspan and weight for these platforms range between less than a meter up to 5 m, and under 2 kg up to several hundred kilograms. The sensors weigh between a few grams to several kilograms, and they are currently available to collect images from drones in the visible, near IR and thermal regions. Despite the legal limitations on drones for civil applications, they offer high flexibility in acquiring low-cost imagery, higher spatial resolution, and easy operation by end users.

(c) The satellite platforms follow typically elliptical orbits around the Earth. The time taken to complete one revolution of the orbit is called the orbital period. The satellite traces a path on the Earth's surface as it moves across the sky. As the Earth below is rotating, the satellite traces a different path on the ground in each subsequent cycle. Remote sensing satellites are launched into orbits such that the satellite repeats its path after a fixed time interval. This time interval is called the repeat cycle of the satellite.

When a satellite follows an orbit parallel to the equator in the same direction as the Earth's rotation and with the same period of 24 h, the satellite will appear stationary to the Earth's surface (geostationary orbit), so it will be positioned all the time over the same spot on Earth. Satellites in the geostationary orbits are located at a high altitude of 36,000 km. They are commonly used for weather observations as they can monitor large areas continuously, i.e., acquiring one image of the same area every 30–60 min.

A near-polar orbit is one with the orbital plane inclined at a small angle to the Earth's rotation axis. A satellite following a properly designed near-polar orbit passes close to the poles and can cover nearly the whole Earth's surface in a repeat cycle. Nevertheless, Earth observation satellites usually follow sun-synchronous orbits, i.e., an orbit whose altitude is such that the satellite will always pass over a location at a given latitude at the same local solar time. In this way, the same solar illumination condition can be achieved for the images of a given location taken by the satellite.

As a function of the orbit (distance to the Earth) and the type of sensors carried by the satellite platform, the satellite imaging systems can be classified into low (>1000 m), medium (100–1000 m), high (5–100 m), and very high resolution (< 5 m).

38.6 Applications: Reflectance and Vegetation Indices

Most applications of remote sensing of vegetation use reflectance to calculate vegetation indices due to their correlation with plant traits. A vegetation index (VI) is a mathematical combination of reflectance bands collected at different spectral regions that are used as a proxy of vegetation characteristics. Depending on the bands used in the VI, the resulting number will be sensitive to different aspects, such as the concentration of plant pigments, water content, or leaf area density, among others. VIs have been developed for several applications, and each index has unique strengths and weaknesses. Many VIs are based on normalized differences of reflectance that minimize instrumental errors and atmospheric effects in the reflectance, providing more robust correlations than other VIs based on direct ratios. Commonly used VIs include the Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI), and the Soil-Adjusted Vegetation Index (SAVI). These indices are very sensitive to the amount of green leaf area and are often used as biomass or fractional cover proxies. However, other VIs are sensitive to the chlorophyll content (chlorophyll has very high absorption of red and blue radiation) and other photosynthetic pigments; therefore, they have been used routinely as proxies for mapping crop nutrition, and in precision agriculture applications targeting variable rate application of fertilizers (Table 38.1).

Applications requiring the quantification of specific pigments or water content can use VIs incorporating bands within the spectral regions of the absorption of these components. For example, the Normalized Difference Water Index (NDWI) replaces the red band of the NDVI with a band in the shortwave IR, which falls within the major water absorption bands. Therefore, the higher the crop water content, the smaller the NDWI. In the case of pigments, the Carotenoid Reflectance Index (CRI) or the Anthocyanin Reflectance Index (ARI) incorporate specific bands (510 and 550 nm in the case of CRI and ARI, respectively) that make the indices sensitive to these pigments while minimizing the influence of chlorophyll. These specific indices have been developed at the leaf level, and their application at the canopy level is not straightforward since the canopy architecture or the sun and

Table 38.1 Example of vegetation indices

Name	Formula	Quantifies
Normalized Difference Vegetation Index	$\text{NDVI} = \dfrac{\text{NIR} - \text{red}}{\text{NIR} + \text{red}}$	Vegetation density and health
Enhanced Vegetation Index	$\text{EVI} = \dfrac{2.5(\text{NIR} - \text{red})}{\text{NIR} + 6\,\text{red} - 7.5\,\text{blue}}$	Similar to NDVI but addresses soil background effects
Soil Adjusted Vegetation Index	$\text{SAVI} = \dfrac{(1+L)(\text{NIR} - \text{red})}{\text{NIR} + \text{red} + L}$	Compares vegetation cover in areas with varying soil backgrounds
Normalized Difference Red Edge	$\text{NDRE} = \dfrac{\text{RE} - \text{red}}{\text{RE} + \text{red}}$	Chlorophyll content and plant stress
Normalized Difference Water Index	$\text{NDWI} = \dfrac{\text{NIR} - \text{green}}{\text{NIR} + \text{green}}$	Water content in vegetation
Carotenoid Reflectance Index	$\text{CRI} = \dfrac{1}{\text{R510}} - \dfrac{1}{\text{R550}}$	Carotenoid content relative to chlorophyll
Anthocyanin Reflectance Index	$\text{ARI} = \dfrac{1}{\text{R550}} - \dfrac{1}{\text{RE}}$	Concentration of anthocyanins in vegetation

NIR near IR, *RE* reflectance in the red edge spectral region. R510 and R550 are the reflectance at 510 and 550 nm, respectively. L: empirical coefficient for SAVI
Refererences: NDVI: Rouse et al. 1974. Third ERTS Symp Significant Results, Vol. 1: 309-317. EVI: Liu & Huete. 1995. IEEE Trans Geosci Remote Sens 33: 457–465. SAVI: Huete. 1988. Remote Sens Environ 25:295–309. NDRE: Sims & Gamon.2002. Remote Sens Environ 81:337–354. NDWI: Gao.1996. Remote Sens Environ, 58:257–266. CRI: Gitelson et al. 2002. Photochem Photobiol 75:272–281. ARI: Gitelson et al. 2003. J Plant Physiol, 160:271–282

camera relative positions will significantly impact the reflectance. This can be modelled with radiative transfer models that can simulate the behavior of light within the canopy, providing a framework to upscale from the leaf to the canopy and allowing the development of functions for correcting the VIs for the specific observation conditions.

Machine learning (ML) algorithms have recently become widespread in remote sensing, particularly with hyperspectral data. The high dimensionality of hyperspectral reflectance, where each pixel or observation contains hundreds of spectral bands, makes this data ideal for the application of ML. The principle of ML is to train (calibrate) empirical models using many observations of a given trait (e.g., leaf N concentration) linked to spectral reflectance. These models can then be used to predict (infer) this trait from reflectance and applied at a large scale (e.g., with images). The biggest drawback of this approach is that it requires large amounts of data for calibration and validation. Also, these models are specific to the training dataset (e.g., sensors, species, varieties, range of variation) and cannot be transferred easily to other conditions.

38.7 Applications: Thermal and Active Sensors

The applications of RS based on sensors sensitive to the emitted radiation are very different from those based on reflected light. In the case of thermal imaging, sensors register the signal emitted by observed objects that is a function of their temperature. Canopy temperature depends mainly on the crop energy balance; therefore, it is a function of the incoming radiation, air temperature and humidity, and wind speed, but it is also influenced by crop transpiration. Generally, a well-watered crop will have a lower temperature than a water-stressed crop due to the difference in stomatal conductance and transpiration. This simple rule can be used to examine the canopy temperature differences in a thermal image to identify stressed plants. Furthermore, canopy temperature can be used as an input into energy balance models for calculating sensible heat and transpiration. However, similar to the vegetation indices, simple indicators have been developed to normalize canopy temperature into a simple, easily interpreted number. The most widely adopted index based on canopy temperature is the Crop Water Stress Index (CWSI), which was developed to correct the effects of air temperature and vapor pressure deficit on crop temperature and allows quantifying water stress (see Chap. 21).

Thermal imaging requires calibration and atmospheric correction to obtain the actual canopy temperature. Infrared sensors operate by measuring the emitted energy by the object. This energy needs to travel across the atmosphere between the object and the sensor, which has a given transmissivity and attenuates the signal but can also contribute to the thermal radiance emitted by the air. These effects can lead to bias in the estimated temperature and must be corrected even at low altitudes, where drones operate. This bias can introduce large errors in calculating CWSI or energy balance components based on IR temperature.

Active sensors have the advantage of not relying on environmental conditions and, therefore, can be operated under cloudy conditions or even at night. The main active sensors used for monitoring crops are indicated below.

38.7.1 LiDAR (Light Detection And Ranging)

Its energy source is a laser that emits pulses and measures the distance to the object by determining the time of flight of the light pulse. The pulses follow a scanning pattern, measuring the distance for different angles which makes it possible to estimate the 3D coordinates of each laser hit. The result is a 3D canopy model whose resolution depends on the sensor specifications and distance. The intensity of the reflected light is also very valuable; depending on the laser's wavelength, it can provide information about the crop status. For instance, a red laser can be sensitive to chlorophyll. The main applications of LiDAR in crop monitoring are measuring plant height, canopy architecture analysis, and biomass estimation. An example is shown in Fig. 38.4.

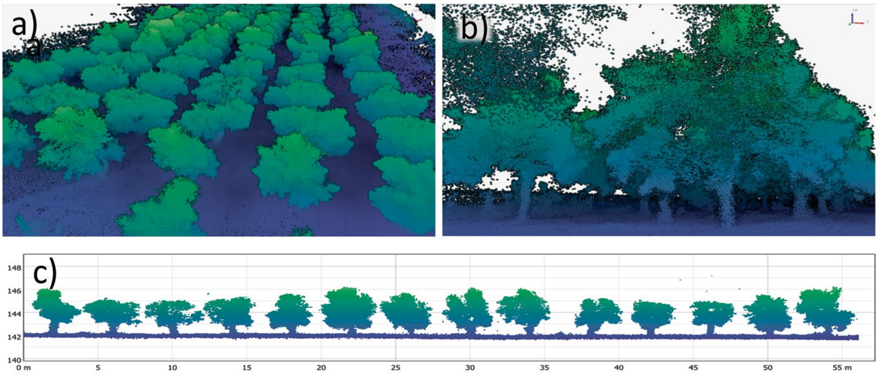

Fig. 38.4 Example of a LiDAR dataset obtained in an experimental olive tree orchard with different cultivars, showing a 3D overview of the orchard (**a**), a close-up view from the ground (**b**), and a 2D profile across the orchard (**c**). The data was obtained with a prototype of a handheld ground-based LiDAR acquisition system. (AgroLiDAR)

38.7.2 RADAR (RAdio Detection And Ranging) or SAR (Synthetic Aperture Radar)

This method uses microwave radio signals covering the scanning area, often emitted from large antennae in satellites. The main advantage of RADAR remote sensing is that microwaves can penetrate clouds, making it the only available technology in areas almost permanently covered by clouds. The RADAR signal processing is based on analyzing the reflected signals (backscattering) at different angles, which can provide information about the topography, surface roughness, or crop phenology. Some applications of RADAR allow estimating soil moisture by measuring the changes in the dielectric properties of the soil as these modify the RADAR signal. However, when applied from space, the penetration of the microwaves in the soil is limited to a few centimeters, and vegetation will also interfere with the signal. Alternatively, when operated on the ground (ground penetrating radar or GPR), the method provides information about the soil properties so it is often used for mapping soil moisture, salinity, and texture.

38.8 Phenomics

Plant breeders and agronomists evaluate certain plant traits that differ depending on the genotype and environmental interactions, also known as the phenotype. These traits include plant establishment (number of plants per square meter), ground cover, plant height, biomass, yield, and visual scores for disease and pest damage. The use of remote and proximal sensing in phenotyping has been called phenomics, in analogy to other "omic" technologies. Phenomics allows measuring at a large scale with higher precision and avoids the subjectivity sometimes present due to the human factor in many measurements. Moreover, phenomics is essential for obtaining the large amount of data required to link genetic information to the phenotypes across multiple environmental conditions, which is critical in genome-wide association studies and gene function discovery.

Phenomics can be applied at different scales, from single plants growing under controlled conditions in growth chambers and greenhouses to more extensive field trials distributed geographically. The sensing technologies used in phenomics also range from hyperspectral to determine the biochemical composition of plant organs, thermal for estimating stomatal conductance or 3D-RGB, and LiDAR for canopy architecture, height, or biomass. In field phenomics, sensors can also be operated on platforms like ground vehicles (often known as phenomobiles) or aerial vehicles (including autonomous drones). Each of these platforms has unique advantages. In the case of ground vehicles, the proximity to the crop allows higher resolution for applications requiring single-plant imaging. At the same time, aerial sensors can map the entire field trial in just a few seconds. This fast acquisition is critical for applications like thermal imaging, where changes in environmental conditions can conceal the phenotypic differences in canopy temperature.

One significant advantage of using remote and proximal sensing tools in phenomics is that it allows repeated and non-destructive measurements of dynamic traits over time. This provides, for instance, crop growth rates or biomass accumulation dynamics without cutting and processing biomass samples from the field so plot size and sampling errors can be minimized.

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Site-Specific Agriculture

39

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Abstract

Site-specific agriculture (SSA) enhances resource use efficiency by exploring temporal and spatial variability in agricultural fields. SSA, also called precision agriculture, is based on the computation and analysis of intra-field variability of soil or plant variables that affect the relationship between input application and crop productivity. The overall objective is to match crop demand and input supply while minimizing traffic. The development of GPS systems and new sensors and the ability to locate interventions have significantly boosted site-specific applications. The application of site-specific management follows three steps: (i) assessing variability and developing management and prescription maps, (ii) applications using the variable rate approach, and (iii) output evaluation. To address field spatial variability, the commonly employed strategy is the

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development of management zones based on similar crop production potential and the response to input application. The most effective strategy for implementing precision agriculture schemes is to define management zones based on yield patterns, which can be derived from yield monitors installed in harvesters or modeled using vegetation indices. The primary advancements have centered around the localized application of inputs, such as irrigation, fertilization, and herbicides, which have been facilitated by the development of tools for input precise application.

39.1 Introduction

Precision agriculture, or site-specific crop management, is a farming management concept based on observing and responding to intra-field variability. It is defined as a management strategy focused on the implementation of technologies and practices to apply the inputs according to the spatial and temporal variability, as opposed to a uniform application based on mean values. The inputs are thus applied according to the 4R's rule: from the right source, at the right time, in the right place, and at the right rate. Precision agriculture has been practiced for site-specific nutrient or pesticide applications, varying seeding rates, controlling field traffic, etc.

The benefit associated with site-specific crop management depends on the local heterogeneity of the field; it is thus useful only if there is substantial intra-field variability. This variability must also respond to a clustered (nonrandom) distribution. There is no benefit in applying site-specific strategies to an ideal completely uniform or entirely random field. In agricultural fields, these extremes are never found, and the distribution of physical and chemical soil properties favors the application of site-specific management. When there is a uniform application in a field with a given coefficient of variation (*CV* of 20% in the example plotted in Fig. 39.1), half of the area will receive lower inputs than needed, while the other half will receive an excessive amount. The amount of under- and over-applied product is related to the intra-field variation (shaded areas in Fig. 39.1a). With site-specific management, the area is split into different zones (four zones in Fig. 39.1b), and each zone is managed independently. As a consequence, the input mismatch is reduced, and thus, resource use is optimized.

Precision agriculture involves several methods, technologies, and equipment that can be grouped into three activities, i.e., assessing variability, managing variability, and output evaluation.

39.1.1 Assessing Variability

The first objective is quantifying the variability of the crop status or soil properties that would determine the response to the input application (i.e., water, nutrients, or pesticides). Techniques for assessing this spatial variability are already available and often are focused on proximal or remote sensing. Point sensors distributed

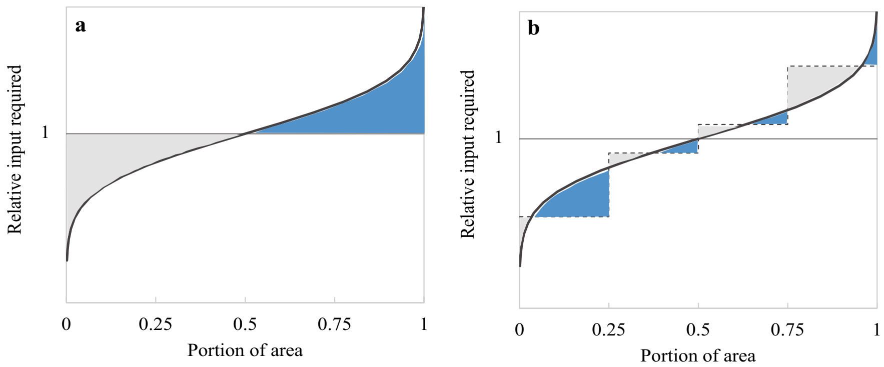

Fig. 39.1 Distribution of relative input required over a field for a normal distribution with a coefficient of variation of 20%. The gray- and blue-shaded areas correspond to excess or deficit of inputs, respectively. In (**a**), the average applied input satisfies the needs of only 50% of the field and exceeds the needs of the other 50%. In (**b**), the field is divided into four management areas

across the field and remote sensing imagery are the most commonly found data sources to account for natural heterogeneity. These data must be compiled in a geographic information system (GIS) and ingested into more or less complex models that calculate the necessary input applications in the field according to sensor data. Often, the models estimate crop yield penalties associated with the different management strategies. Treatment decisions are taken according to the economic threshold in the particular case of weed, pest, and disease management. In any case, the models must provide accurate and spatially distributed results in time within a prescription map.

39.1.2 Managing Variability

The prescription maps are thus used to apply the inputs according to known field conditions. *Variable rate technology* (VRT) has been developed to apply a variable amount of inputs in the field using prescription maps and GPS systems. These systems differ according to the purpose. The most straightforward system is the flow-based control system. In this case, a microprocessor calculates a servo valve's flow and aperture according to the specifications and the speed. More complex systems are based on modulated spraying-nozzle control, where the system controls the moment and duration of the discharge from nozzles, which is regulated by high-speed valves.

39.1.3 Output Evaluation

The evaluation of the site-specific operations should cover agronomic, economic, and environmental aspects. The profitability of the operations and the associated potential improvements in environmental quality are the most critical factors to evaluate. Techniques and models used in the variability assessment can be applied again for this evaluation. Some practices, such as those associated with soil health improvement, are not easy to evaluate and require long-term modelling approaches.

39.2 Positioning and Automation

High-precision positioning systems like GPS are key technologies for SSA. The systems record the geographic coordinates of the field and management zones and locate and navigate agricultural vehicles with an accuracy of a few centimeters.

There are different levels of automated steering. Assisted steering systems show drivers the path to follow in the field, but the farmer still needs to steer the wheel. Automated steering systems take full control of the steering wheel along the row, allowing the driver to watch the machine in use (sprayer, seeder). Intelligent guidance systems allow different guidance patterns adapted to the shape of the field.

Management zone maps, automated steering, and variable rate technology are used jointly to adjust machines to apply, for instance, seed or fertilizer according to the spatial variations in plant needs.

Data sensors can be mounted on moving machines also. Grain yield monitoring is becoming very popular. It consists of devices and sensors installed in the harvester that calculate and record grain yield and machine position as it moves, resulting in a yield map that can be useful for delineating management zones.

39.3 Definition of Management Zones

One of the most widely applied strategies to deal with spatial variability in SSA is the definition of management zones. In this case, the field is divided into zones that include areas with a similar crop production potential and that respond similarly to input application. This analysis is based on spatial statistics, searching for patterns according to point measurements and remote sensing-derived information. The spatial variability in fields can be associated with static variables (i.e., soil and topography properties) or can change dynamically along the cycle according to water and nutrient availability or crop health. In most situations, the management zones are defined according to soil properties because of their stability. Soil properties, such as texture or depth, largely influence crop performance, although its determination is time-consuming and challenging. In the case of site-specific irrigation, the technique most widely used by practitioners to define field zones is the electromagnetic induction survey of soil apparent electrical conductivity ($EMI\text{-}EC_a$). In nonsaline soils, $EMI\text{-}EC_a$ varies primarily with soil texture, water content, and cation exchange capacity. Therefore, $EMI\text{-}EC_a$ maps are combined with soil sampling to determine those spatially variable soil properties efficiently. $EMI\text{-}EC_a$ mapping is usually complemented by topographic, yield, soil, and multispectral vegetation indices maps to delimit management zones. The canopy temperature of crops at the onset of water stress could be used to determine the spatial variability of the critical soil water deficit. If the crop is not watered after heavy rainfall or uniform irrigation, canopy temperature will increase first where the critical soil water deficit is the lowest.

Continuous monitoring of soil water content or soil water potential allows the introduction of real-time management decisions. The location of the sampling points may be based on *EMI-EC*$_a$ maps. Regarding plant-based measurements, the most widely used vegetation index is the *NDVI*, which is associated with radiation interception and, thus, with plant growth. It is of special interest when the management zones are designed for inputs, such as fertilizers, or planning harvest operations. The characteristics of the different sensors are discussed in Chap. 21. The development of robust wireless networks facilitates the installation of sensors in the field without interfering with cropping operations.

39.3.1 Yield Maps

Yield is the main measure of success in agricultural production and the main driver of the farmer's revenues. The within-field variability in yield results from the interactions between management, climate, and soil environment. When the source of variability is identified, we can redesign the management strategy. Because of the relevance of spatial yield patterns, the definition of management zones based on this parameter is the best strategy for implementing precision agriculture schemes.

In most cases, the analysis mainly focuses on spatial variability, but it is also important to consider the relevance of these variations in the resulting growth rates that may affect the pace of yield formation. This aspect might be particularly interesting for crops requiring multiple harvests for uniform and consistent maturity.

Yield maps can be derived from:

- Yield monitors installed in harvesters: Mainly developed for grain crops, the yield monitors have been available since the early years of the 1990s and can quantify yield in real time as the crop is harvested. The yield monitor is mounted on combine harvesters, usually placed near the grain tank, where the grain is stored after being separated from the straw.
- Empirical models that relate yield to remote sensing data like *NDVI* or thermal bands (Fig. 39.2). These models can be used before harvest but cannot be extrapolated to other regions.

39.4 Site-Specific Irrigation

Although the term *precise irrigation* usually refers to the application of precise amounts of water to crops at precise locations and at precise times—uniformly across the field—*precision irrigation*, as part of SSA, differs markedly from this general meaning. It refers to water application in a volume and at a time needed for

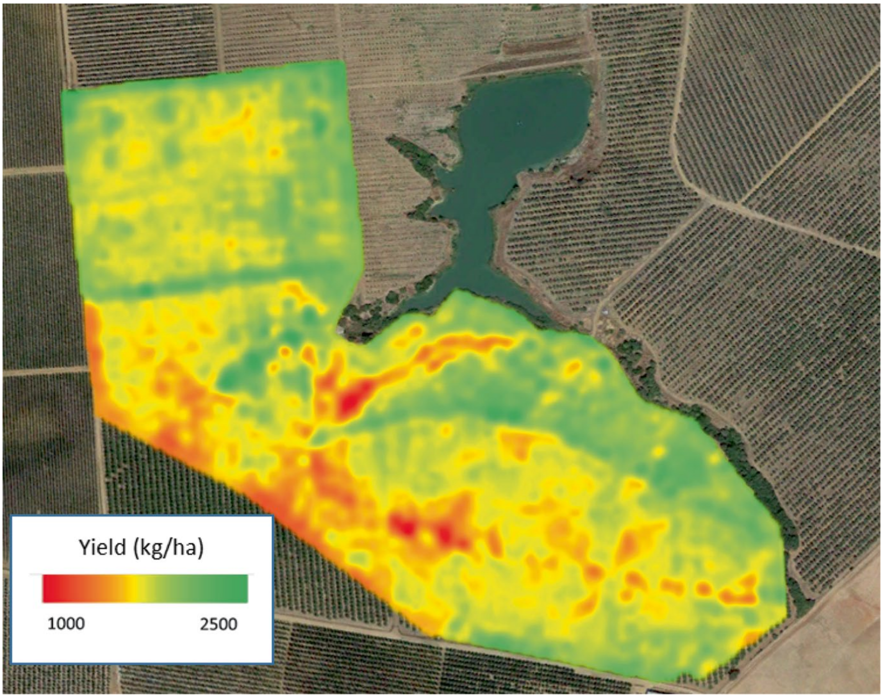

Fig. 39.2 Yield map in an almond orchard, derived from thermal and hyperspectral high-resolution imagery in Southern Spain

optimum crop production, or another management objective at each particular zone in the field. Soil texture and depth are naturally heterogeneous, and so are the physical characteristics associated with soil water retention and hydraulic conductivity. Exogenous factors, such as the nonuniform distribution of irrigation water or the compaction related to traffic, can also increase the spatial variability of vertical and lateral water flows within a field. Site-specific irrigation considers the overall effect of these aspects on the soil water balance to maximize irrigation water productivity.

39.4.1 Precision Irrigation Technology

Site-specific irrigation has been developed commercially for self-propelled center pivot and linear move irrigation systems. In contrast, site-specific micro-irrigation (drip/trickle, micro-sprinkler) has not yet emerged from academia or industry. Center pivot and linear move manufacturers have produced commercial equipment to regulate water application in time and space (variable rate irrigation). The irrigation machine is governed by a GPS controller, and the operator can enter irrigation prescriptions in the control panel directly or remotely. The prescription maps are based on field-distributed soil or crop sensors, which collect and transmit data that will be used to determine precisely the timing and amount of water applications. Thermal-based indices based on sensors installed on the pivot and a nearby weather station may also support real-time management decisions. More recent studies have focused on using remote information acquired using UAVs or satellites although the design of the prescription map from this information is not straightforward.

39.4.2 Opportunities Provided by Site-Specific Irrigation

The overall objective of site-specific irrigation strategies is to save water and optimize crop yield by avoiding losses and deficits of water. In practical terms, it is associated with the adjustment of water application according to local conditions. Site-specific variable rate irrigation (SS-VRI) adapted to irrigation machines allows stopping irrigation over roads, ponds, water courses, rocky outcrops, or any other landscape element that does not require irrigation. If various crops are grown under the same center pivot or linear move system, irrigation can be scheduled according to the needs of each crop.

Another case that may benefit from site-specific irrigation is if runoff occurs. It is more likely to happen in steep slopes, where soil infiltration capacity is low, and at the distal end of center pivots, where the application rate is highest. SS-VRI allows water to be applied at a reduced rate where infiltration should be increased to minimize runoff.

In very arid environments, rainfall contribution to soil water storage is usually negligible for irrigated crops. Under these circumstances, uniform irrigation designed to prevent surface flow will result in even soil water storage as long as irrigation is scheduled for the field zone where the critical soil water deficit (SWD_c; Chap. 20) is lowest. Therefore, site-specific irrigation does not help save water or improve yield in arid and semiarid environments. The situation is different in subhumid or Mediterranean environments in the spring where the contribution of rainfall to the irrigated crops' water consumption may be significant. Using SS-VRI, the irrigation depth can be adjusted to each zone by applying less water where the water storage is greater. The crop will keep utilizing the rainfall water storage, where available, so that total irrigation will be reduced.

The response of yield to evapotranspiration of most crops is a linear function (Chap. 14). If irrigation ensures the field does not suffer water scarcity, the yield would be maximal, and site-specific irrigation would not represent any yield advantage. However, some indeterminate crops and trees yield maximum under moderate deficit irrigation. Any deviation from optimal evapotranspiration for those crops will translate into yield loss. This deviation may be caused by variations in soil water storage due to nonuniform water application (rain, snow, or irrigation), variability of the soil water holding capacity, and lateral flow during or after the precipitation event.

Evapotranspiration differences may occur across the field due to differences in canopy cover. An appropriate way to estimate evapotranspiration for site-specific irrigation schedules is by computing spatially distributed crop coefficients based on multispectral vegetation indices related to the fraction of intercepted radiation as the *NDVI*. The so-derived evapotranspiration would account for the spatial variation of canopy cover and represent the non-stressed crop's water needs. The idea is only valid before the full canopy cover.

39.5 Site-Specific Nutrient Management

The excess of fertilizer has resulted in the degradation of the environment by surface and groundwater pollution and the greenhouse gas emissions of some nitrogenous compounds. Excessive nitrogen and phosphorus concentrations in water have led to the eutrophication of rivers and lakes in agricultural watersheds. Broadcast uniform application of fertilizer may lead to overfertilization in some areas, while others remain underfertilized (Fig. 39.1). Site-specific nutrient management aims to optimize crop nutrient use over space and time. Its successful application can increase yield and profit by providing optimum plant nutrition and reducing nutrient leaching and nitrous oxide emissions.

39.5.1 Nitrogen

Site-specific N management relies on the advanced technologies and data analysis characteristics of SSA, such as proximal sensors, remote sensing, variable rate machinery, and GPS mapping.

Proximal sensors acquire the measurement close to the crop canopy ($\approx$ 1m) and may be handheld or tractor-mounted. Most of them are active, meaning that they generate their own light at different wavelengths and have receptors that measure the reflectance of light. The wavelengths are mainly located in the far-red and the near-infrared regions to calculate an *NDVI*-like index, but some sensors incorporate also the near-green, a region strongly correlated with chlorophyll activity that allows the calculation of other indices. Tractor-mounted sensors linked to variable rate N fertilizer spreaders have shown a significant potential for site-specific N fertilizer application. The reading from the proximal sensor is transmitted in real time to the spreaders, and the application of an algorithm allows fitting N fertilization to the estimated requirements. Being active, these sensors can be used on cloudy days and are increasingly used by advanced farmers with technical expertise.

Remote sensing technologies such as airborne sensors and satellite imagery can be used to monitor crop growth and assess the crop's nutritional status. This information can be used to create prescription maps loaded on the variable rate spreaders and guide fertilizer application on a site-specific basis. Usually, prescription maps define several management zones within the field, and each zone receives a different N fertilizer rate. Most of the remote sensing to assess N crop status is based on collecting the canopy reflectance of sunlight. The sensors most commonly used are multispectral, and the measured wavelengths allow the calculations of a multiple set of indices related to crop N status. Satellites that provide multispectral imagery, like *Sentinel-2* or the *Landsat* family, are used to create prescription maps for N fertilization. Hyperspectral sensors mounted on aircraft have shown the potential to improve crop N status estimation but require large investments. Hyperspectral sensors are becoming more accessible, light equipment has recently appeared to mount on drones, and a new constellation of satellites (i.e., CHIME, Landsat Next) launched by the space agencies will become available in the next decade.

Remote sensors' reflectance imagery can be combined with additional information to improve the reliability of prescription maps (Fig. 39.3). Combination with yield maps from previous crop seasons has shown the potential to improve the definition of management zones. The N and water interaction may create a confounding effect on the fertilizer recommendation; therefore, combination with thermal imagery contributes to apply the fertilizer where water availability ensures that the crop takes up the N and avoid fertilizer application in field areas limited by water stress.

Most of the algorithms to adjust N fertilizer recommendations are based on the estimation of either the N nutritional status (i.e., NNI) or the yield potential. The decision algorithm follows either the "robin hood" or the "landlord" approach. The "robin hood" applies more N fertilizer in the sites where the crop shows an N deficit, and the goal is to avoid overfertilization and obtain a more homogeneous yield within the field. The "landlord" approach applies more fertilizer where the yield potential is higher, enhancing yield differences and seeking higher productivity. The equipment allows the user to choose the approach that better suits his goals.

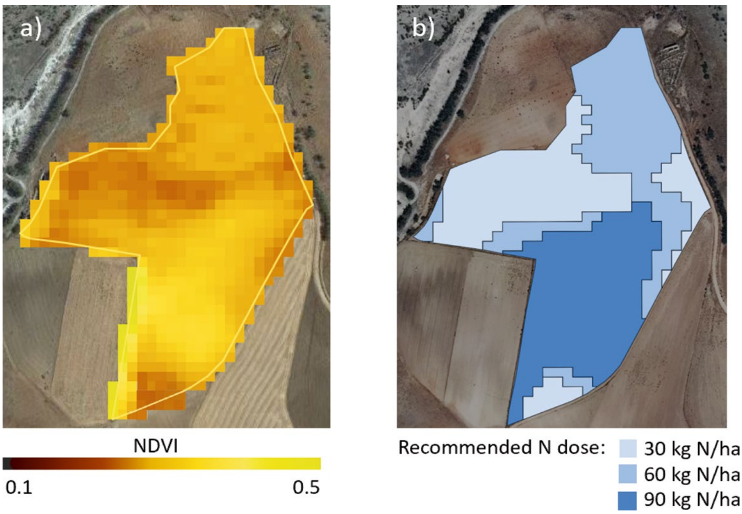

Fig. 39.3 (**a**) *NDVI* map for a wheat field (6 ha) at stem elongation, and (**b**) the prescription map for N fertilizer recommendation in which three management zones were calculated based on the *NDVI* map, a digital elevation map of the field and yield maps from previous years

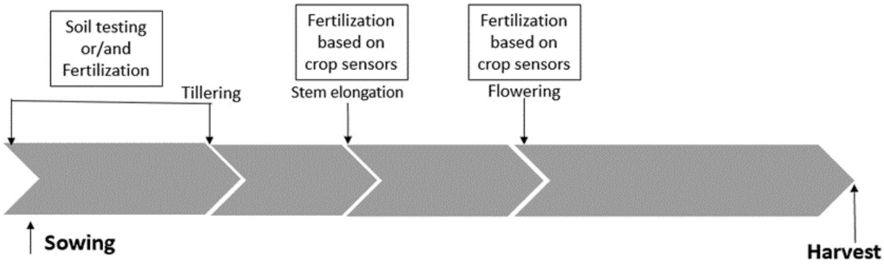

Fig. 39.4 Schematic timeline of the nitrogen fertilization program combined with crop sensor technology on wheat crop. Fertilization refers to nitrogen application at pre-sowing (first application) or as a top dressing in the second and third applications. (Adapted from Raya-Sereno et al. 2021. Remote Sens 13: 1373)

The application of spectral information is not efficient at the start of the growing cycle as the crops are too small to provide enough information at this stage. Combining conventional soil testing and crop sensors is the most promising strategy.

Practical fertilizer recommendations for wheat are a good example (Fig. 39.4). The first step is to determine the N requirements based on the expected yield. Then, the N fertilization is split into two or three applications. Despite the importance of N availability at tillering, we cannot use crop sensors to obtain a reliable assessment at this stage. The options are (1) apply 20% of N fertilizer before sowing, (2) apply 20% of N at the beginning of tillering, and (3) tailor this application based on a soil test at the beginning of tillering (not needed if topsoil inorganic N >40 kg N ha^{-1}). The next application at wheat stem elongation can be tailored with crop sensors, if possible including a reference strip in the field that is fertilized at the recommended rate. Sensor readings above 95% of that measured in the reference strip show the sites that will not respond to additional N. A similar rule may be applied to an eventual third application applied at flowering to enhance grain protein content.

The machinery first designed for variable rate application were spreaders for liquid fertilizers. Site-specific machinery for broadcasting solid granules and organic fertilizers, either in liquid or solid form, have been developed later. Overall, site-specific N management allows farmers to apply N fertilizer more efficiently based on the specific needs of different areas within a field but needs to be integrated with other agriculture practices to optimize crop production and resource use better while minimizing environmental impacts.

39.5.2 Other Nutrients

Top-dress applications are feasible for N but not for P and K. Also, P and K concentrations in the plant are not related to canopy reflectance which limits the potential of precision agriculture for those and other nonmobile nutrients.

Positive results have been obtained with the visible and near-infrared spectra (Vis-NIRs) in the lab, for the fast and simultaneous acquisition of data related to soil fertility, such as N, P, K, organic matter, carbonates, and clay content.

The only practical proposal for improving P and K with precision agriculture is to link the N application maps to variations in P and K to be applied as the total doses are directly related.

Regarding iron, chlorophyll deficiency may be detected using portable chlorophyll meters or multispectral remote cameras. However, chlorophyll content is not only related to iron but also affected by N, Mg, K, and other nutrient deficiencies, which limits its practical application. Thus, using chlorophyll-related spectral measures, mainly in the visible range, is practical when users have the security of having only one nutrient affecting the spectral traits of the crop. This explains why canopy spectral traits have been used more for nitrogen since it is usually the most limiting nutrient for crops.

39.6 Site-Specific Crop Protection

Site-specific crop protection (SSCP) aims to protect crops from pests, diseases, and weeds to avoid yield losses while minimizing the application of treatments. According to FAO, 20–40% of global crop production is lost due to pests and diseases. Disease control mainly relies on pesticide application. At the global scale, 2.7 Mt of active ingredients were used in 2020. Under conventional application, the product is applied when the biotic stressor density exceeds the economic threshold level (Chap. 33). As a result, the pesticide is broadcast at a uniform rate that may be insufficient in more affected areas and excessive in areas unaffected. Overusing pesticides might result in hazardous environmental impacts and residues in the products. Site-specific application of treatments according to the presence and severity of biotic stresses reduces the total application amount. In this case, the treatment is only applied where the biotic stress causes a reduction in yield that exceeds the economic threshold, avoiding the application in areas with low infestation levels. The optimized application of site-specific crop protection depends upon the rapid and accurate assessment of infested areas and the quantification of yield losses.

39.6.1 Site-Specific Weed Management

Conventional weeding methods are labor intensive and costly. They have been based on the uniform application of herbicides, which has led to an overuse of agricultural chemicals and the rise of environmental and public health concerns. These problems could be alleviated by considering the spatial distribution of weeds. Fields present weed-free zones where weed control is unnecessary, allowing a potential reduction in herbicide use and the possibility of optimizing the fuel consumption, field operating time, and cost of the weeding operations.

Site-specific weed management (SSWM) is a strategy that seeks to apply weed control treatments only in the areas where weeds are located, adapting the treatments to the variation in location, density, and composition of the weed population. SSWM is a cyclical process that can be divided into four steps: (1) weed detection, (2) design of the site-specific weed control treatment, (3) execution of the treatment, and (4) evaluation of the safety, environmental impact, and economic profitability of the treatment. Depending on whether weed detection and control are performed by different machines or the same equipment, SSWM can be carried out in a map-based or real-time approach. In the first one, weeds are detected and mapped by one equipment, then the weed control treatment is designed, and another machine performs the weed control operations. In the real-time approach, weed detection, decision-making, and control are carried out with the same equipment.

SSWM can be performed at three different levels according to its spatial resolution: (1) treatment of wide management zones or weed patches, (2) treatment adapted to a grid tailored to the weed control actuation unit (chemical or mechanical), and (3) treatment of individual weeds. The first level of spatial resolution is best suited to large stable weed patches, and the second one is well adapted to weeds growing in smaller patches distributed in the field. An SSWM map-based approach can address both levels of spatial resolution. The treatment of individual plants requires the use of ultrahigh resolution images usually acquired by on-ground platforms in real time.

39.6.1.1 Map-Based Approach

The data required to generate weed maps are usually acquired using remote sensing platforms. This avoids the need to circulate along the field, which, together with the optimization of routes for weed treatment applications achieved through the creation of weed treatment maps, helps reduce traffic and, consequently, soil compaction. The data for generating weed maps could also be obtained through proximal sensing using on-ground platforms, although this would increase the traffic on the field and, consequently, the fuel consumption.

The first works for weed mapping using remote sensing platforms were performed using traditional platforms such as satellites and airplanes. The relatively coarse spatial resolution of these platforms only allowed weed mapping in the late season when weeds and crops were fully grown. Late-season weed mapping was used to design SSWM treatments for subsequent years based on the relatively stable location of weed patches from one growing season to the following. Furthermore, late-season weed maps would also allow for estimating the location of the weed seedbank in the field. In most cases, weed control must be carried out in the early season when weeds and crops are in their first stages of development. Weed detection through remote sensing at these early growth stages has been possible only in recent years through the acquisition of ultrahigh spatial resolution imagery using Unmanned Aerial Vehicles (Fig. 39.5). Using images taken by UAVs and machine learning has allowed the mapping of weeds between and within the crop rows and to discriminate monocotyledons and dicotyledons. These achievements were not possible when working with satellite and airplane imagery.

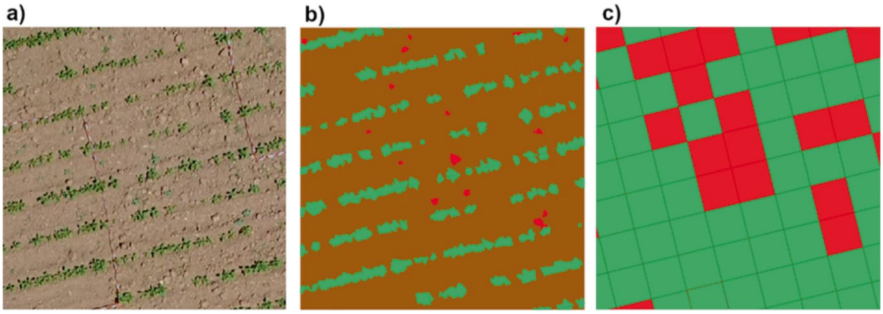

Fig. 39.5 Example of the generation of a weed treatment prescription map using UAV imagery: (**a**) detail of original UAV orthomosaic in the early stage of a sunflower crop; (**b**) image classification (brown for soil, green for crop, and red for weeds); (**c**) prescription map (areas to be treated appear in red)

Once the weed maps are created, the next step is the generation of weed treatment prescription maps. The map-based approach is associated with creating management zones or grids where a decision about weed removal treatments must be made. The presence of weeds in a management zone or grid does not automatically imply the need for control, which depends on the competitive ability of the weeds, the market value of the crop, and the cost of control. The weed density above which a treatment will be applied is known as the weed threshold. There are competitive and economic thresholds depending on the factor dominating the definition of the weed threshold. A competitive threshold refers to the level of weed infestation at which the crop begins to suffer significant negative impacts, such as reduced growth, yield, or quality. Economic thresholds are defined as the weed density whose control cost equals the benefit of controlling the weeds.

39.6.1.2 Real-Time Approaches

In real-time SSWM, a ground vehicle equipped with sensors performs the detection of weeds, the decision-making, and the control operations while circulating along the field at a constant speed. Using sensors near the ground allows the acquisition of images with even larger spatial resolution than the ones acquired by UAVs. The advances in precision robotics make possible the control of weeds at the plant level. These facts, in combination with the latest advances in deep learning image analysis that allow the identification of weed species, make it possible to adjust the treatment to the specificities of each species. For example, endangered or low-competitive species can be excluded from treatments, benefiting the biodiversity of the agroecosystem. On the other hand, weeds belonging to highly invasive species could be eradicated before creating a persistent seedbank.

Real-time approaches in SSWM can be performed in two different ways: by tractors equipped with the necessary technological implements or by fleets of small autonomous vehicles. The last option has advantages:

– Price: Farmers can purchase the equipment in an increasing manner.
– Fault tolerance: The failure of a small vehicle would only require the re-coordination of the remaining vehicles, whereas the failure of a tractor would stop the weeding operation.
– Safety: Small vehicles are safer for their own and the crop.
– Reduction of soil compaction

39.6.2 Site-Specific Pest and Disease Management

Site-specific pest and disease management (SSPDM) is not as developed as for the other domains described above. An aggregated spatial distribution (hot spots) of pests and diseases is typically found in the field. This pattern eases the implementation of SSPDM as clumped spatial patterns are especially suited for site-specific strategies. On the other hand, a clear-cut identification of affected zones is essential as untreated areas may serve as a refuge for susceptible pest populations and enhance resistance to pest management. Consequently, the level of risk perceived by growers may overcome the potential benefits of SSPDM. An alternative consists of combining SSPDM with a strategic broadcast application that can decrease the pest or disease prevalence in areas not targeted by the site-specific applications.

39.6.3 Weed, Pest, and Disease Control Operations in SSCP

Although mechanical weeding is possible in a map-based approach using techniques such as hoeing or flaming, weed, pest, and disease control operations in this SSCP form are usually based on pesticide spraying. Independent of chemical or mechanical weeding, the prescription map must consider the biotic stressor density and the machinery available to the farmer to execute the necessary operations. The spatial resolution of the prescription map must be in accordance with the ability of the farmer to execute it; for example, more complex spray maps can be applied with sprayers that have more nozzles across the boom and graduated control of each nozzle.

In real-time SSWM, control operations can also be carried out by mechanical or chemical means. The recent advances that allow the location and control of individual plants make the use of novel thermal technologies for weed control viable. Using lasers, electrical discharges, or microwaves was not economically viable in large-scale fields. Still, the ability to target these control measures to individual plants can make these techniques as resource-efficient as the application of herbicides.

In the case of pests and diseases, the spraying control can be adjusted to canopy density, considering that more dense canopies would require more product than sparse canopies. After the treatment application, the last step in the operations is monitoring the outcomes to assess the performance by the economic and environmental evaluation of the applications.

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Crop Models

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Abstract

Crop models are simplified mathematical representations of crop systems that can be classified as mechanistic or empirical. The former uses the scientific knowledge of the system behavior to propose mathematical equations for the crop response to the environment. The latter are not constrained by scientific principles and use regression or curve fitting to observational data to predict system outputs. Crop models have been extensively applied in agricultural research to help interpret experimental findings, separate casualty from causality, synthesize research understanding, facilitate the development of preliminary hypotheses, and optimize crop performance across environments. Beyond research applications, crop models have been used in decision-making. Decision Support Systems are computer software tools that integrate external information (soil, weather, sensors) with crop models to assist farmers, stakeholders, and policymakers in making informed decisions. Crop models have undergone continuous development since their inception in the 1960s. Starting in the 2000s, the integration of machine learning techniques into crop modelling has shown success, particularly in

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addressing identification and classification challenges within the mechanization of harvest and postharvest operations, as well as crop protection. Nevertheless, machine learning should be used with caution for yield prediction.

40.1 Introduction

A model is a simplified representation of a system. In agronomy, we commonly refer to crop simulation models, which are a set of mathematical equations that describe different processes like biomass accumulation, yield, and/or water and energy fluxes. In a broader sense, we use mathematical models as static, empirical relationships between an input (e.g., rainfall) and an output (e.g., yield). In this chapter, we will focus on *dynamic deterministic models* that track system behavior through time, making definite predictions (e.g., on July 1, the dry biomass of this potato crop will be 2000 kg/ha).

Crop models, as we conceive them today, appeared in the 1960s, thanks to the works by Cornelis Teunis de Wit at Wageningen University and Bob Loomis at UC Davis. Professor de Wit was a physicist who first proposed the use of physical and biological principles to model agricultural systems. Later, in the early 1970s, during the Cold War, knowledge of expected yields in the Soviet Union, China, and elsewhere became a strategic issue that boosted US public funding in crop models to predict wheat production worldwide using satellite data. The project, led by Joe T. Ritchie at the USDA, resulted in the family of *Ceres* models during the 1980s. At the same time, Jim Jones and colleagues developed the *Gro* models for legumes at U. Florida. Currently, we are experiencing a research networking explosion. The development of new open-source research communities, which freely exchange scripts through different platforms following the open-source rules, place crop model development in a new era.

40.2 Basic Concepts

Following the concepts developed in *Systems Science* during the 1950s, we can represent the crop using a set of state variables, like leaf or seed mass. We also need to define the equations describing the change of these state variables in time, i.e., the rates, as a function of other state variables or external inputs (environment, management). This formulation is based on our knowledge of the biological, chemical, and physical principles behind crop functioning. Then we will integrate numerically the equations of the system to predict the time course of the state variables. The integration that shows the time course of our system state variables is what we call a simulation. Therefore, a crop simulation model is a dynamic mathematical model that defines the state variables, the inputs, and the rates of the crop. It is, thus, a simplification of the system as it does not incorporate all possible processes in the crop. For instance, we have many crop models that respond to nitrogen nutrition but not to other nutrients.

The level of simplification—or model complexity—will vary depending on the model's purpose and the system's characteristics. As crop models are based on a reductionist approach, they will be wrong at some point. As the statistician G. P. Box said, "All models are wrong, but some are useful." Simplification, therefore, will frame model capabilities, preventing us from using it in situations where it does not hold. This idea should always be present when performing one of the key processes of model development, the validation.

Biological systems exhibit a hierarchical structure wherein each level of organization represents an aggregation of lower levels. For instance, cells combine to form tissues, which in turn make up organs, and ultimately these organs results in a plant. When formulating a model, it is crucial to consider the properties inherent to hierarchical systems. One of the most significant aspects is that each level possesses its distinct temporal and spatial scales. Consequently, one should limit the number of integrated levels in a model typically to two or three at most. For example, when modelling a plant, it is advisable to simulate organs (such as leaves and roots) or tissues at most, rather than attempting to integrate processes at lower scales, such as cells or organelles.

40.2.1 Model Formulation

The state of the system at a given time t can be defined by the value of its state variables. The state variables, define the characteristics of the system being modelled. For instance, state variables can be the dry matter of leaves or stems or the soil water content. The scope of the model is therefore defined by the state variables selected, as they will represent our system. Since we are dealing with dynamic systems, we can mathematically define them using first-order differential equations:

$$\frac{dX}{dt} = f\left(X, P, E\right) \tag{40.1}$$

In equation 40.1, the rate of change in the state variable X, is a function of the state variable itself, the parameters (P), and the explanatory or external variables (E). The parameters are constants in the rate functions. In mechanistic models, P should have a physiological meaning (like the specific leaf area or the radiation use efficiency). The E typically includes the value of the state variable at time zero, management inputs, and climate variables.

Usually, Eq. 40.1 can only be integrated numerically, which is frequently performed using Euler's method, i.e., assuming that the rate of change is constant during the time interval Δt:

$$X\left(t+\Delta t\right) = X\left(t\right) + \Delta t\, f\left(X\left(t\right), t\right) \tag{40.2}$$

Box 40.1: Construction of a Simple Biomass Accumulation Model

Let us consider an annual crop like wheat. We want to simulate how leaf biomass (W_l) (our state variable) will change throughout the growing season.

From Chap. 13, we know that the rate of change in crop biomass can be modelled using the fraction of light intercepted (f_i), the incoming par radiation (R_{sp}, $MJ_{PAR}\ m^{-2}day^{-1}$), and the radiation use efficiency (RUE, g/MJ_{PAR}):

$$\Delta B / \Delta t = RUE\ f_i\ R_{sp}$$

We can calculate the rate of increase in leaf biomass as:

$$\frac{\Delta W_l\left(t\right)}{\Delta t} = LPC \Delta B / \Delta t$$

where LPC is the Leaf Partitioning Coefficient, i.e., the fraction of total biomass invested in new leaf growth. Therefore,

$$\Delta W_l\left(t\right) / \Delta t = LPC\ RUE\ f_i\ R_{sp}\left(t\right)$$

In Chap. 3 (Eq. 3.14), we saw that f_i can be computed from the leaf area index (LAI, $m^2_{leaf}\ m^{-2}_{soil}$) and the extinction coefficient (k):

$$f_i = 1 - e^{-k\,LAI}$$

LAI is related to leaf biomass (W_l) at time t by:

$$LAI = W_l\left(t\right) SLA$$

where SLA is the specific leaf area (m^2/g).

We will calculate the increase in leaf biomass each day as:

$$\frac{\Delta W_l\left(t\right)}{\Delta t} = LPC\ RUE\left(1 - e^{-k\,W_l(t) SLA}\right) R_{sp}\left(t\right)$$

Note that the rate is calculated as a function of one state variable (W_l) at time t, four parameters (LPC, RUE, k, SLA), and one external variable (R_{sp}).

Once the rate of change of the state variable is calculated, we will update its value following the procedure depicted in Eq 40.2:

$$W_l\left(t + \Delta t\right) = W_l\left(t\right) + \Delta W_l\left(t\right)$$

40.2.2 Calibration and Validation

The calibration and validation processes are fundamental pieces of model development. Model calibration involves determining the model parameters. In mechanistic models, these parameters have a biophysical significance, making it possible to measure directly some of them. For instance, the specific leaf area (see Box 40.1) can be determined as the ratio of leaf area and dry mass from a leaf sample. Ideally, we should measure all the parameters. However, in many cases, it becomes impractical or costly to do so. Consequently, calibration is performed using optimization algorithms, which seek parameter values that minimize the discrepancy between the simulated and observed data.

Various optimization procedures are available. For "simple" models with less than 10 parameters, multiple alternatives exist (e.g., *Simplex*, *Complex*). For instance, within the *DSSAT* package, cultivar parameters can be calibrated using *GenCalc*, which employs a gradient search method. However, models with more than 10 parameters need more robust tools like global optimization algorithms, which systematically vary parameter values according to specific criteria to identify a global minimum. An example of a global optimization tool is *GLUE* (Generalized Likelihood Uncertainty Estimation), also included in DSSAT. It is important to note that numerical methods carry the risk that a combination of incorrect parameters may yield correct model results. This risk is proportional to the number of parameters being calibrated, underscoring the need for caution when employing numerical calibration methods.

As previously mentioned, crop models offers a simplified view of the systems they aim to simulate. The "art" of modelling, therefore, lies in the ability to simplify without compromising the model's capacity to represent the system. Simplifications will be driven by model objectives. For instance, a researcher aiming to analyze potential yields of a specific crop in diverse environments may not consider the equations that describe the effects of water or nitrogen deficits. Hence, simplifications should remain a focal point during the validation process.

Validation for model accuracy has been widely described in the scientific literature. The idea is to compare observation data (independent of those used in the calibration) with model simulations to test, through different statistical indicators, if the model correctly represents the observations. Some examples of statistical indexes are presented in Table 40.1.

Model validation should not be overrated for different reasons:

– Scientific principles: A model is a set of hypotheses on crop functioning. The basis of hypothesis testing is rejection based on experiments. In other words, the only valid test of a model is showing that it is not valid in a given situation. Unfortunately, most literature on crop models shows instances where the model is right, which is of little help for users, as one cannot be sure that the model will also be right if used in different conditions.
– Data quality and completeness: On most occasions, validation is performed with data from experiments not specifically designed for that purpose. Hence, some key input variables may be missing and are estimated, which preconditions the results of the validation. On the other hand, agricultural experiments are prone to large errors which may be systematic (e.g., incidence of a pest or disease, poor experimental design) or random (soil variability).
– Independence of validation and calibration data: Yield data obtained in different years in the same farm with the same management may be divided into a calibration and a validation set. Are they truly independent? For a statistician, yes. For

Table 40.1 Examples of statistical indexes

Name	Equation
Non-normalized indexes	
Mean Squared Error (*MSE*)	$MSE = \frac{1}{n}\sum_{i=1}^{n}\left(O_i - S_i\right)^2$
Root Mean Squared Error (*RMSE*)	$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(O_i - S_i\right)^2}$
Mean Absolute Error (*MAE*)	$MAE = \frac{1}{n}\sum_{i=1}^{n}\left\lvert O_i - S_i\right\rvert$
Normalized indexes	
Efficiency factor (*EF*)	$EF = 1 - \frac{\sum_{i=1}^{n}\left(O_i - S_i\right)^2}{\sum_{i=1}^{n}\left(O_i - \overline{S}\right)^2}$
Willmot index (*d*)	$d = 1 - \frac{\sum_{i=1}^{n}\left(O_i - S_i\right)^2}{\sum_{i=1}^{n}\left(\left\lvert S_i - \overline{S}\right\rvert + \left\lvert O_i - \overline{S}\right\rvert\right)^2}$

S_i = the i_{th} simulated value
S = the simulation average
O_i = the i_{th} observed (measured) value
n = the total number of values

an agronomist interested in applying the model in other sites with different environmental conditions, probably not.

Rather than solely relying on straightforward observed-predicted comparisons, model testing should encompass sensitivity analysis and response studies. The former assesses the model outputs' sensitivity to variations in inputs or parameters, while the latter examines whether the model's reactions to gradual alterations in a specific input (such as irrigation) align with the expected responses or not.

Box 40.2: Hypothesis Testing and Model Validation

During model validation, we will need to plot predictions against observation. The null hypothesis we want to test is that model predictions are equal to observations, i.e., H_0: slope = 1.

We first test for the regression Y = observed, X = predicted. We will reject the hypothesis if the confidence interval does not include 1. Otherwise, **we do not reject the hypothesis; thus, it can be tested further.** Now we will fit the regression Y=predicted, X=observed. The null hypothesis of this second test is also that the slope is equal to 1. If the confidence interval now does not include 1, then we

(continued)

Box 40.2 (continued)

will reject the hypothesis that model predictions are equal to observations, even if the preliminary test (*Y*=observed, *X*=predicted) did not allow rejecting the hypothesis.

In summary, it is important to recognize that hypothesis testing is designed to reject rather than confirm. If either the first or the second test results in rejection, the model is statistically different from the observed data. It is crucial to emphasize that model validation does not aim to prove for model correctness but to identify potential flaws or discrepancies. It should serve as a means of demonstrating the presence of errors rather than confirming models' accuracy.

40.2.3 The Need for Models in Agriculture

Agriculture is a unique field characterized by a combination of traditional wisdom, trial and error, and scientific knowledge. The former represents the conventional routine where practices are employed based on their known effectiveness. Conversely, scientific knowledge offers a rationale to explore if a different routine will perform better or to provide alternatives when our agroecosystem changes.

Traditionally, agricultural research has relied on field experiments, involving the comparison of crops under contrasting conditions, and applying statistical techniques to interpret the resulting data. However, this approach is not only resource-intensive but also time-consuming. Additionally, statistical techniques alone fail to differentiate between causal and casual relationships. To overcome these challenges, models emerged as invaluable research tools. They aid in interpreting experimental findings, synthesizing research understanding, and facilitating the development of preliminary hypotheses, ultimately saving time and resources in experimental design.

One of the most successful uses of crop models in agricultural research has involved optimizing crop performance in diverse environments. A good example is the research conducted by Kirkegaard et al. (2014. Crop Pasture Sci 65:583–601) in Australia. The authors involved research groups from diverse areas of expertise to propose and evaluate novel management strategies aimed at improving rainfed wheat water-use efficiency (*WUE*) by 10% across Southern Australia where annual rainfall ranges from 300 to 700 mm. Simulation studies provided initial insights that were subsequently validated through experimental trials. The authors demonstrated that the inclusion of break crops or the earlier sowing of appropriate varieties, among other strategies, could result in *WUE* surpassing the initial 10% target.

During the last decades, concerns about climate change and food security have boosted the integration of crop models into agronomy research. While global and regional circulation models have been employed to project climate trends, it is essential to interpret this information in terms of its impact on crop responses to the environment. For example, Asseng et al. (2015. Nature Clim Change 5:143–147) showed that global wheat production is projected to decline by 6% for each degree

Celsius of temperature rise, primarily due to a shortened growing period. Crop models possess the capability to process this data and to separate the contributions from different climate variables. Such distinction is vital in proposing effective adaptation and mitigation strategies.

40.3 Classification of Crop Models

Since crop models are developed for different purposes and crops, modelling approaches can vary widely in complexity, input requirements, robustness, and accuracy. Hence, we must be very careful in selecting the right model for the task at hand. We will focus on dynamic deterministic models, i.e., not including a probabilistic distribution as stochastic models do. Therefore, for a single input, we will obtain a single and specific output. Crop models may be classified according to different criteria, but in this section, we will focus on the distinction between models that are not directly constrained by scientific principles or any knowledge of the system mechanisms (empirical models) and those that are concerned with the structure of the simulated system (mechanistic models).

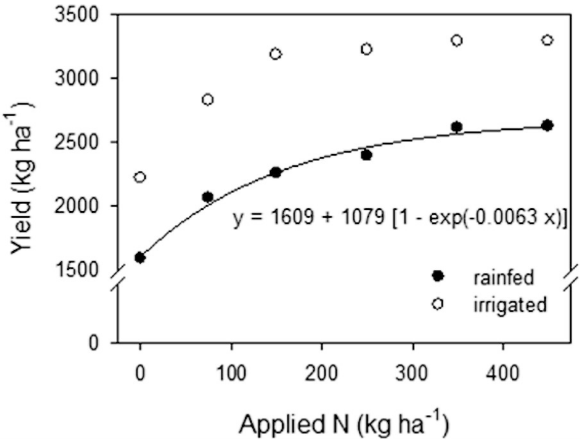
40.3.1 Empirical Models

Empirical (also called *statistical*) models relate the output of a system to a set of environmental or management input variables providing no information on how the system works. The lack of an explicit description of the cause-effect relation between inputs and outputs has led to the name of *black box* models. Nonetheless, empirical models can be extremely useful for many practical applications and have been widely used in agricultural research.

The formulation and calibration of empirical models stems from empirical data and often involves defining the equation or set of equations that best fit experimental results. Figure 40.1 gives a simple example. Black circles show observed yield responses of a rainfed sunflower crop to the level of N applied with fertilization. The function that best fits the data is also depicted. The fitted curve represents an empirical model that predicts crop yield as a function of the N fertilization level. Note that the model (fitted equation) does not provide any new information beyond the original data per se or give insight into why the yield response to the application of N is as it is. Yet, the model may still be useful to estimate the expected yield from a given amount of N applied under rainfed conditions.

The example above illustrates that empirical models are potentially very accurate, which explains their success in agricultural research. However, they face important limitations when applied to conditions differing from those used for model calibration. This is also illustrated in Fig. 40.1. White circles show yield responses to N fertilization taken from the same experimental site and year under irrigated conditions. In this case, the fitted curve (solid line) for rainfed conditions is useless for describing crop responses to N under irrigation as both N and water

Fig. 40.1 A simple empirical model of crop yield response to N applied fitted to data for rainfed conditions (black circles). The model is unable to capture crop responses to N application in the same experiments if the crop is irrigated (white circles)



were co-limiting crop yield in the original set. This model, therefore, would fail to reproduce yield responses for seasons or sites with contrasting rainfall regimes to those prevailing in the original experiment. Moreover, the response of yield to N applied may be affected by additional factors (e.g., differences in the initial inorganic N in the soil) (see Chap. 26). Empirical models can be powerful tools in agronomy but should not be extrapolated to different environmental or management contexts than those considered in the calibration stage.

40.3.2 Mechanistic Crop Models

Mechanistic crop models are commonly known as process-based models since they incorporate our current understanding of how specific processes function. One of the main characteristics of mechanistic crop models is that parameters and variables should have a biophysical meaning. As mechanistic models are complex, they require more input data and rely on many assumptions when the body of knowledge is limited, so they can be less effective than empirical models in predicting actual data. However, given their ability to show the dynamics of the system and the interactions between its components using biophysical equations, they can be applied in conditions differing from those considered during their development. Furthermore, these features make them suitable for addressing the performance of crops under nonexisting scenarios (see Sect. 40.2.3).

The number and diversity of mechanistic crop models available nowadays are huge, but most share several structural features. The simulation of plant development is typically independent of other model components and based on the concept of thermal time. Accordingly, genotype-specific thermal time thresholds are usually defined for triggering transitions from a given phenological stage to the following. In addition, exposure to low temperatures and day length intervals are also considered at certain stages in models dealing with crops or genotypes with photoperiod or vernalization requirements.

Historically, the two main schools of thought in crop modelling have been:

(a) *Wageningen-type or photosynthesis-driven models*: Inspired by pioneering work by de Wit and colleagues in the 1960s, models in this category estimate biomass production from the balance of gross assimilation and respiration; the latter usually split into maintenance and growth components. The simulation of gross photosynthesis requires a detailed characterization of plant morphological and physiological traits. Examples of models in this family include *ORYZA* (for rice) and *WOFOST*, a universal model (i.e., valid for any crop species).
(b) *Radiation-use efficiency models*: These models estimate biomass accumulation from the product of radiation interception and radiation use efficiency. The first models within this group (*Ceres* family) were developed by Joe T. Ritchie and colleagues in the 1980s and 1990s in the United States and most of them are species specific (i.e., valid for a single species). This family is included in the DSSAT package along with the *Gro* family of models (e.g., *Soygro* for soybean) that includes also a photosynthesis submodel.

Today, we have a wide range of approaches and combinations of submodels. For instance, *OliveCan*, the model of olive orchards, combines photosynthesis and stomatal conductance models, making OliveCan sensitive to changes in CO_2 concentration.

One key aspect in crop model formulation is how the impact of stresses is accounted for. Each model considers a different set of abiotic or biotic stresses, and we may even find some models that disregard all of them, just being useful for assessing crop potential growth. As water and N deficiency represent the major limiting factors for crop growth, these are the abiotic stresses accounted for by most crop models. Simulating the impact of limited water or N uptake requires modelling the main water fluxes within the soil-crop system (infiltration, percolation, evapotranspiration, irrigation, etc.) and N transformations and fluxes in the soil (mineralization, nitrification, denitrification, and leaching).

Most existing crop models have been built for annual species while only a few have been developed for fruit trees (e.g., *OliveCan*; Lopez-Bernal et al. 2018. Frontiers Plant Sci. 9:632) because of the lower relevance, the larger complexity, and the scarcity of good data sets for calibration and validation. Access to crop models is becoming increasingly easier as many are freely available, along with online manuals and video tutorials. Models may be integrated into packages like DSSAT, which allows sharing of some components and the same graphical user interface (Table 40.2).

Table 40.2 Summary of main features of empirical and mechanistic models

Feature	Empirical models	Mechanistic models
Comprehension of the system	None	High
Based on biophysical principles	No	Yes
Time-dependency	No	Yes
Complexity	Low	High
Input/calibration requirements	Low	High
Predictive power	High (within the calibration range)	Low to medium
Universality	Low	Medium to high
Utility as research tool	Low	High

40.4 Machine Learning

Machine learning (ML) includes different mathematical techniques used for fitting empirical models for prediction and decision-making using qualitative and/or quantitative data. ML was first applied to identification problems, which led to the development of Artificial Neural Networks (ANN). Later, ANNs and decision trees were used for regression problems.

Applications of ML in agronomy have thrived since the 2000s. ANNs have been used successfully for identification and classification problems in mechanization of harvest and postharvest operations and crop protection. ANNs have been also widely used in regression problems as a more flexible alternative than Linear Models (LM) for fitting empirical quantitative models. A single hidden layer ANN with enough cells can fit any continuous mathematical function within a given interval. However, ML algorithms should be used with caution for yield prediction for several reasons:

– Conditions in the farm or the agricultural system change very rapidly so we cannot obtain enough data for fitting the model.
– Testing of the models requires separate data sets with different requirements depending on the objective of the model. Random partitioning of data for training and testing leads to underestimating model errors as compared to time-dependent partition. Only when we want the model for past predictions (see Box 40.3) the random partitioning is valid. However, for applying the model to future data or different areas, validation should be conducted in separate locations and in later years than those used during calibration.

Finally, it is important to bear in mind when using ML algorithms for yield prediction that Random Forests are usually better than ANNs as they will always be at least as good as the best guess estimate (average of the farm yield on past data).

Box 40.3: Predicting the Past or the Future

The term "prediction" has a dual meaning. In statistics, prediction is a part of statistical inference: We fit a statistical model to a data set and use the model to estimate (predict) values of the dependent variable. Therefore, we can use the model to predict something that happened in the past. For instance, we may want to check if the yield data declared by farmers is true. We could build an empirical model of yield as a function of fertilizer and water applied in the farms of a given region. Then we would use the model to detect if yield data of each farm departs from the general model. We make predictions on a system as it was at a moment in time. On the other hand, in many sectors, including agriculture, we are interested in forecasting yields. Market regulations, stock management, planning of purchases of inputs, all benefit from the availability of yield forecasts. We can do that using models, but model testing should be stricter than when predicting the past.

40.5 Decision Support Systems in Agriculture

Decision Support Systems (DSSs) are computer software tools that integrates external information and crop models to aid farmers and agricultural stakeholders in making informed decisions. By leveraging data from various sources such as weather stations, soil characteristic, crop management, and market trends, DSSs provide real-time insights and recommendations for optimizing agricultural practices.

Some examples of free DSSs software include DSSAT (https://dssat.net/) and *FertiliCalc* (https://www.uco.es/fitotecnia/fertilicalc.html). The latter is a free DSS for N, P, and K fertilizer requirement calculation. It offers versions for Windows, Android, and iOS. On the other hand, DSSAT (Decision Support System for Agrotechnology Transfer) comprises simulation models for over 42 crops, including those within the *CERES* family (for the main cereal crops), the *GRO* family (for legumes), and other models like *OilcropSun*, for sunflower (Villalobos et al. 1996. 88(3):403–415). DSSAT has been used for the last 35 years by researchers and stakeholders worldwide for different purposes like on-farm and precision management, regional assessments of the impact of climate variability and climate change, gene-based modelling, and breeding selection, among others.

One of the primary strengths of DSSs lies in their capability to analyze intricate data sets and generate meaningful recommendations. While the advent of personal computers promoted the utilization of DSSs, the smartphones and the Internet of Things (IoT) have been a complete game-changer by providing widespread network connectivity and enhanced computing power. Furthermore, the emergence of satellite programs such as Copernicus and Landsat have resulted in an unprecedented availability of data for informed decision-making in agriculture. DSSs has open a new era of data-driven decision-making. By evaluating the impact of various factors on crop yields, disease prevalence, pest control, and resource allocation, DSSs empower farmers to tailor their actions to the specific characteristics of their fields. Consequently, they can optimize irrigation, fertilization, and pesticide application, minimizing environmental impact and promoting the efficient use of resources.

The combination of real-time data with forecasts facilitates proactive decision-making by providing early warning systems and risk assessments. By monitoring weather conditions, soil moisture, and pest populations, DSSs can alert farmers in advance. This enables timely interventions, such as adjusting irrigation schedules, applying targeted pesticides, or implementing preventive measures, minimizing yield losses, and reducing the environmental impact of farming practices. Finally, DSSs foster a deeper understanding of the intricate interplay between variables, enabling farmers and policymakers to make informed decisions to enhance productivity and sustainability. However, several challenges remain. One key factor is the need for user-friendly applications. Farmers are often reluctant to invest significant time and effort in learning how to navigate complex DSSs unless the benefits are readily apparent. Therefore, the development of novel DSS applications should prioritize usability and intuitive interfaces to ensure farmer acceptance and engagement. Another area that requires improvement is the inclusion of historical information analysis within DSSs. Many current DSSs lack the capability to employ effectively historical data. Incorporating such analyses can provide valuable insights for farmers and policymakers to identify changes in trends and develop innovative strategies. Despite these challenges, DSSs hold immense potential for revolutionizing agriculture by harnessing the power of data analysis and modelling.

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Climate Change Adaptation and Mitigation

41

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Abstract

Earth's climate projections for the next decades raise concerns about the impacts on agricultural productivity and food security. Agricultural research is called to adapt crops and their management to the changing conditions although experimental work is difficult and expensive so crop models are needed. Higher temperatures will alter crop phenology shortening developmental phenophases; thus, different managements and targeted cultivars will be needed. On the other hand, new areas may become suitable for agriculture. In many cases, temperate tree crops will need new cultivars with lower chilling requirements or will move to colder locations. On the other hand, the higher CO_2 concentration will boost Gross Primary Productivity, especially in C3 crops, and increase the water use efficiency, thus offsetting (at least partially) the negative impacts (higher water use, shorter cycles). Agriculture should also contribute to climate change mitigation although its real potential is still a matter of debate. Conservation agriculture aiming to enlarge the soil carbon pool and management options to reduce carbon emissions are the best options to ensure that farms are carbon sinks. Globally, intensive agriculture has more CO_2 mitigation potential than extensive, low-input alternatives that would require more land for food production at the expense of forests.

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41.1 Introduction

Embedded in the climate variability that agriculture has experienced since its invention, there is now a consensus that the climate is warming as CO_2 concentration increases due to human activities (burning fossil fuels, deforestation). The average temperature of the Earth has increased by about 0.8 °C since 1880, while the magnitude of future warming is uncertain depending on the future scenarios of CO_2 emissions and the Global Circulation Models used to project the climate. Current models predict a temperature increase of 1–4 °C with CO_2 concentrations in the atmosphere between 500 and 700 ppm by the end of this century.

Although changes in Earth's climate did happen many times—some of them already during the agricultural era—it seems clear today that the actual climate deviation is happening at an unprecedented rate, and its origin is anthropic. This acknowledgment raises serious concerns about the impacts we should expect in crop productivity under the future climate and adds uncertainty to the already strained expectations of world food security for the 10 billion population expected by the end of the twenty-first century.

Research on the response of crops to climate change (CC) is hindered by substantial experimental limitations as it is mainly limited to strictly controlled environments. Except for a few high-budget experiments, the costs and difficulty of maintaining crops in the open under an altered microclimate make field trials impracticable. Therefore, the impact of this global change on agriculture has been studied mainly using crop simulation models (Chap. 40). Crop models often predict a general decrease in agricultural productivity, mainly caused by phenological mismatches with the new climate and increased crop evapotranspiration. However, most studies have not fully considered the effects of the elevated atmospheric CO_2 concentration on photosynthesis. Higher CO_2 leads to lower canopy conductance (therefore reduced water use) and will increase photosynthesis in C3 plants, the majority of crops. Simulations with advanced climate and crop models suggest that the overall result of these contrasting effects may either enhance or decrease productivity in the future, depending on the crop and site.

41.2 The Carbon Cycle

The carbon cycle is among the most complex biogeochemical cycles on Earth. The largest C pool is stored in carbonate rocks like limestone. The rest is in the ocean, atmosphere, plants, soil, and fossil fuels (Table 41.1).

The fluxes between these pools occur at very different rates: it takes millions of years to move C in or out of the lithosphere and deep ocean pools and to form fossil fuels, whereas the interactions between the biosphere and atmosphere are much faster. The latter C pool has increased from 580 to 800 Gt in the last 300 years only, due to burning fossil fuels, the main anthropogenic emission.

Things are somewhat simpler at the scale of an agricultural field or any natural vegetated surface. Here, we may simplify the cycle to three pools: atmosphere,

Table 41.1 Main carbon pools on Earth

Pool	Gt C
Lithosphere	$65–100 \cdot 10^6$
Ocean	$35–40 \cdot 10^3$ (97% in deep sediments)
Soil	$1.5–2.0 \cdot 10^3$
Biosphere	500–650 (83% in plants)
Atmosphere	800
Fossil fuels	$10 \cdot 10^3$

plants, and soil. Photosynthesis removes carbon from the atmosphere; the respiration of the plant returns part of it, and the rest is stored in the crops' living biomass. At harvest, part of the biomass is exported as yield (thus, it will return to the atmosphere in some other place, in months or very few years, depending on the product life cycle); the rest are residues, part above and part belowground. The carbon stored in the aboveground residues may return immediately to the atmosphere if burned. Otherwise, part of it will eventually enter the soil pool where it will serve together with the dead roots of the crop as an energy source for microorganisms (heterotrophic respiration), thus returning over time to the atmosphere. The rate of heterotrophic respiration depends on soil management, soil water content, and temperature. The biomass C pool of field crops increases substantially during the growing season, whereas the soil organic carbon changes slowly.

The carbon exchange with the atmosphere of an agricultural field (Net Ecosystem Exchange, NEE) depends on the net balance between two opposite fluxes: the Gross Primary Productivity (GPP), the C extracted from the atmosphere by photosynthesis, and the Ecosystem Respiration (R_{eco}), the sum of C released from the respiration of living organisms. The latter may be plants (autotrophic respiration) or microorganisms in the litter and soil (heterotrophic respiration).

$$\mathrm{NEE} = \mathrm{GPP} - R_{eco} = \mathrm{GPP} - R_{auto} - R_{het} \tag{41.1}$$

The continuous variation of NEE can be measured with advanced instrumentation (Eddy Covariance, Chap. 9). GPP is nil at night (thus NEE = − R_{eco}), and the field is a net C source to the atmosphere. Crops are C sinks when actively growing (GPP roughly scales with *LAI* or canopy ground cover) and net C sources when the soil is bare or during the cold season. The C balance of a field is influenced by the climate and the interannual meteorological variability; therefore, the assessment of the C balance of a crop or a cropping system needs many years of experiments or simulation. When NEE is integrated over time, we have *NPP* (Net Primary Productivity). A positive *NPP* means that the sum of C pools of the soil and the plants is increasing so the field is a C sink. The carbon balance can be manipulated by agricultural management. Irrigation and fertilization increase GPP, while soil conservation practices (Chap. 18 and Sect. 41.6.1 below) tend to reduce R_{het} fluxes.

An agricultural field also emits carbon of exogenous origin to power machinery and other agricultural operations such as irrigation. Additional C emissions will occur off-farm in manufacturing equipment and materials used in agriculture (Chap. 37).

41.3 Main Effects of Climate Change on Crop Production

The two changes that have been documented are the increase in air temperature and CO_2 concentration, which has gone from 360 to 420 ppm in the 2000–2023 period. Warming implies higher evaporation and presumably more precipitation at the global scale. Another prediction, not proven statistically, is the increase in the frequency of extreme events, such as droughts or floods. Agricultural productivity is determined by the weather experienced in a particular season and location. How the global changes would be translated locally is a question that cannot be answered at this time although models at the regional scale are being built to downscale global predictions.

The temperature increase affects crop growth and development in different ways. If low temperatures limit productivity, as in the northern latitudes, crop growth rates would increase in response to the higher temperatures. On the contrary, in the lower latitudes, where air temperature does not limit growth, a temperature increase would increase respiration, resulting in a lower crop growth rate. Furthermore, high temperature extremes may affect certain processes, such as pollination, reducing the Harvest Index (Chap. 15). Higher temperatures hasten crop development, which shortens developmental phases, leading to lower biomass production (Chaps. 11 and 13). The warming already experienced has had measurable effects on plant phenology all over the planet as documented by botanical gardens and other institutions. For instance, the peak cherry blossom date in Kyoto, Japan, has advanced about 10–15 days on average over the last 50 years. The effects of rising air temperatures would vary depending on the crop and location. In the high latitudes (Northern Canada, Russia), where low temperatures currently limit production, a crop such as wheat would have higher yields under CC. On the contrary, in warm areas (e.g., Sudan), wheat would have a shorter growing season and lower productivity. In extreme cases, there would be crop substitutions; for example, wheat would be introduced in areas where only rye or barley are grown because the environment is currently too cold with a high risk of frost damage in wheat.

Another cropping system under risk is the grapevine for wine production. Currently, grapes are produced in a wide variety of climates in both hemispheres, but increasing temperatures may have different effects. In addition to the advancing harvest date, there will be effects on grape composition, primarily in sugars and acidity, but also on polyphenols, aromas, and other compounds influencing wine quality. It is anticipated that wine quality will decline in warmer areas with high nighttime temperatures, while areas previously considered too cold to grow wine grapes are now going into production. The huge diversity in grape cultivars and wine types demands specific studies to delineate the optimal environments for future production of the different wines.

The effects of CC on rainfall amount and distribution are uncertain because of the limitations of the current regional hydrologic models. Higher evaporation is predicted under CC due to the influence of temperature in the Penman-Monteith equation that computes the reference *ET* (ET_0; Chap. 10). However, higher ET_0 does not imply higher transpiration because the increase in CO_2 induces partial stomatal closure, which partly offsets the increase in transpiration. The impact of stomatal closure due to elevated CO_2 varies depending on the degree of coupling of the canopy to the atmosphere. In general, transpiration will change little in smooth, short canopies and may decrease in tall, rough canopies such as trees and vines.

While most opinions predict negative consequences for crop production under CC, the increase in CO_2 concentration will enhance photosynthesis and therefore crop productivity although the effect is stronger in C3 than in C4 crops. The responses to CO_2 at the crop level have been experimentally assessed with open-top chambers or with a carbon enrichment technique named FACE (Free Air CO_2 Enrichment). The growth stimulation by CO_2 has been generally higher in open chamber experiments than in FACE experiments that are considered more representative of the effects of CC under field conditions.

41.4 GHG Emissions from Food Production

The capacity of a gas to produce greenhouse heating is named Global Warming Potential (*GWP*) and is expressed as the ratio with the warming potential of CO_2. GHG emissions are then quantified in terms of mass of CO_2 equivalents, independent of the gaseous species emitted.

Agricultural systems generate around 12.2 Gt CO_2 eq/year (not including 5.0 due to land use change). The GHGs emitted are CO_2 (5.4 Gt CO_2 eq/year), methane (4.7 Gt CO_2 eq/year), and N_2O (2.1 Gt CO_2 eq/year).

Energy use on the farm (fuel and electricity for agricultural machinery and irrigation) is responsible for 0.17 Gt CO_2 eq/year while fertilizer production and transport generate 0.67 Gt CO_2 eq/year.

N_2O is the most harmful of the naturally produced greenhouse gases. It has *GWP* = 273 and a lifetime in the atmosphere longer than 100 years. N_2O is emitted mostly by denitrification in saturated soils (Chap. 26). The process is favored in pastures with direct grazing and when organic fertilizers are used.

Methane has a *GWP* of 81 and slightly more than 10 years of lifetime in the atmosphere. Methane emissions from agriculture are generated by the enteric fermentation of ruminants, manure management, rice cultivation, and burning of residues. Enteric fermentation alone generates 3.2 Gt CO_2 eq/year. The first two sources of methane (enteric fermentation and manure management) are linked to the inclusion of animal protein in human diets. However, ruminants have been the only chance to exploit numerous ecosystems where limiting factors preclude growing food crops (dry savannah, cold deserts, waterlogged soils). Soils may capture a large proportion of methane emissions, but their capacity is reduced when cultivated.

41.5 Crop Adaptation to Climate Change

41.5.1 Annual Crops

The two main phenomena associated with global change, higher atmospheric CO_2 concentration and higher air temperature, require different adaptation approaches.

The increase in CO_2 may improve crop photosynthesis, mainly in C3 crops. However, this increase is limited by other factors, especially the availability of photosynthetic enzymes (*Rubisco*) in the leaves. Furthermore, the yield increase may be lower than the increases in biomass because of limitations in reproductive growth; in other words, the Harvest Index may suffer reductions, which are difficult to predict. Higher temperatures may partly offset the advantages of high CO_2 as heat events will eventually reduce the Harvest Index.

The adaptation of annual crops may come from adopting new cultivars and changing agronomic practices. Breeding programs are focused on reducing the impact of heat damage on reproductive growth and increasing seed numbers. However, breeding for a higher photosynthetic response to high CO_2 has failed so far.

In terms of management, the possibilities include:

– Modification of sowing date and/or adoption of shorter season cultivars: In most situations, we may reach an adequate thermal environment around flowering, which is the critical stage for yield determination.
– Increased N fertilizer: This will allow higher photosynthetic capacity to improve biomass accumulation (i.e., an adaptation to match the high-carbon supply) and a higher N concentration in fodder and grains.
– Irrigation management: The increase in ET_0 will be partly offset by the increase in stomatal resistance brought about by high CO_2. This compensation will only be partial for very short crops. Therefore, irrigation requirements should not vary by much. However, the negative effects of high temperatures during flowering may be alleviated by a good water supply, i.e., the benefits of irrigation may increase with global change.
– Pests: Changes in thermal conditions will likely cause changes in the incidence of pests and diseases. Although C4 weeds are already the main problem around the globe, their abundance will probably increase in colder areas, which will require adapting control measures.

41.5.2 Tree Crops and Vines

All trees have C3 carbon fixation pathway; thus, their gross photosynthesis increases—all else being equal—with the concentration of CO_2 in the atmosphere (Chap. 13, Eqs. 13.1 and 13.2). Model simulations and a few long-term experiments with CO_2 enrichment suggest large increases in the growth and productivity of tree crops under future climate conditions. Models predict that the increase in photosynthetic efficiency of tree crops should more than compensate for the negative effects expected by warming, like the increase in water use or the reduced amount of rainfall in some regions. Fertilization will also need to adapt to the increase in biomass or productivity.

Nevertheless, the distortions expected in the phenological development of fruit trees due to climate warming are cause for concern. Higher temperatures may accelerate tree development, but this may be compensated by the chilling requirements in many species (Chap. 11). Models predict bud-burst, flowering, and fruit ripening to occur earlier in the season in species with low chilling requirements, which may have undesirable effects, like reducing the cumulative carbon assimilation associated with a phenophase (see Sect. 41.3 above). In many cases, the more detrimental effects will be a consequence of extreme temperatures occurring in sensitive stages, like bud-burst, flowering, or fruit set; also, the drop of developed fruits may occur in some species under high temperatures. However, the direct effects of temperature on the chemical composition, appearance, and quality of the fruit may also be extremely negative (see Chap.11, Box 11.2 for an example).

The adaptation measures to cope with phenological mismatching have been in use for thousands of years. Farmers' selection continuously modified the developmental traits of fruit trees since domestication, as the growing areas expanded over the centuries, which generated strains adapted to new climates. The process accelerated in the last century when modern breeding appeared, and strains with very different phenological cycles were made available within the same species or even as subvarieties to suit the markets. The task of phenological adaptation of fruit trees to a changing climate seems affordable for modern breeding science in many species. Despite the relatively long time needed for obtaining new varieties in tree crops, the appearance and acceptance of new adapted cultivars are rather quick in the fruit production sector worldwide.

A slightly different concern is vernalization failure. Temperate fruit trees evolved a vernalization mechanism to synchronize their annual development to the seasonal cycle; the development of flower buds is induced only after exposure to temperatures lower than a threshold for a minimum amount of time ("chilling hours"; see Chap. 11). The number of chilling hours required for flowering varies among species but also cultivars, with great amplitude: Apple trees in general have very high chilling requirements, but some genotypes can flower in subtropical climates. The future warmer winters will not supply enough chilling for some fruit cultivars in their actual growing areas, which will lead to changes in their geographical distribution.

41.6 Mitigation

41.6.1 The Role of Conservation Agriculture

Two main avenues are considered for mitigation of CC by agriculture: reducing the emission of GHGs and sequestering carbon. Conservation agriculture (CA) has a large mitigation potential as reducing or eliminating tillage may reduce CO_2

emissions and increase soil organic carbon (SOC). Avoiding tillage will minimize the disruption of soil aggregates and oxidation of SOC. However, increasing SOC and improving soil structure requires permanent soil coverage by residues or cover crops. The topsoil layer will then be protected from raindrops while providing organic material for the micro- and macrofauna. Conservation agriculture also pays attention to crop rotation to help with weed and pest control and residue management.

Although CA is effective for soil conservation, its potential for CC mitigation is questioned. Regarding carbon sequestration, the combination of no tillage and maintenance of residues generally results in higher SOC in the topsoil centimeters than in conventionally tilled soil. When a deeper soil profile is studied, differences are often nonsignificant as buried residues can result in higher SOC in deeper layers of conventional systems. Nevertheless, positive effects of CA are expected in the long term and in arid and semiarid conditions. Higher biomass productivity does not imply a higher potential for C sequestration as it will depend also on the decomposition rate. Irrigation may result in more crop biomass but might also accelerate C losses under the typically high temperatures of irrigated agriculture.

Regarding soil CO_2 emissions, the impact of reducing tillage has variable results. On the one hand, fewer operations reduce fuel consumption and associated CO_2 emissions, a benefit partly offset by using more herbicides and fertilizers under no tillage (Chap. 37). On the other hand, different methodologies for determining the emissions, different interpretations of CA practices (e.g., the duration of reduced/no tillage), and the agroclimatic conditions make it hard to evaluate the potential benefits. Disturbing the soil releases the CO_2 contained in the pores within the soil, in proportion to the tillage depth. The CO_2 in the soil is the result of heterotrophic respiration from soil organisms and autotrophic respiration from plant roots. Soil organisms use residues as an energy source and the process is favored after tillage by increasing soil-residue contact and porosity (aeration). High temperatures also favor microbial activity. Under heavy tillage systems, decomposition of residues is mainly driven by bacteria populations, while under conservation systems, by fungal species. Residues high in lignin and with high C:N ratio have lower decomposition rates.

The role of CA in climate change mitigation is also questioned because it can increase N_2O emissions, in most cases when the soil is compacted and poorly aerated. Another indirect effect of CA is improved soil water infiltration resulting in lower runoff and dissolved nitrates although the risk of leaching may increase.

Under aerobic conditions, soils uptake CH_4 for oxidation through methanotrophic bacteria. Tillage has little effect on CH_4 emissions although well-drained soils are likely to become better sinks. Thus, if CA leads to waterlogging, the soil will emit more CH_4 than in the conventional systems. In any case, except in rice production, the CH_4 emission or uptake associated with crop production is small.

41.6.2 Permanent Crops and Forests

The carbon balance of a permanent crop or a forest is similar to that of an annual, with a critical difference: The living biomass pool is not reset every season or crop cycle, but part is maintained in the permanent plant skeletons (wood and coarse roots) so that the standing carbon pool increases over time. The rate of increase of the living biomass carbon pool of stands varies considerably with the climate, the species, the availability of nutrients, etc., but is higher in young communities. In some cases, like in tropical forests, the biomass pool of tree stands may be comparable in size to that of the soil organic carbon pool. It can be depleted abruptly by cutting or fires in forests or renewing/replanting in orchards. On the other hand, the standing biomass C pool can be rebuilt much faster than the soil C pool. While natural forests may last millennia, modern orchards have a life span of a couple of decades at most; nevertheless, the long-term size of their living biomass pool can be considered permanent as long as the land use is maintained.

There is consensus that forests are net global sinks of atmospheric CO_2, thus key to the global strategy of climate change mitigation. It is critical to prevent deforestation and even to increase the extension of forests in competition with agricultural land to meet the growing food demand. The expected world population of more than 10 billion at the end of the century will require higher agricultural productivity per unit of land. Intensive agriculture, perceived as a threat to the environment, will be the only way to stop deforestation. The key task for agronomy in the next decades will be to match intensification with environmental sustainability.

The carbon budget of orchards has been less studied. The living biomass C pool of tree crops is on average lower than that of forests, and their contribution to the increase of the soil carbon pool is questionable. However, the use of cover crops and other practices of soil conservation or soil C enrichment may foster soil carbon accumulation. Nevertheless, the few short-term measurements and the simulations (Fig. 41.1) suggest that they are active carbon sinks during their growth phase even considering the anthropic carbon emissions. The living biomass C pool is a net advantage of permanent crops for climate change mitigation compared to annuals.

Box 41.1. The Climate Change Mitigation Market

The Kyoto Protocol (1997) and the Paris Agreement (2015) signed by most countries set global carbon emissions targets and created an international carbon market. The system sets the allowance for the emission of a ton of CO_2 as an exchangeable commodity–the carbon credit—whose price is dynamically set by market laws. Carbon credits are issued by national or international organizations. Companies seeking a reduction in their carbon footprint can buy carbon credits generated by other companies dedicated to implementing mitigation projects. When the trade occurs directly between companies, the ton of CO_2 is called a carbon offset. Heavy CO_2 emitters like a cement

(continued)

Box 41.1 (continued)

manufacturing company or a metal foundry may reduce their net carbon footprint at will by buying carbon credits or offsets from other companies or groups dedicated to the production of these virtual commodities through mitigation projects: for example, reforestation or the production of biofuels.

Forestry and agriculture generate benefits to society called ecosystem services like the regulation of hydrological flows or the C sequestration into the soil and biomass pools. Carbon credits and offsets may be part of this philosophy.

Using economics to interpret and manage ecology is a difficult task and is very prone to misconceptions and huge estimation errors. Nevertheless, it would be fair to compensate farmers for the services they provide. The market for carbon credits and offsets is beginning to reach the farmers in some countries through companies and projects dedicated to inventories of stocks and estimation of fluxes at a farm level. If this process succeeds, carbon sequestration may become a standard part of farms' revenue, promoting the adoption of conservation agriculture techniques.

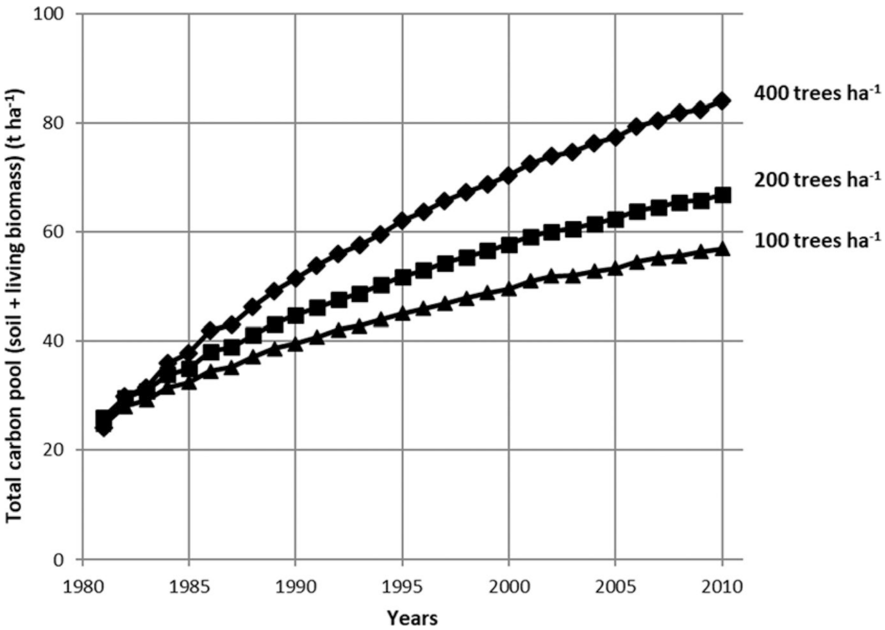

Fig. 41.1 Simulation of the total carbon pool (soil C pool + living biomass) over time for irrigated olive orchards of different planting density in the climate of Tuscany. The simulation starts with very low soil carbon content. (Adapted from Mairech et al. 2020. Agric Sys 181:102816)

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Agronomy and the Sustainability of Crop Production

42

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Abstract

Lessons learned since the discovery of agriculture suggest that good agronomy, as an integrative science, is essential for improving the sustainability of current agricultural systems. To meet the challenges of producing sufficient, safe, and nutritious food for a growing population, future agronomists will have to combine advances in plant breeding and biotechnology with new approaches to increase further the efficiency of nutrient and water use in agricultural production. There is significant potential in many areas to increase yields by bridging the gap between potential and actual yields, but as average yields increase with time, such potential diminishes. The threats of soil degradation and water scarcity will require widespread adoption of conservation practices based on strong extension efforts and new IT technologies. The most likely path to the sustainable intensification of production would be through continuous, small productivity improvements rather than through a few revolutionary discoveries, at least in the short term.

42.1 Introduction

Agriculture started with the domestication of cereals around 10,000 years ago (10,000 BP). Today, the same species (wheat, rice, maize) constitute the basis for global food production. Before 10,000 BP, seeds from some grass species were collected and processed to increase digestibility, as part of a diverse human diet that included fruits, game, and fish. Climate variations (colder, drier periods) probably

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reduced the availability of natural food sources, making it difficult to gather wild plants and hunt animals in sufficient amounts. That explains why humans were forced to move up the trophic chain as herbivores have greater conversion efficiency than carnivores. Humans found that the productivity of natural grass populations increased with some management operations (e.g., weeding). While doing so, these proto-farmers, unconsciously, started selecting plants with favorable characteristics (larger seeds, lack of dehiscence, absence of dormancy), and after harvest, some seeds were saved for planting subsequently in other fields. This domestication occurred independently at about the same time in several areas such as the Far East, Mesoamerica, and the Near East where wheat and barley originated. Rice cultivation in China began 11,500 years ago, while squash was domesticated in Central America about 9000 years ago. That was the start, and very rapidly, a few species of cereals and legumes achieved the desired agricultural characteristics. At the same time, early farmers probably observed the advantage of concentrating useful plants in fields that could be protected from herbivores or neighbors and cleaned from other competing plants. This also allowed for a more efficient harvest.

Most hunter-gatherers had a varied diet of wild plants and animals although sometimes they subsisted almost entirely on meat or a few plant species. As agriculture developed, some wild species were selected under domestication for different purposes, leading to different crops. For instance, *Brassica oleracea* has been selected for its leaves (cabbage), stems (kohlrabi), flower shoots (cauliflower), and buds (Brussels sprouts).

The development of modern civilization started with agriculture. Increases in food production led to technological development because food surpluses could be used to feed full-time craftspeople and inventors, leading also to the diversification of human activities. It also led to social stratification, political centralization, and militarization by feeding full-time aristocrats, bureaucrats, and soldiers. These advantages enabled agricultural societies to eventually displace most hunter-gatherers toward marginal environments.

Early agriculture was rainfed so it could only thrive in areas where enough rainfall could sustain grain production, which in the case of wheat and barley represents a minimum of 200–300 mm/year. In the arid zones, where precipitation was erratic and insufficient to sustain crop production, irrigated agriculture appeared in 6000 BP in Egypt and Mesopotamia by merely diverting water from rivers to adjacent fields during flood periods. This soon evolved into sophisticated systems of water distribution which required a strong social organization for operation and maintenance. Similarly and at about the same time, irrigation techniques were developed in Mesoamerica and China. Interestingly, a lack of knowledge about the need to control salinity and remove excess water from irrigation through drainage led to the decline of some ancient civilizations in the arid areas of the Near East that had expanded, thanks to irrigated agriculture.

Continuous cropping of the same field soon showed declining yields due to the loss in soil fertility from extraction and cultivation. This led to shifting cultivation systems such as *slash-and-burn* agriculture, a primitive mode of rotation aimed at concentrating mineral nutrients after many years of forest growth and then releasing them by burning the vegetation, which allowed a few years of cultivation with sufficient production. This form of agriculture could be made sustainable if the turnaround time for burning the forest would be long enough to allow for building back the natural soil fertility. However, population growth increased the pressure on land use and slash and burn expanded in many world areas. It was in the end responsible for the deforestation and land degradation of many regions, when population pressure led to unsustainably low ratios of forest to cropped land.

The different agricultural techniques evolved in parallel. Tillage started using the ard which only cuts a small furrow (drill) in the soil and is therefore helpful for sowing but not for weed control, incorporation of residues, or clearing new land. The ard appeared around 7000 BP in parallel with the domestication of cattle. The most primitive form of planting must have used a stick to drill a hole in the ground, place the seeds, and cover them with soil, a practice used by most indigenous societies. Moldboard plows appeared much later and were designed to turn the soil for more effective weed control. The plow, pulled by man or animals, became popular in Europe around 1500 AD, allowing a more complete and deeper soil disturbance and the upturning of the soil, which was the only way to control aggressive weed invasions. The Europeans exported the plow to America, Asia, and Africa, enabling the expansion of commercial agriculture with limited human labor inputs. In some areas, particularly within the tropics and subtropics, moldboard plowing has become unsustainable due to enhanced soil erosion and land degradation problems.

Animal husbandry also evolved in parallel with crop agriculture. Domesticated animals not only provided for food and clothing but contributed as draft power for tillage, allowed the exploitation as pastures of lands unsuitable for crop production, and contributed to nutrient cycling by redistributing nutrients within the agricultural systems. Other domesticated animals had a more specific role like cats as hunters of grain-eating rodents or dogs as guardians in rural areas. Production of animals and their products by grazing pasture and range lands in an extensive fashion is a practice that has ecological values such as contributing to the conservation of biodiversity or preventing soil erosion.

Giant steps forward in agricultural science and technology have taken place in the last two centuries with the development of machinery, breeding of new cultivars, and use of mineral fertilizers and pesticides, all at an accelerated pace since the middle of the twentieth century. Modernization of agriculture has led to the separation of the different activities that once were all part of the life of farms and has transformed human society. Before mechanization, the manual labor of most farming activities represented a physical effort that required large numbers of farmworkers with very low productivity. Additionally, life as a farmworker was not very pleasant, which inspired the mechanization of many farm operations. As technology improved, more specialization was required so farmers could concentrate on fewer activities for which they had to develop the proper skills and afford the required machinery and infrastructure. Rural societies thus experienced a revolution that changed how farming was conducted and led to land consolidation, fewer farmers, and vast migration movements from rural areas to cities in search of a better life. Before mechanization, farmers exploited crops, pastures, and forests using animals for different uses (food, draft, transportation). At that time, the life of most of the world's population was based on agricultural activities, and even by 1950, more than 70% of the population lived in rural areas. Since the 1950s, the challenge of feeding a population growing at unprecedented rates was more than met by an evolving agriculture in what is now considered one of the most remarkable success stories of mankind. In 1950, about 2500 million people lived in rural areas and about 750 million in the cities. By 2024, the total population had reached 8100 million with more than 4000 million in urban dwellings and yet, agriculture produces 25% more calories *per capita* than in 1950. There continue to be, however, serious limitations in food distribution and access, primarily in remote, rural areas, as evidenced by the persistence of extreme poverty and hunger in hundreds of millions of persons. Furthermore, there are concerns regarding the sustainability of present agricultural systems as to whether the recent productivity increases have been achieved at the cost of resource base degradation, with the ultimate consequence of reduced productivity in the future.

Although there is wide diversity among the different agricultural systems currently in existence, commercial agriculture has now been transformed into a set of industries where crops or animals are grown that may provide inputs for each other but operate in isolation. This new specialized agriculture has succeeded in increasing productivity but its long-term sustainability remains unclear. In the following sections, we will discuss some important issues that represent future threats and challenges to agriculture and food production as it is presently carried out.

42.2 Climate, Soil, and Water

Agriculture takes place outdoors and plants are primarily dependent on the weather for growth and development, and on the soil for nutrient and water supply. The local climate determines what species can be grown and also the risk for selecting crops sensitive to extreme climatic features. As the climate becomes more limiting, the risk of very low yields or even crop failures increases (risk being the product of probability and impact), so crop choice is reached as a compromise between profit expectations and risks. While agriculture has always been pushing at the margins by approaching the climatic limits of the viability of higher-value crops, farmers are generally risk avoiders and always try to balance profitability against risk. An additional factor to consider is the normal climate variability that agriculture must deal with. Some of the variability can be explained by regional phenomena such as the warming of ocean waters in the Pacific, an event called El Niño, which occurs with a periodicity of several years and causes excess rainfall in some regions and drought in others. In some areas such as Eastern Australia, predictive tools based on prior observations of El Niño events coupled with barometric pressure oscillations (El Niño-Southern Oscillation) have been developed to anticipate whether the upcoming season would be wetter or drier than normal. This information is critical to optimize planting dates and the application of fertilizers and other inputs. Seasonal predictions are still in their infancy in many world areas but improving their reliability is essential to minimize the risks in farming. As climate science advances in the coming years, better seasonal predictions will lead to more predictive farming strategies and reduced risks.

42.2.1 Soil Degradation

Over the centuries, the conversion of lands for use in crop production has included fragile areas prone to degradation. The exploitation of soils without maintaining their fertility by restoring nutrient extraction and their physical properties (Chap. 28) also leads to soil degradation. Exposure of bare soil to rainfall and tillage operations enhances soil erosion and the loss of the most fertile surface layers. A single soil erosion episode represents an amount of soil loss that exceeds by orders of magnitude the rate of soil formation. Despite the advances in methods of Earth observation, there are no good statistics on the degree of soil degradation around the world but estimates indicate that the problem is very relevant, requiring periodic monitoring to assess its severity in the different regions. Soil erosion will continue to be a major threat to the sustainability of agricultural systems around the world. The expansion of conservation agriculture (Chap. 18) is helping in many areas to control erosion but agricultural techniques (machinery, cultivars, pest control) have to be adapted to local conditions. Some soils require periodic tillage to maintain some physical properties, and in some regions, crop residues needed to protect the soil surface as part of conservation agriculture are used for animal feed and therefore are not available for soil protection. Intensification may lead to the production of enough crop residues for both uses. Soil salinization is another threat to sustainability that affects possibly up to 15–20% of the world's irrigated area. Again, new monitoring methods can reduce the risk and help to introduce salinity control measures to prevent the problem (Chap. 24).

The long-term maintenance of soil fertility is essential to ensure the sustainability of agriculture. This is particularly important concerning phosphorus as sources for P fertilizers are limited (Chap. 28). Efforts here should focus on P recycling and on increasing the availability of soil P to plants. In the case of N, the availability of N fertilizers will depend on energy prices, so the inclusion of legumes in crop rotations would be a partial solution when needed. Nevertheless, the use of synthetic N fertilizers in agriculture is extremely efficient in energy terms. If N concentration in grain is around 2%, each additional kilogram of N added to the crop will support a yield increase of 50 kg. The average energy required for producing the N fertilizer is 77 MJ/kg (Chap. 42), and since the energy content of the grain is around 18 MJ/kg, the marginal efficiency would be 900/77 = 11.7. Innovative approaches for improving the efficiency of N fertilizer use will reduce N fertilization rates and the consequent non-source pollution that affects surrounding ecosystems and water quality in many intensive production areas.

42.2.2 Water Scarcity

Irrigated agriculture expanded greatly in the second half of the twentieth century, increasing from 120 to about 300 Mha. In fact, given that the productivity of irrigated systems is about 2.75 times more than that of rainfed systems on a worldwide basis, today the production of sufficient food relies significantly on irrigated agriculture. Irrigation expansion has come at a cost for the environment. On the one hand, the construction of reservoirs for irrigation has changed the natural environment and had an impact on river ecology. On the other hand, the return flows from irrigated lands constitute a major source of nonpoint pollution, unavoidable to some extent if irrigated agriculture is to be sustainable. This is because the maintenance of the salt balance through drainage is essential to prevent salinization of irrigated areas. Additionally, irrigated area expansion and agriculture intensification require large amounts of water to the point that irrigation is the primary consumer of the water diverted by man for various uses. More than two-thirds of diverted water is consumed in irrigation worldwide. Contrary to other uses (e.g., domestic) where water used can be recovered and reused after appropriate treatment, much of the water used in irrigation is evaporated and thus leaves the basin. While a fraction of the irrigation water can be reused, as irrigation becomes more efficient, such fraction diminishes and the *ET* process dominates irrigation water use. With increases in efficiency, due attention must be paid to the maintenance of salt balance in areas of low rainfall and/or where saline waters are used for irrigation.

An emerging problem that threatens the sustainability of irrigation in some areas is the excessive use of groundwater beyond the long-term recharge. Groundwater usage may exceed aquifer recharge in droughty years provided that the excess extraction is eventually replenished in the long run. However, long-term decline in water table depths as it is occurring now in some regions of China and India is an indication of unsustainable use. In extreme cases, land subsidence can reduce aquifer capacity permanently or cause seawater intrusion in coastal areas with the permanent deterioration of water quality. Better assessment of groundwater resources combined with recharge programs and wise and strict resource management can bring solutions to this problem.

At present, irrigation is under scrutiny by the other sectors of society that perceive that its share of water usage is too high. This is particularly critical in areas or times of water scarcity, where competition with other uses becomes fierce and urban and other demands have higher priority. Thus, while there is a need to expand irrigation as one option for production intensification to meet future food demands, competition for scarce water with other sectors, including the environment, is going to restrict such expansion forcing irrigated agriculture to do more with less water. Although many advanced technologies are available for improving irrigation management, widespread dissemination has been limited so far. The time has come for many irrigated areas to promote the large-scale adoption of efficient irrigation practices to meet both increased productivity needs and societal goals. Independent certification of efficient use of water in food production with appropriate indicators would be welcomed by consumers and the rest of society.

Promoting the efficient use of water in rainfed agriculture is also a very promising goal for production intensification in the future. The approaches should focus on other factors co-limiting yields (such as nutrients) and on accepting more risks, abandoning the conservative approaches to rainfed farming that avoided risk but that had little reward on good years. Acceptance of more risk in rainfed farming requires new tools such as reliable seasonal forecasts and advisory services that will assess risks quantitatively and offer flexible options adapted to local conditions. In its simplest view, risk equals the product of probability by impact, and the avoidance of extreme events that could impact the viability of farming irreversibly causing famine has dominated past rainfed strategies. In this regard, the resilience of the agricultural system, that is, its capacity to recover after a perturbation, is critical for the sustainability of the system. As new technologies and policies enhance the resilience of rainfed systems, accepting more risk will lead to productivity increases in the future.

42.3 The Role of Plant Breeding

The development of modern plant breeding technologies after 1950 has produced new cultivars which are highly productive and widely adapted. The major plant feature that has been improved in the major crops is its harvest index whereby current varieties have *HIs* 50% greater than those of 50 years ago. The success of the recent agricultural intensification has often been attributed to the new varieties without recognizing that varieties or agronomic inputs produce nothing in isolation. It was the combination of new varieties and new agronomy together with adequate management what enhanced the productivity of agricultural systems until now.

Plant breeding techniques are nowadays more powerful and more efficient due to genetic engineering whereby genes or traits from other organisms are introduced into crop plants. This has led to new cultivars labeled "transgenic" (Genetically Modified Organisms, GMO). Transgenic crops have been highly successful so far by addressing crop features related only to a few genes. For example, the quality of the seed may be improved (e.g., golden rice with beta-carotene) or the plant may acquire insecticidal properties (e.g., Bt maize) or resistance to a given herbicide (e.g., Roundup-Ready soybean). The primary goals were to reduce production costs (lower pesticide use) and, by reducing/eliminating some pesticides, to improve human health and the environment. The improvements in farm profitability have been such that transgenic soybeans, maize, and cotton have been widely adopted in less than 20 years, not only in the United States where more than 90% of the three crops are now transgenic but also in some developing countries as India or China. Plant breeding efforts to produce transgenics are now being extended to other crops to address biotic stresses or crop quality problems.

By contrast, the promises of improving plants against abiotic stress (drought/salinity) using GMOs have not been fulfilled so far. This is firstly due to the complex nature of the problem. What is drought? Is the pattern of water deficit the same every year? Should we look for plants that are "water savers" or "water expenders"? The former would grow slowly thus allowing more soil evaporation to occur but would generally have more water for completing seed growth, thereby ensuring a high *HI*. On the contrary, a "water expender" leads to higher biomass production and probably higher yield in good years at the expense of lower *HI* and yield in dry years. Thus, the best cultivar for rainfed conditions depends on local conditions (climate, soil) and changes from year to year. Furthermore, the tight relationship between assimilation and transpiration (Chap. 14) must be considered. Water use efficiency is mostly dependent on the evaporative demand (air *VPD*) so little can be achieved by breeding for high *WUE* under specific conditions. Breeding for high *WUE* could result in cactus-like cultivars that would keep their stomata closed most of the time! Breeding efforts should be directed instead at manipulating development to fit the most probable drought patterns and tuning stomatal aperture to periods of low VPD.

Despite the success of the first transgenic crops, there are concerns about the use of this technology mostly related to perceived risks in food safety and the environment and the loss of autonomy of farmers for seed production. The risk for humans is unfounded and unfair as there are strict regulations regarding food safety and environmental impact assessment during the breeding process. Additionally, the improved GM varieties allow an important reduction in pesticide use thus reducing a potential toxic effect. The other concerns deal with broad social issues and intellectual property rights and are beyond the scope of this book. Recent developments in genome editing permit modification of the genome to introduce desired traits, paving the way for increasing the precision and scope of plant breeding. One advantage of genome editing is that it does not have the adverse public opinion that transgenic crops have in some circles. Advances in crop improvement may accelerate in the coming years due to the array of new genomic techniques applied to plant breeding which has allowed for increasing productivity and adapting crops to new environments. This will be even more important as global warming continues and crops have to be adapted to warmer environments or cold areas of the higher latitudes not suitable for agriculture until now. Every major crop species has many thousands of varieties offering wide adaptation that can be tested and adapted to specific environments through advanced plant breeding combined with new agronomy and management; thus, as in the recent past, crop adaptation will be a key target for the future of agriculture.

42.4 Alternative Agricultural Systems: Organic Farming

The intensification of agricultural production in recent decades with extensive pesticide use and episodes of environmental nonpoint pollution have given way to movements that question mainstream agricultural practices, viewing them as unsustainable and unhealthy. Such movements present forms of "alternative" agriculture that are different from what they termed "conventional" agriculture. The usual ingredients of alternative systems include some ecological principles and "traditional" knowledge, with emphasis on sustainability but with some disregard for the productivity and profitability of farming. These alternative movements have been met positively by some urban societies that perceive "industrial" agriculture to be unsustainable and as a threat to human well-being and to the environment. Periodically, new forms of alternative agriculture are proposed as being more sustainable than conventional agriculture, for example, regenerative agriculture, based on leaving residues on the soil, high crop diversity, and use of animal husbandry. Needless to say, among the technical and ecological diversity of current agricultural systems, such principles have been widely practiced for a long time. The search for innovative methods to make current agricultural systems more sustainable is very positive but should not ignore the wide diversity that exists worldwide in what is called conventional agriculture.

The most popular alternative agriculture system is organic farming based on several rules whereby only organic fertilizers such as manure may be applied and plant protection methods that forbid synthetic pesticides and are founded on biological pest control. Eliminating pesticide use has been welcomed by consumers and reduces the environmental impact of agriculture but organic farming has also established a set of rules without scientific basis, particularly those related to soil fertility, which are solely based on the naïve idea that natural is good and synthetic is bad. Molecules such as nitrate are the same independent of the origin of the fertilizer, so they produce the same benefits to the crop or may lead to the same environmental problem (groundwater pollution). Thus, when their systems are based on following a set of strict rules, organic farmers may be condemned to low yields/income if organic fertilizers are scarce and/or expensive. Often, additional land is required to fix the N needed in the soil with green manure crops. While organic agriculture has been successful in finding a market niche among the urbanites of affluent societies, the feasibility of expanding organic farming beyond a relatively small share of world agricultural production is highly questionable. Global N fertilizer consumption in 2021 was around 109 Mt N. If we eliminated synthetic fertilizers, we would require legumes incorporated into the soil as green manure. Assuming an average input of 100 kg N/ha/year, green manure would take 1100 Mha, which is impossible to achieve as total arable land is only 1500 Mha. In other words, green fertilization would reduce current world productive arable land to one-third of the current value.

Organic farming (OF) has expanded recently to meet the growing demand of societies suspicious of conventional agricultural production. Still in 2021, OF represented only 1.5% of the global farming area, while it is up to 10% in Europe. Agronomic improvements, particularly in crop protection, have raised the productivity of organic farming. Productivity comparisons between organic and nonorganic production are meaningful only when conducted at the farming systems level, where the crop productivity ratios organic/nonorganic are low, varying from 0.3 to 0.7, because in OF we would need additional land to produce the plant or animal manures. Nevertheless, farm profitability is another matter and there may be consumers willing to pay the higher prices that organic produce fetch in urban markets.

42.5 Agriculture as an Energy Source

Primary production is an inexhaustible energy source and has been used by man since the discovery of fire. During the energy crisis of the 1970s, agriculture was first considered a potential energy source, either through novel, energy crops or using some of the main crops for converting biomass and grain into fuels. Since that time, most of the energy crops that have been proposed have not fulfilled their initial promises (although newly found C4 tropical species might be a viable option) and the focus has shifted to ethanol production from sugarcane and maize, with some attention paid to converting edible oils into biodiesel. The contribution of fossil fuels to global warming and the high prices of oil in the recent past have fostered policies for promoting the use of biofuels produced in agricultural lands, particularly in South (sugarcane) and North America (maize). Globally, while the use of biofuels reduces greenhouse gas emissions, the competition between food and energy production is the subject of debate in ethical and environmental terms. For instance, the incentives for producing biofuels have contributed to the expansion of oil palm at the expense of food crops or the maintenance of tropical forests thus increasing deforestation. This debate is sided by proposals to use only crop residues as the energy source. This promise of "second generation" biofuels based on the use of residues by conversion of cellulose to sugars, which would then turn into alcohol, has been achieved in technical terms, although production costs are still high relative to those of biofuels from sugarcane or maize. However, crop residues have an important role in soil conservation and maintenance of soil organic matter (Chap. 18), and as animal fodder in many farming systems. If sugars can be produced from residues, they could also be used for food production. As with alternative agriculture, new proposals to use biomass for energy appear periodically, lately for its conversion to aeronautical fuels or hydrogen. These proposals have yet to be economically viable and are associated with the pressures to contribute to climate change mitigation.

The relative capacity of agriculture as a potential energy producer may be quantified by comparing the energy contained in food products against the energy burnt in fossil fuels. The total global consumption in 2022 of liquid fossil fuels (gasoline, refined fuel oils, etc.) mostly used in transportation was 101 million barrels/day, equivalent to 191 10^{12} MJ/year. For the same year, global agricultural production was 4573 Mt of dry matter (Table 42.1) which corresponds to a total energy of 85.6 10^{12} MJ which is less than 45% of the energy of liquid fuels. The EU established the goal of supplying 10% of fuel as biofuels by 2020. If that rule is applied globally, it would require 19.1 10^{12} MJ, equivalent to 22% of agricultural production.

Table 42.1 Global crop production in 2022 classified by crop type and equivalent energy captured

Crop type	Crop production Mt dry matter	Energy content MJ/kg	Equivalent energy PJ
Grains	2692	17	45,764
Oil	762	27	20,574
Legumes	86.4	19	1641.6
Sugar	546	17	9282
Starch	181	17	3077
Fruits and vegs	263	17	4471
Nuts	15.7	23	361.1
Nonfood	27	17	459
Total	4573		85,630

Source: FAO

42.6 The Role of Research, Extension, and Information/Communication Technologies

The returns on past investments in agricultural research have been so high that some consider agricultural research the best business of the public sector ever. Modern agricultural research started in the last decades of the nineteenth century, primarily in Germany, the United States, and England. After the Second World War, given the need to produce more food for a growing population, there was an initiative led by private foundations and some countries to develop a system of international agricultural research which eventually became the Consultative Group of International Agricultural Research (CGIAR) with research centers located in developing countries. The CGIAR developed the first cultivars of dwarf wheat and rice that were more productive than previous tall cultivars, leading to what was later called “the Green Revolution.” All countries have since developed their agricultural research systems contributing to the sustained increases in food production worldwide since 1950.

Along with agricultural research, some countries as the United States developed in parallel a system of agricultural extension for disseminating the new results among farmers, promoting the adoption of new techniques as they were developed by researchers. Agricultural extension has also been very successful and there are many examples of fast adoption of new techniques that were experimented locally and tested by extension. Many newly developed techniques require adaptation to local conditions as a prerequisite for adoption by farmers. Without a good extension system, farmers hesitate to adopt new ideas that have not been adapted and tested locally, and progress is slower. Also, being extension services part of the public sector, they are independent of private corporations and free of biases toward certain varieties or products. Agricultural extension started in the United States before the end of the nineteenth century and has been largely responsible for the expansion and productivity increases of US agriculture. Other countries have created effective extension systems but many developing countries have not invested sufficiently in them, which is limiting the rate of adoption of viable solutions to increase productivity and sustainability. One limitation is the huge number of small farmers that exist in many countries, which will require a large extension force to carry out the work in the field if extension is to be conducted as it has been until now, face to face. However, new communication technologies such as cell phones readily available in most areas could serve as innovative ways to reach the large populations of small farmers effectively.

In general, communication technologies have accelerated access to vast amounts of information but cannot guarantee its quality. Information delivered by private companies is often biased toward promoting the benefits of their products and sometimes it escapes regulations on false advertising. It is common to see Web pages where companies mention "studies performed at different universities" (without more detail) to support their products. Public research/extension systems will be required to address the needs of farmers and the whole society, in particular, providing assessments on long-term issues or large-scale effects on agricultural systems (e.g., soil erosion).

Given the predictions of global population and economic development, it is estimated that 70% more food will have to be produced by 2050 (see below). The magnitude of this challenge cannot be underestimated given the current productivity trends of the major crops. Agricultural research will play an important role in meeting this challenge as it has done in the past, provided that governments around the world realize the difficulties ahead and invest sufficient resources to tackle the research issues related to increasing production in a sustainable fashion. The associated extension efforts, which will be badly needed, will increasingly be based on the use of crop simulation models and the development of decision support systems tailored to the specific needs of the farmers and communicated through the Web.

Box 42.1: Visualizing the Future

A farmer in 2050 is planning to sow wheat by November 1. By October 15, a sampling robot is sent to the different fields of the farm where it automatically samples the soil in different locations and produces maps of nutrients (nitrate, P, K) and soil water content, which the farmer checks against similar observations obtained two weeks ago from a satellite service that he subscribes. The robot also takes some samples that are packed and sent to the regional research center to test for soil pathogens or insects. On the same day, a drone flies over the farm and collects visual and NIR images to map the weed spots in the fields to be sown. Then, the farmer looks at a DSS that shows the estimated soil water content in the different fields. With that data and the local rainfall forecast for the next two weeks, the system connects with the websites of seed companies, collects information on the different cultivars available, runs a simulation model of the crop based on a reliable seasonal weather forecast, and compares which are the best options to purchase the seed, considering seed price, expected yields, product prices, and local availability. The farmer buys online the seed required.

(continued)

Box 42.1 (continued)

The same DSS builds also a map of recommended applications of N, P, K, and contact herbicides and calculates the quantities to be ordered by checking the actual stocks. The farmer compares online the prices and conditions of different suppliers and confirms the order. According to the weather forecasts, dry conditions are expected by October 22 and 23 with rainfall afterward. These are appropriate for applying the N and the herbicide. By October 20, an email is received from the regional research center advising the use of an insecticide at a given rate along with the seed. The farmer confirms online the use of the insecticide, which is registered on an external public database of pesticide use.

On October 22, the robot fertilizer-sprayer goes to the fields and applies urea at variable rates depending on need. It also sprays herbicide only on the spots where weeds had been previously detected. After the job is done, the farmer confirms online the amounts of N and herbicide used in each field. This information goes to the external databases for subsequent N fertilizer and pesticide use.

On November 1, the robot seed drill is sent to the fields to sow and apply localized P and K fertilizers at variable rates. The planter will follow always the same path as all other machinery to avoid compaction due to traffic.

42.7 Food Security and Food Safety

Concerns for food security, understood as a situation where all humans will have access to sufficient and nutritious food, have increased around the world in the last 15 years. Food security is now high on the agenda of many countries that are planning for an uncertain future where, at the same time that global food trade is reaching historical levels, food sovereignty issues related to the capacity of each country to be self-sufficient in food production are increasingly important given the current political climate. Food trade is effectively balancing supply and demand and is the major instrument now to cope with instability in production caused by extreme weather events and by changes in food demand due to diet changes or other economic features. One recent threat to food security is the appearance and dissemination of emerging pests that can threaten agricultural systems. Olive production in Southern Italy or citrus production in Florida, where orange production decreased by 90% in 10 years, are two examples of emerging pest problems that are difficult to contain in their centers of origin. The expansion of global trade among plant nurseries is a main cause of concern for the dissemination of emerging pests and diseases.

Food safety refers to health issues from the standpoint of ensuring that marketable foods are both healthy and nutritious. Health-related problems in food production may appear like the mad cow disease, caused by dubious animal feeding practices. These problems attract substantial attention from a society more and more distant from agriculture and food production processes. Periodically, episodes of food chemical or biological contamination occur in many countries and generate alarms regarding food safety. One important source of contamination is irrigation with untreated wastewater, still common in many world areas and that must be avoided by appropriate water treatment. Alarms due to food contamination cause great concern among consumers and this is rightly forcing more control and regulation of food production processes from farm to fork. Agronomists must ensure that products leaving the farm are always safe for consumption, the major issue being inadequate pesticide usage. Another important goal is to enhance the nutritional qualities of the food produced. The contents of protein, essential amino acids, vitamins, and other nutritional factors must be enhanced where possible by good agronomy. Another interesting aspect refers to the positive interactions between nutrition and health of certain products such as red wine, nuts, and olive oil that have proven health-related benefits but where the content of the beneficial chemical products depends in part on the growing conditions. Finally, given the increasing importance of gastronomy in affluent societies, agronomists should focus more on ensuring or improving organoleptic quality.

Although predictions vary, it is estimated that agricultural production should increase by 70% to meet the demand of 9 billion people expected in 2050. Is the world going to provide food security for all by 2050? First, it is important to consider that not all agricultural products are used directly for food. Around 10% is devoted to industrial crops including biofuels. The remaining 90% is shared between food (65%) and animal feed (35%), which results in an overall efficiency of crop production for food of 0.65. This low efficiency is due to the low conversion efficiency of animals mainly for meat production. Here, there are ample differences in efficiencies among animals, with chickens being the most efficient and cows the least (Table 42.2). However, ruminants exploit rangelands (which occupy more land than that used in agriculture) that otherwise would not be used for food production. This must be taken into consideration when addressing meat production in global food assessments. Calls have been made to reduce meat consumption in developed countries and this could have an impact on future food security. For instance, if feed for meat production was reduced by half, the overall efficiency would increase theoretically from 0.65 to 0.74, a 14% increase in calories available to humans. Such a

Table 42.2 Distribution of uses of edible crops and all crops circa 2020

	Edible crops	Total crops	Efficiency
	Fraction used	Fraction used	Fraction
Humans	0.65	0.59	1
Pork	0.12	0.11	0.1
Dairy	0.09	0.08	0.4
Beef	0.05	0.05	0.03
Chicken	0.05	0.05	0.12
Eggs	0.04	0.04	0.22

The efficiency of conversion for energy is taken 1 for humans as direct consumption. Using this data, a general efficiency of global crop production to food of 0.65 is estimated as the weighted average of the efficiencies, taking the fraction of use as weighing factors drastic change would not free as many calories for humans as computed above, as animal feed includes pastures, residues, and other nonfood components, so grain may be just a supplement and not the basic animal diet. On the other hand, there are clear health-related advantages of reducing the amount of animal products in human diets, particularly in countries of high consumption where obesity is a growing problem.

Another area where improvements will contribute to future food security is reducing food waste. The nature of waste varies in different food chains but generally speaking, food waste in developing countries is primarily due to postharvest losses caused by pests and diseases. By contrast, in the developed countries, the majority of food losses occur at the consumers' end of the food chain. Although efforts are being made to reduce waste, much of it is related to social and cultural factors, which, as in the meat consumption patterns, are difficult to change. The current hype on reducing food waste is probably the result of some overstatements. FAO published recently a study providing global "estimates" of losses at different levels of the food chain, namely, primary production, processing and distribution, and consumption. That study concluded that one-third of the food produced globally was lost. Thus, one may conclude that available food would increase by 50% if those losses were avoided. The problem lies in what is included in the definition of food losses and waste while ignoring alternative uses. Our concern should be how much additional food could be made economically available. In fact, only food waste arriving at waste processing facilities could partly be avoided. Using data from urban waste in Mexican cities, a value of 5% of food dry matter is being lost and that includes inedible parts (fruit peels, animal bones, etc.), so the actual value of food waste might be only 3–4%. Excessive emphasis on food losses derives from studies on perishable products like vegetables where supply and demand imbalances have generated surpluses. However, the relevance of vegetables is small when referenced to dry matter, representing only 50 Mt versus the 3000 Mt of major crops (cereals and oilseeds) in 2022.

The FAO report computes high food losses in primary production, processing, and distribution. However, those "losses" have alternative uses like feed or are economically unavoidable. For instance, in the mechanical harvest of winter cereals, a 3% loss is deemed acceptable. It could be physically possible but not economical for humans to pick up that 3% by hand. The same goes for losses during transportation and handling: They are the result of the best available technologies.

How can then agronomy contribute to food security in the future? We must make current agricultural systems more sustainable without losing sight of the need to intensify production in existing farmlands. The option of expanding agricultural land has significant ecological limitations and is not sustainable, as most of the best lands have already been put into production. Thus, the sustainable intensification of production by introducing new techniques adapted to local conditions should continue that path of increased productivity. Ample opportunities exist for increasing both agricultural productivity and sustainability by using good agronomy and appropriate crop management practices.

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Quantitative Analysis of Crop Production in an Irrigated Farm (Part I)

43

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Abstract

Degrees in agricultural engineering or agronomy include specific courses studying crop production techniques derived from agronomy, covering all or part of the contents described in this book. In the practical sessions of our class of Principles of Agronomy for Sustainable Agriculture at the University of Cordoba, a project-based learning methodology is used. The students, grouped in pairs, undertake diverse calculations for a specific location and crop rotation throughout the course. Each student is assigned a crop within the rotation, but some cooperative work is required in some sections, promoting teamwork. At the end of the course, each group produces a final report and gives an oral presentation defending its results. The report and the presentation are used as evaluation instruments and contribute to determining the student's final grades. This chapter presents an example of the report for a leek-pepper rotation grown in Belmez, Spain. The practical project is divided into several sections dealing with (1) analysis of weather data and calculations of (2) potential productivity, (3) seed rates, (4) irrigation schedules, (5) required leaching fraction, (6) fertilizer programs, and (7) energy requirements.

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43.1 Introduction

The class of Principles of Agronomy for Sustainable Agriculture (PASA) may require between 6 and 9 credits according to the European system (1 credit = 25 h of student's work), depending on the actual background of students or the specific interests in some of the topics (e.g., irrigation chapters may be skipped in humid environments). This would be equivalent to between 60 and 90 classroom hours with basic lectures and practical work split 50%.

In the practical sessions of our PASA course at the University of Córdoba, teams of two students undertake diverse calculations for a specific practical project that includes both individual and cooperative work. Each project has a given location (with its climate characterized by a real weather station) and a crop rotation (e.g., barley/soybean), so each student has a specific crop species assigned. At the end of the semester, each group submits a written report on the project results for evaluation. Likewise, each group gives an oral presentation summarizing the main outcomes of the project (10 min plus 10 min for questions). At this time, the teacher may ask specific questions to check the ability of the students to support their calculations. The quality of the presentation and the report and the answers to the teacher's questions are major determinants of the student's final grade.

The practical projects we propose are unique as they deal with different locations and periods, implying a different weather data set. The other calculations depend on the weather data, so they will be different in each case. If no weather data is available for a specific location, a weather generator like *ClimaSG* (https://www.uco.es/fitotecnia/climasg.html) may be used.

This chapter presents the statement of the practical project used in our PASA course (Sect. 43.2) and an example of a written report (Sects. 43.3, 43.4, 43.5, 43.6, 43.7, 43.8 and 43.9). Additional or alternative sections of the practical project are presented in Chap. 44. At the end of the day, the teacher decides the sections that should be included and other aspects of the organization. For instance, groups of 3 students could analyze a 3-year rotation or split the farm into half with field crops (2-year rotation) and the other half with fruit trees or a fodder crop.

The last section of the written report should be a list of references. Apart from this book, the students should cite the sources of information for maximum yields in their region (Sect. 43.4) and fertilizer prices (Sect. 43.8).

43.2 Practical Project Statement

We will work in groups of 2 students, each with a different crop and the 2 crops will make the crop rotation. There are sections that must be performed by each of the students with the corresponding crop or option (2, 3, 4, 5, 6, 7). Sections 6 and 7 require cooperative work by the team, while the two students are equally responsible for section 1. Data on the location, crops, irrigation system characteristics, soil fertility, and water quality are shown in Tables 43.1 and 43.2. Water is taken from a well using a pump with a diesel engine.

Table 43.1 Location and crop rotation assigned for the practical project example

		Student 1		Student 2	
Group	Location	Crop	Sowing	Crop	Sowing
1	Belmez, Spain	Leek	1-October	Pepper	1-May

Table 43.2 Additional data regarding the soil, the irrigation system, and groundwater for irrigation in the practical project example

	Soil analysis 30 cm depth				Irrigation system			Groundwater	
Soil depth (m)	Texture	P Olsen (mg/kg)	K (mg/kg)	SOM (%)	Spacing (m)	Discharge (L/h)	Application efficiency (%)	Depth (m)	EC_w (dS/m)
1	Sandy loam	18	300	1.15	12 × 12	1080	0.85	90	1.7

Soil pH = 8

The sections of the practical project are:

1. Analysis of agrometeorological data:

   Download the available weather data for your location from the Web. Take only complete years starting with the present and going backward. Calculate mean monthly values of:

   (a) Maximum temperature
   (b) Minimum temperature
   (c) Solar radiation
   (d) Wind speed
   (e) Total precipitation
   (f) Effective rainfall (FAO method)
   (g) Day length
   (h) Vapor pressure deficit
   (i) Clear-sky solar radiation (i.e., assuming no clouds)
   (j) Net radiation over grass
   (k) ET_0 using the Penman-Monteith-FAO equation
   (l) ET_0 using the Hargreaves equation
   (m) Number of rainy days (considering only those with 0.5 mm or more rainfall)

2. Productivity:

   Calculate for each crop:

   (a) Thermal time from sowing to harvest. Assume that crop duration is equal to that defined by the four stages of the FAO method of K_c.
   (b) The exact duration of each of the stages of the FAO method and the complete cycle for the last season with weather records
   (c) Intercepted PAR: Estimate the fraction of intercepted *PAR* (f) for each stage considering the following constraints:

Stage A: $f_{PI} = 0.1$
Stages C and D: $f_{PI} = K_c - 0.3$
Stage B: Interpolate between the values of stages A and C.

(d) Potential yield
(e) Compare your estimate of potential yield with typical yields for this crop in the region

3. Seed rates:
   Calculate the seed rates for the two crops.
4. Irrigation schedule:
   Calculate the irrigation programs for the two crops (dates, amounts, and durations for each irrigation event) using data for the last year of the series. Assume that the soil water deficit is zero at sowing.
5. Required leaching fraction:
   Calculate the amount of irrigation that should be added to that calculated in the previous section to obtain maximum yield considering the electrical conductivity of the irrigation water (Table 43.2).
6. Fertilizer program:
   Consider that the average yield of the crops is 80% of the estimated potential yield. Assume that all crop residues are left in the field. For each crop and the crop rotation, calculate:

   (a) N fertilizer requirements
   (b) Average fertilizer requirements of P and K
   (c) The cost of the fertilizer program (excluding the application cost)
   (d) Use *FertiliCalc* (https://www.uco.es/fitotecnia/fertilicalc.html) to check your calculations. If differences are found, discuss the possible causes.

7. Crop calendar and energy requirements:
   (a) Establish the crop calendar for the two crops. Choose a soil conservation system (tillage or no tillage) and indicate dates and operations to be performed (sowing, tillage, application of fertilizers and pesticides, harvest).
   (b) Calculate the energy requirements of your farm with the current rotation.
   (c) Use *CropEBal* (https://www.uco.es/fitotecnia/cropebal.html) to check your calculations.

43.3 Analysis of Agrometeorological Data

Weather data was downloaded for the assigned location from a public network of weather stations in Andalusia ("Red de Información Agroclimática de Andalucía," https://www.juntadeandalucia.es/agriculturaypesca/ifapa/riaweb/web/). The weather station in Belmez is located in the north of the province of Cordoba, Spain (38.3°N, 5.2°W, 523 m altitude). At the time of preparation of this report, the weather station had been operating for 13 complete years. Downloaded data included daily values of maximum (T_{max}, °C) and minimum temperature (T_{min}, °C), maximum (RH_{max}, %) and minimum relative humidity (RH_{min}, %), solar radiation (R_s, MJ m^{-2}), precipitation (P, mm), and average wind speed (U, m s^{-1}).

Table 43.3 Mean monthly values of maximum and minimum daily temperatures, solar radiation, wind speed, precipitation, and effective precipitation in Belmez, Spain

Month	T_{max} (°C)	T_{min} (°C)	R_s (MJ m^{-2} day)	U (m s^{-1})	P (mm month^{-1})	P_e (mm month^{-1})
1	12.5	1.6	8.7	2.13	48.2	18.9
2	13.9	1.9	12.1	2.25	52.6	21.6
3	17.1	4.8	16.1	2.33	61.8	27.1
4	19.9	6.6	21.2	2.33	59.9	25.9
5	24.8	9.7	24.9	2.03	38.1	12.9
6	31.5	14.4	28.5	2.08	10.3	0
7	34.6	16.4	29.9	2.22	1.6	0
8	34.2	16.9	26.1	2.09	10.0	0
9	28.7	14.0	19.7	1.94	36.7	12.0
10	22.6	10.0	13.6	2.11	82.9	39.7
11	15.8	4.5	9.5	2.15	61.4	26.8
12	13.0	1.9	7.7	1.99	69.7	31.8

Table 43.4 Mean monthly values of day length (N_s), vapor pressure deficit (VPD), maximum solar radiation ($R_{s,clear}$), net radiation over grass (R_n), reference evapotranspiration (ET_0) estimated by the Penman-Monteith-FAO and Hargreaves methods, and number of rainy days per month (NRD) in Belmez, Spain

Month	N_s (hours)	VPD (kPa)	$R_{s,clear}$ (MJ m^{-2} day^{-1})	R_n (MJ m^{-2} day^{-1})	ET_0 PM-FAO (mm day^{-1})	ET_0 Hargreaves (mm day^{-1})	NRD (days month^{-1})
1	9.7	0.36	12.1	2.4	1.0	1.2	7.62
2	10.6	0.46	16.0	4.7	1.7	1.8	7.15
3	11.8	0.62	21.3	7.7	2.6	2.7	7.85
4	13.1	0.80	26.4	11.3	3.7	3.9	7.85
5	14.1	1.25	29.8	13.7	4.9	5.5	5.69
6	14.6	2.14	31.1	15.4	6.7	7.4	2.15
7	14.3	2.74	30.3	15.4	7.7	8.1	0.31
8	13.4	2.63	27.3	13.0	6.8	6.9	1.15
9	12.2	1.67	22.5	9.3	4.6	4.5	4.15
10	10.9	0.94	17.2	5.6	2.7	2.7	7.69
11	9.9	0.49	12.9	2.9	1.5	1.5	6.85
12	9.4	0.35	11.0	1.9	1.0	1.1	6.85

Table 43.3 shows the average values of all weather data. Averages and totals were computed using Microsoft Excel. Effective precipitation was estimated from monthly rainfall with the FAO equations (Eqs. 8.22a and 8.22b).

Table 43.4 shows the results for the other variables requested. Calculations were performed for each day as described below; then monthly averages and totals were deduced:

- Day length (N_s, h) was computed from solar declination, which depends on the date (Eq. 3.4) and the latitude (Eqs. 3.8 and 3.10).
- Average vapor pressure deficit (VPD, kPa) was calculated with Eq. 5.7, which implicitly assumes that the maximum and minimum relative humidity occur at the time of minimum and maximum temperature, respectively.

- Clear-sky solar radiation ($R_{s,clear}$, MJ m^{-2} day^{-1}) was calculated for clear-sky conditions as 75% of extraterrestrial radiation (i.e., for n_s/N_s = 1 in Eq. 3.5). The latter was estimated from the day of the year and the latitude using Eq. 3.7.
- Net radiation over grass (R_n, MJ m^{-2} day^{-1}) was computed from Eq. 3.13, where the albedo (α) was set to 0.23 (grass) and the longwave radiation losses were calculated with Eq. 3.11. The actual ratio n_s/N_s and average vapor pressure were estimated by inverting Eq. 3.5 and applying Eq. 5.6, respectively.
- Reference evapotranspiration (ET_0, mm day^{-1}) was calculated with the Penman-Monteith-FAO (Eq. 10.3) and the Hargreaves (Eq. 10.2) methods. For the latter, the coefficient was set to 0.16, as Belmez is far from the coast.
- The number of rainy days per month (NRD, days month^{-1}) was calculated by considering only those days with precipitation exceeding 0.5 mm as "rainy."

43.4 Productivity

43.4.1 Leek Sown 1 October

The average duration of the 4 stages assumed for the calculations were 30-30-120-30 days. The base temperature is 3 °C. Using average monthly temperatures for this location (estimated as the average of the T_{max} and T_{min} values for each month in Table 43.3) and assuming months of 30 days, the thermal time required to complete each of the 4 stages (TT) is:

Stage A (October):

$$TT_A = 30\times(16.3-3) = 399\,°\mathrm{C\,day}$$

Stage B (November):

$$TT_B = 30\times(10.15-3) = 214\,°\mathrm{C\,day}$$

Stage C (December, January, February, March):

$$TT_C = 30\times(7.4-3)+30\times(7.1-3)+30\times(7.9-3)+30\times(11-3) = 641\,°\mathrm{C\,day}$$

Stage D (April):

$$TT_D = 30\times(13.2-3) = 307\,°\mathrm{C\,day}$$

Using the mean daily temperatures of the last campaign (2012/2013), we summed thermal time starting from October 1 until we accumulated the thresholds indicated above. According to this, the end of the four stages was estimated to occur on November 2 (stage A), November 27 (stage B), April 7 (stage C), and May 4 (stage D).

The fraction of intercepted photosynthetically active radiation (PAR) (f_{PI}) was calculated for each day as a function of the crop coefficient (see Sect. 13.7 in Chap. 13). The maximum K_c for leek is 1.2 and the final K_c is 1.0. According to the project statement, we assumed f_{PI} = 0.1 in stage A and $f_{PI} = K_c - 0.3$ in stages C and D. The values for stage B were calculated by linear interpolation between 0.1 (November 2) and 0.9 (November 27). Likewise, the values for stage D were calculated by linear interpolation between 0.9 (April 7) and 0.7 (May 4).

Intercepted PAR for each day ($IPAR_i$) of the growing cycle was determined as:

$$IPAR_i = 0.45 \times R_s \times f_{Pi}$$

where 0.45 is the ratio of *PAR* over solar radiation. Summing the values for the whole growing cycle, a total intercepted *PAR* of 846 MJ m^{-2} was obtained.

The expected Radiation-Use Efficiency (*RUE*) was calculated with Eq. 13.11. Yield composition was taken from Appendix in Chap. 35. On a dry matter basis, 9% is protein and 2% is fat. For simplicity, it is assumed that the remainder (89%) are carbohydrates. In the calculations, we considered an *RUE* for carbohydrates (RUE_c) of 2 g MJ^{-1} (C3 species) and a harvest index of 0.5, which led to an expected *RUE* of 1.94 g MJ^{-1}.

Potential yield (on a dry matter basis) was calculated with Eq. 13.8:

$$Y = HI \times RUE \times \sum_{\text{emergence}}^{\text{harvest}} IPAR_i = 0.5 \times 1.94 \times 846 = 819\,\text{g}\,\text{m}^{-2}$$

Fresh yield was calculated by considering the fraction of dry matter in the harvested organ (f_{dm}), which is 17% (Appendix in Chap. 35):

$$Y_{fresh} = Y / f_{dm} = 819 / 0.17 = 4817\,\text{g}\,\text{m}^{-2} = 48.2\,t\,ha^{-1}$$

The average fresh yield in Spain is around 33 t ha^{-1}, which is lower than the calculated yield. The difference may be attributed to other factors limiting yield (water and nutrient deficiencies, pests and diseases, incorrect management, etc.).

43.4.2 Pepper Sown 1 May

The average duration of the 4 stages assumed for the calculations were 20-35-40-20 days. The base temperature is 7 °C. Using mean monthly temperatures for our location, the thermal time required to complete each of the 4 stages was:

Stage A (May 1–May 20):

$$TT_A = 20 \times (17.3 - 7) = 206\,°\text{C}\,\text{day}$$

Stage B (May 20–30, June 1–25):

$$TT_B = 10 \times (17.3 - 7) + 25 \times (23 - 7) = 503\,°\text{C}\,\text{day}$$

Stage C (June 26–30, July, August 1–5):

$$TT_C = 5 \times (23 - 7) + 30 \times (25.5 - 7) + 5 \times (25.6 - 7) = 728\,°\text{C}\,\text{day}$$

Stage D (August 6–25):

$$TT_D = 20 \times (25.6 - 7) = 372\,°\text{C}\,\text{day}$$

Using the mean daily temperatures of the last campaign (2012/2013), we summed thermal time starting from May 1, until we accumulated the thresholds above. According to this, the end of the four stages was estimated to occur on May 25 (stage A), July 1 (stage B), August 8 (stage C), and August 24 (stage D).

Again, the fraction of intercepted *PAR* was computed for each day as a function of K_c. The maximum K_c is 1.1 and the final K_c is 0.85 (mid values of the intervals shown in Appendix C in Chap. 10). We assumed f_{PI} = 0.1 in stage A and $f_{PI} = K_c - 0.3$ in stages C and D. The values for stage B were calculated by linear interpolation between 0.1 (May 25) and 0.8 (July 1). Similarly, the values for stage D were calculated by linear interpolation between 0.8 (August 8) and 0.55 (August 24).

Intercepted *PAR* was estimated daily as in leek. Summing the values for the growing cycle, total intercepted *PAR* was 748 MJ m^{-2}. According to Appendix in Chap. 35, the average composition of red pepper on a dry matter basis is 11.3% protein and 2.8% fat. For simplicity, it is assumed that the remainder (85.9%) are carbohydrates. In Table 13.1, the maximum value for the *HI* of pepper is 0.6. A value of 0.55 was considered for the calculations. As we are dealing again with a C3 species, RUE_c was set to 2 g MJ^{-1}. Under these conditions, the expected *RUE* was 1.92 g MJ^{-1}.

Using Eq. 13.8, yield (dry matter) was 790 g m^{-2}. According to Appendix in Chap. 35, f_{dm} is 12.5%, leading to a fresh yield of 63.19 t ha^{-1}. The average fresh yield of field-grown pepper in Andalusia, Spain, in 2012 was 32.52 t/ha, around 50% of the calculated yield. The difference may be attributed to other factors (different growing cycles, water and nutrient deficiencies, pests and diseases, incorrect management, etc.).

43.5 Seed Rates

In the calculations, we assumed that high-quality certified seed is used, so high viability (f_1 = 0.9) was considered for both crops.

43.5.1 Leek

According to Table 16.2, typical values of seed weight and planting density for leek are 2.8 mg $seed^{-1}$ and 25 plants m^{-2}, respectively. The seeds are very small, so a low fraction of emergence (f_2 = 0.7) was assumed. Applying Eq. 16.1, the estimated seed rate yielded 1.1 kg ha^{-1}.

43.5.2 Pepper

According to Table 16.2, seed weight ranges between 5 and 10 mg $seed^{-1}$ (we took 7.5 mg $seed^{-1}$) and planting density between 4 and 6 plants m^{-2} (we took 5 plants m^{-2}). The seeds are very small, so a low fraction of emergence (f_2 = 0.7) was assumed. Applying Eq. 16.1, the seed rate yielded 0.6 kg ha^{-1}.

43.6 Irrigation Schedules

43.6.1 Leek

The initial crop coefficient ($K_{c,ini}$) was calculated as a function of average daily ET_0 and the number of rainy days in stage A. In the last season (2012/2013), we had 7 rainy days in 33 days (Phase A). Thus, the fraction of wet days (f_w) was 0.21 and the wetting interval (WI):

$$WI = \frac{1}{0.75\, f_w \left(1 - f_w\right)} = 8\,\text{days}$$

As $WI > 4$ days, Eq. 10.6b was applied, yielding a $K_{c,ini}$ of 0.57. The mid and final values of the K_c for leek are 1.2 and 1.0, respectively. With these values and the duration of the 4 phases, the K_c curve was built (Fig. 43.1). Daily ET was calculated as the product of K_c and ET_0.

The soil is of medium texture, so a plant available water (PAW) of 120 mm m^{-1} was assumed. Allowable Depletion (AD) was calculated using Eq. 20.5, where a value of 0.14 was used for F_{AD}. As leek is not in Appendix C in Chap. 10, we adopted the value for onion, which is a close relative. The maximum ET_0 during the cycle was 3.7 mm day^{-1} (April). As a result, AD was 0.51. The maximum rooting depth of leek was not given in Appendix C in Chap. 10. By analogy, we adopted the minimum value (0.5 m) of the range reported for onion (interval 0.5–0.8 m).

The critical soil water deficit (SWD_c) was calculated as the product of PAW, AD, and rooting depth (Eq. 20.2), yielding 30 mm. Following the basic rule for irrigation scheduling (Chap. 20), irrigation was applied whenever SWD was expected to exceed 30 mm and the applied depth was equal to the value of SWD to restore soil

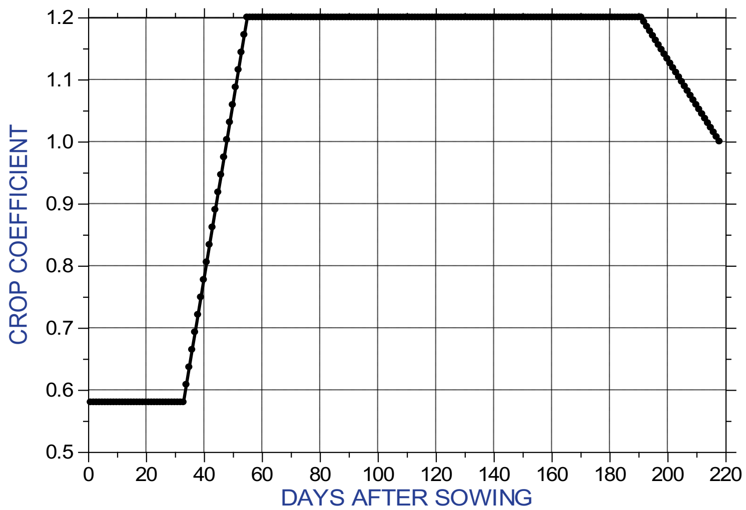

Fig. 43.1 Crop coefficient curve for leek sown October 1, 2012, in Belmez, Spain

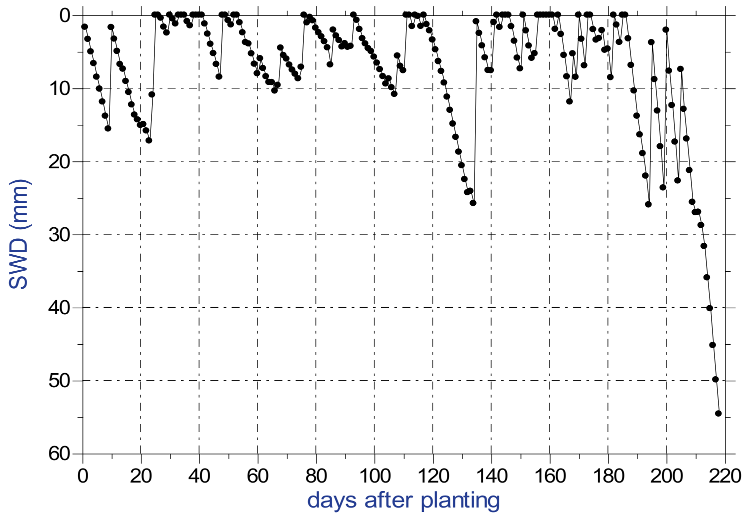

Fig. 43.2 Time course of soil water deficit for a leek crop sown October 1, 2012, in Belmez, Spain)

water to field capacity, minimizing the number of irrigations (Fig. 43.2). As rainfall is frequent during most of the growing season, we did not bother calculating the variation of SWD_c in the initial stages of crop growth, using directly its maximum value.

According to the rules, five irrigations would be required on dates 44, 104, 108, 114, and 123 (day of the year). However, the final irrigation was recalculated to leave the soil as dry as possible and to save water. Typically, field crops may end their growing cycle depleting 80–90% of *PAW*, but we should be more conservative as leek is harvested green. Considering a 60–70% use of *PAW*, the target *SWD* at the end of the cycle is around 36–43 mm. This was achieved by eliminating the last irrigation, which led to a final *SWD* of 44 mm and total net irrigation requirements of 120 mm for the season.

The hourly net application rate is calculated from the discharge rate of the sprinklers (q), their spacing (A), and the application efficiency (AE), all of them given in Table 43.2:

$$\frac{q \times AE}{A} = 6.375\,\text{mm}\,\text{h}^{-1}$$

This value is used for calculating the duration of irrigation events. The irrigation schedule includes four 4.7 h irrigations on the days of year 44, 104, 108, and 114.

43.6.2 Pepper

In phase A (May 2013), we had 4 rainy days in 25 days and the average ET_0 was 4.4 mm day^{-1}. Therefore, f_w and WI were 0.16 and 9.6 days, respectively.

These values led to a $K_{c,ini}$ of 0.41 using Eq. 10.6b. The mid and final values of K_c were 1.1 and 0.85 (Appendix C in Chap. 10). The K_c curve is shown in Fig. 43.3. Daily ET was calculated as the product of K_c and ET_0.

In the calculation of SWD_c, a PAW of 120 mm/m was again considered. The maximum ET_0 during the cycle was 7.7 mm day^{-1} (July) and F_{AD} is 0.14 for pepper according to Appendix C in Chap. 10. Following Eq. 20.5, AD results −0.08. As this value is below zero, we adopt an AD of 0.2. The maximum rooting depth of pepper was taken from Appendix C in Chap. 10. We adopted the maximum value for the interval (1.0 m) which equals soil depth. Otherwise, SWD_c takes a small value not suitable for sprinkler irrigation. Considering all this, the calculated SWD_c was 24 mm.

Following the basic rule (Chap. 20), irrigation was applied whenever SWD was expected to exceed 24 mm and the applied depth was equal to the existing SWD to restore soil water to field capacity (Fig. 43.4). In May 2013, the SWD was eventually negative, which means that some percolation could occur, but it was assumed as negligible. According to the rules, 23 irrigations of 24 mm would be required from DOY 133 to DOY 233. However, we need to leave the soil as dry as possible. Considering that the crop is harvested green, we were conservative and adopted a 60% use of PAW by the end of the cycle, which implies finishing the season with a SWD of 72 mm. This was achieved by eliminating the last two irrigations, leading to total net irrigation requirements of 504 mm for the season.

As seen before, the irrigation system delivers 6.375 mm h^{-1}, so irrigations should last 3.76 h. Irrigation should be applied in the days of year 133, 159, 165, 172, 176, 179, 182, 185, 188, 191, 193, 197, 200, 203, 206, 210, 213, 216, 219, 222, and 225.

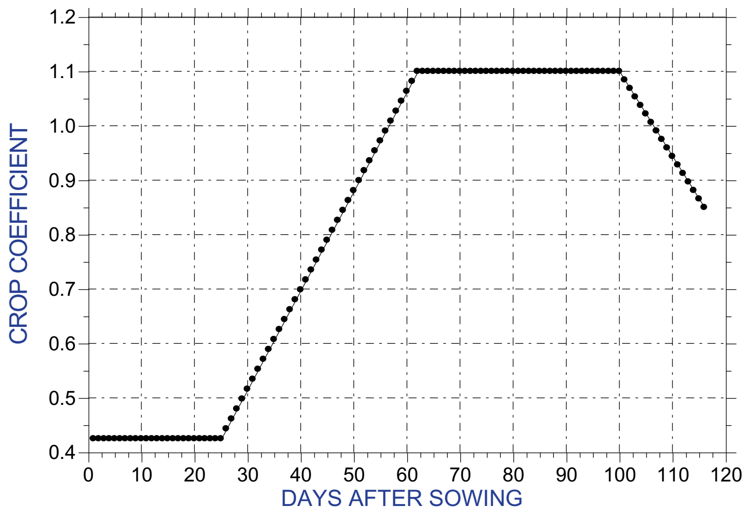

Fig. 43.3 Crop coefficient curve for a pepper crop sown May 1, 2013 in Belmez, Spain

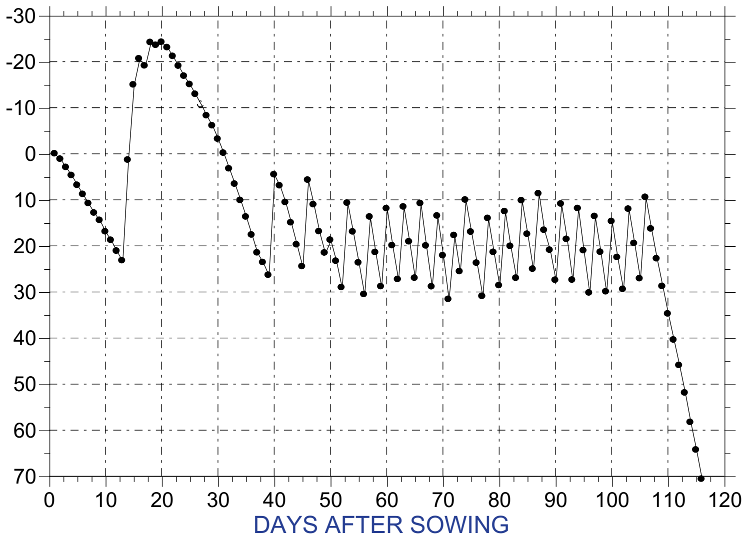

Fig. 43.4 Time course of soil water deficit for a pepper crop sown May 1, 2013, in Belmez, Spain

43.7 Leaching Fraction Required

The amount of irrigation that should be added to that calculated in Sect. 43.6 to obtain maximum yield is calculated here. Irrigation water has an EC_w of 1.7 dS m^{-1} (Table 43.2).

43.7.1 Leek

Appendix in Chap. 24 shows the threshold EC for maximum yield (EC_{eu}) for different crops but does not include leek. We adopted the parameters of a closely related species, onion (EC_{eu} = 1.2 dS/m). As we use sprinkler irrigation, Eq. 24.10 was applied, yielding a required Leaching Fraction (LF_r) of 0.56. Now, the amount of water to maintain maximum yield will be (Eq. 24.9):

$$I = \frac{120}{1 - 0.56} = 273\,\text{mm} = 2730\,\text{m}^3\,\text{ha}^{-1}$$

The duration of irrigations should be corrected accordingly. This implies that the 4.7 h duration should be increased to 10.7 h.

43.7.2 Pepper

EC_{eu} for pepper is 1.5 dS m^{-1} (Appendix in Chap. 24). As we use sprinkler irrigation, Eq. 24.10 was applied, yielding a required Leaching Fraction (LF_r) of 0.38. The amount of water to apply must be:

$$I = \frac{504}{1-0.38} = 813\,\text{mm} = 8130\,\text{m}^3\,\text{ha}^{-1}$$

Therefore, the duration of irrigations (3.76 h) should be increased to 6.06 h.

43.7.3 Farm

The average irrigation requirement for the whole farm is obtained as the average for the two crops, which is 5430 m^3 ha^{-1}.

43.8 Fertilizer Program

43.8.1 N Fertilization

The N fertilizer requirement (N_f) was estimated using Eq. 27.7, with the following assumptions:

- Residual N (N_{end}): 10 kg ha^{-1} (lowest value in the range indicated in Box 27.2)
- Ratio of N in roots and shoots (f_{NR}): 0.2
- Mineralization coefficient (k_{im}): 0.7 (non-legumes with tillage)
- Total N received by atmospheric deposition and irrigation water (N_{other}): 10 kg/ha (upper value in the range indicated in Sect. 27.2.3)
- Fraction of residues left in the field (F_{res}): 1 for the two crops, as indicated in the practical project statement
- Fraction of applied N lost (n): 0.1 (we aim at a high efficiency)

The N in yield and residues was calculated for each crop as:

$$N_{yield} = Y \cdot NC_{yield}$$

$$N_{res} = Y \frac{1-HI}{HI} NC_{res}$$

where Y is dry yield and NC_{yield} and NC_{res} are the N concentrations in the harvested organ and the residues, respectively. Y was taken as 80% of the value calculated in Sect. 43.4, as required by the project statement. NC_{yield} and NC_{res} were taken crop from Appendix in Chap. 26. The values used for the calculations are given in Table 43.5.

Table 43.5 Nitrogen (N_f) and urea requirements for each crop and the rotation

Crop	Y kg/ha	NC_{yield} kg N/kg	NC_{res} kg N/kg	N_{yield} kg N/ha	N_{res} kg N/ha	N_f kg N/ha	Urea kg/ha
Leek	6550	0.014	0.01	92	66	142	309
Pepper	6316	0.019	0.01	120	41	128	279
Rotation						135	294

The values of yield (dry matter), concentration of N in the harvested organ (NC_{yield}) and residues (NC_{res}), and amounts of N in yield (N_{yield}) and residues (N_{res}) are also shown

The calculated N requirements (N_f) were 142 kg N ha^{-1} for leek and 128 kg N ha^{-1} for pepper (Table 43.5). These amounts may be supplied with urea, which has a concentration of 0.46 kg N kg^{-1} (Table 25.2). The results are shown in Table 43.5. The average use of urea in the farm corresponds to the average for the two crops, i.e., 294 kg urea ha^{-1}.

43.8.2 P and K Fertilization

A build-up and maintenance strategy was followed for calculating the P and K requirements (P_f and K_f). According to our data, Olsen P is 18 mg kg^{-1} (Table 43.2). The threshold *STL* is calculated using Eq. 28.1. The soil is sandy loam, so we assume a clay content of 70 mg/kg (Table 8.2) and pH = 8, so the threshold is 17.4. Therefore, we are in the maintenance range and fertilizers should only add the amount of P exported. The same applies to K since the corresponding soil test level (300 mg kg$^{-1;}$Table 43.2) exceeds the threshold (175 mg kg^{-1}; Table 28.3), but it is below the maintenance level (which is twice the threshold, i.e., 350 mg kg^{-1}).

As only yield is exported, P_f and K_f were estimated from:

$$P_f = Y \times PC_{yield}$$

$$K_f = Y \times KC_{yield}$$

where Y is yield (on a dry matter basis), assumed as 80% of the value calculated in Sect. 43.4, and PC_{yield} and KC_{yield} are the concentrations of P and K in the harvested organ, which were taken from Appendix in Chap. 28. Fertilizer requirements were calculated considering their richness in P or K (Table 25.2). We will use straight fertilizers like triple superphosphate (TSP, 20% P) and potassium chloride (KCl, 50% K) for both crops. The results are shown in Table 43.6. The average use of TSP and KCl in the farm corresponds to the average for the two crops, i.e., 83 kg TSP ha^{-1} and 223 kg KCl ha^{-1}.

43.8.3 Cost of the Fertilization Program

Our fertilizer dealer sells TSP at 300 € t^{-1}, KCl at 550 € t^{-1}, and urea at 550 € t^{-1}. Using these prices, the purchase of fertilizers at the farm requires 24.9 € ha^{-1} year^{-1}

Table 43.6 Phosphorous (P_f) and potassium (K_f) requirements and needs of triple superphosphate (TSP) and potassium chloride (KCl) for each crop and the rotation

Crop	PC_{yield} kg P/kg	KC_{yield} kg K/kg	P_f kg P/ha	K_f kg K/ha	TSP kg/ha	KCl kg/ha
Leek	0.0021	0.0106	14	69	69	139
Pepper	0.003	0.024	19	152	96	306
Rotation			16.5	111	83	223

The concentrations of P and K in the harvested organ (PC_{yield} and KC_{yield}) are also given

Table 43.7 Comparison of the estimated requirements of urea, triple superphosphate, and potassium chloride obtained for each crop and the farm with those calculated with *FertiliCalc*

	Urea (kg ha^{-1})		Triple superphosphate (kg ha^{-1})		Potassium Chloride (kg ha^{-1})	
Crop	Calculation	FertiliCalc	Calculation	FertiliCalc	Calculation	FertiliCalc
Leek	309	262	69	69	139	139
Pepper	279	320	96	96	306	306
Rotation	294	291	83	83	223	223

for TSP, 122.4 € ha^{-1} year^{-1} for KCl, and 161.7 € ha^{-1} year^{-1} for urea. Then the annual cost of the fertilizer program (excluding application cost) results in 309 € ha^{-1}.

43.8.4 Comparison with FertiliCalc Outputs

Our estimates of fertilizer requirements for P and K matched those obtained with *FertiliCalc* (Table 43.7). For N, the amounts of urea calculated by *FertiliCalc* were slightly higher for pepper and slightly lower for leek, but the value for the rotation was similar to our estimates.

43.9 Crops Calendars and Energy Requirements

43.9.1 Crop Calendars

We assume that the farm is divided into two fields of equal size (field 1 and field 2) and show in a simple diagram the distribution of the crops (L for leek and P for pepper) during the 2 years of the rotation (Table 43.8).

Then we establish the crop calendar for one of the fields. For instance, the calendar for field 1 is shown in Table 43.9. The crop calendar for field 2 would be the same but starting with year 2.

Table 43.8 Spatiotemporal distribution of the crops within the farm over 2 years

Year	1												2											
Month	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
Field 1					P	P	P	P		L	L	L	L	L	L	L								
Field 2	L	L	L	L													P	P	P	P		L	L	L

L leek, *P* pepper

Table 43.9 Calendar of operations over 2 years in a field with a pepper-leek rotation

Year	Date	Operation
1	1-Mar	Apply P, K, and part of N
1	1-Apr	Harrow
1	20-Apr	Herbicide (contact)
1	1-May	Sowing pepper
1	10-Jun	Apply N pepper
1	15-Jun	Harrow pepper for weed control
1	31-Aug	Harvest pepper
1	1-Sep	Moldboard plow
1	2-Sep	Apply P, K, and part of N
1	7-Sep	Harrow
1	25-Sep	Herbicide (contact)
1	1-Oct	Sowing leek
1	15-Nov	Herbicide leek
2	1-Feb	Apply N leek
2	30-Apr	Harvest leek
2	15-Sep	Moldboard plow

43.9.2 Energy Requirements

Energy requirements associated with the previous list of operations and estimated inputs are calculated from equations and data reported in Chap. 37. The main inputs and outputs of the calculations are provided in Tables 43.10 (operations) and 43.11 (materials). The estimated total energy expenditure on the farm was 45,598 MJ ha^{-1} $year^{-1}$.

43.9.3 Comparison with CropEBal Outputs

The calculation using *CropEBal* gave a total of 44,459 MJ ha^{-1} $year^{-1}$, which was very similar to our estimates.

Table 43.10 Energy expenditure in the operations of a leek-pepper rotation

Operation	No. operations (# ha^{-1} (2 year)$^{-1}$)	No. operations (# ha^{-1} $year^{-1}$)	Energy expenditure (MJ $operation^{-1}$)	Energy expenditure (MJ ha^{-1})
Sow leek	1	0.5	340	170
Sow pepper	1	0.5	340	170
Fertilizer applications	4	2	90	180
Plow	2	1	1200	1200
Harrow	3	1.5	300	450
Pesticide applications	3	1.5	90	135
Harvest pepper	1	0.5	1200	600
Harvest leek	1	0.5	1200	600
Total				3505

Table 43.11 Energy associated to the inputs used in a leek-pepper rotation

Input	Amount	Units	Unitary energy expenditure (MJ)	Total energy expenditure (MJ ha^{-1} $year^{-1}$)
Irrigation	5430	m^3 ha^{-1}		28,005
N fertilizer	135	kg N ha^{-1}	80	10,800
P fertilizer	16.5	kg P ha^{-1}	37	610.5
K fertilizer	111	kg K ha^{-1}	17	1887
Herbicide	1.5	kg a.i. ha^{-1}	358	537
Seed rate	0.9	kg seed ha^{-1}	15	13.5
Total				41,853

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Quantitative Analysis of Crop Production in an Irrigated Farm (Part II)

44

Álvaro López-Bernal and Francisco J. Villalobos

Abstract

In the class of Principles of Agronomy for Sustainable Agriculture at the University of Cordoba, students are grouped in pairs to analyze a crop rotation in a specific location. At the end of the semester, the students produce a written report and give an oral presentation of the main results. These activities are major determinants for the final grade of the students. The previous chapter presents a solved example of a practical project for a leek-pepper rotation grown in Belmez, Spain. Here we show a set of additional assignments for the practical project, presenting the solution for the same location and crop rotation. Sections within this chapter are related to frost protection, crop evapotranspiration, irrigation, salinity, fertilization, soil erosion, runoff, modifying the environment, and pesticide application.

44.1 Introduction

Here we show a series of sections that may be included as additional assignments for the practical project described in Chap. 43. For the sake of simplicity, we present the solution for each of them considering the same crop rotation (leek-pepper), location (Belmez, Cordoba), and farm characteristics.

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The sections are related to frost protection (44.2–44.4), ET (44.5–44.7), irrigation and salinity (44.8–44.10), fertilization (44.11–44.13), soil erosion and runoff (44.14 and 44.15), modifying the environment (44.16 and 44.17), and application of pesticides (44.18).

44.2 Probability of Frost

Calculate the probability of frost after March 1 and before December 1.

The dates of the first and the last frost in every season are shown in Table 44.1.

44.2.1 Probability of Frost After March 1

The probability is calculated using Eqs. 32.2 and 32.1. March 1 corresponds to day 181 after September 1 ($t = 181$), and the mean (m_{LF}) and standard deviation (s_{LF}) of the last frost were, respectively, 194.2 and 11.4 (Table 44.1), so:

$$x = \frac{t - m_{LF}}{s_{LF}} = \frac{181 - 194}{11.4} = -1.15$$

$$P\left(z \le x\right) = 0.5\left(1 - \sqrt{1 - \exp\left(\frac{-2x^2}{\pi}\right)}\right) = 0.12$$

We have several frost events every year ($P_y = 1$), so:

$$P\left(\text{frost after March 1}\right) = P_y \times P\left(z > x\right) = 1 \times \left(1 - 0.12\right) = 0.88$$

Table 44.1 Dates of the first and last frost (expressed as days from September 1) and minimum annual temperature recorded each winter in the period 2001–2013 in Belmez, Spain

Season	First frost	Last frost	Minimum T (C°)
2000/2001	73	174	−5
2001/2003	80	177	−5.5
2002/2003	93	201	−4.5
2003/2004	77	185	−8.7
2004/2005	67	190	−4.3
2005/2006	105	186	−3.6
2006/2007	76	204	−6.6
2007/2008	76	205	−6.5
2008/2009	86	213	−6.9
2009/2010	94	195	−5.4
2010/2011	91	196	−8.9
2011/2012	92	203	−3.9
2012/2013	79	195	−5.82
Average	84	194	−5.82
Standard deviation	10.3	11.4	1.67

Therefore, the probability of frost occurring after March 1 is 88%.

44.2.2 Probability of Frost Before December 1

Equations 32.2 and 32.3 should be applied this time, using the mean (m_{FF}) and standard deviation (s_{FF}) of the date of the first autumn frost (Table 44.1). December 1 corresponds to day 91 after September 1 ($t = 91$).

$$x = \frac{t - m_{FF}}{s_{FF}} = \frac{91 - 83.8}{10.3} = 0.68$$

$$P(z \le x) = 0.5\left(1 + \sqrt{1 - \exp\left(\frac{2x^2}{\pi}\right)}\right) = 0.75$$

$$P(\text{frost before December 1}) = P_y \times P(z \le x) = 1 \times 0.75 = 0.75$$

Therefore, the probability of frost occurring before December 1 is 75%.

44.3 Certainty of Not Exceeding a Minimum Temperature

Calculate the certainty of minimum temperature not being lower than −13 °C in a period of 20 years.

The minimum temperature in the period from September 1 to May 1 is given for each year in Table 44.1. The minimum annual temperature in Belmez has an average (m) of −5.82 °C and a standard deviation (s) of 1.67 °C.

The certainty was calculated with Eq. 32.6. Input parameters are the temperature threshold under consideration ($T_c = -13$ °C), the design period ($n_d = 20$ years), and two coefficients which depend on the mean and standard deviation of minimum temperature ($\alpha = s/1.283 = 1.30$ °C; $\beta = m + 0.577\alpha = -5.06$ °C). Therefore, the certainty of temperature not being lower than −13 °C is:

$$C = \left\{\exp\left[-\exp\left(\frac{-13-(-5.06)}{1.3}\right)\right]\right\}^{20} = 0.96$$

44.4 Date of First Autumn Frost

Calculate the date for the first autumn frost with cumulative probability 5% (the earliest frost in 20 years).

The probability of frost before a given date (t) can be calculated with Eqs. 32.2 and 32.3. These can be inverted for estimating the date of the first frost (t) at a given probability level. In Belmez, we have frosts every year ($P_y = 1$) and the values of m_{FF} and s_{FF} are reported in Table 44.1.

$$P(z \le x) = 0.5\left(1 \pm \sqrt{1 - \exp\left(\frac{-2x^2}{\pi}\right)}\right) = 0.05$$

We take the negative root as x < 0 and invert the equation, which leads to $x = -1.615$. As

$$x = (t - m_{FF}) / s_{FF}$$

we deduce $t = 66$ days after September 1, which is November 5.

44.5 Transpiration of an Isolated Tree

Calculate the transpiration of an isolated cypress with a crown of height of 6 m and width of 1 m in your location during July.

The mean ET_0 in July in Belmez is 7.7 mm day^{-1}. If the tree crown can be represented by a spheroid with length $h = 6$ m and horizontal radius $r = 0.5$ m, the projected envelope area for 1 rad (PEA_1) will be given by Eq. 3.24. For spheroids, the coefficients a_p and b_p are 0.3 and 0.35, respectively, which leads to $PEA_1 = 3.53$ m^2.

The mean interception of the tree envelope for 1 rad (c_1) can be calculated from Eqs. 3.25 and 3.26. For spheroids, $c_p = 0.64$ and $d_p = 0.026$. Assuming a leaf area density (μ) of 2 m^2 m^{-3}:

$$c_1 = 1 - \exp\left[-c_p \frac{\mu \pi h r^3}{2 PEA_1} + d_p\left(\frac{\mu \pi h r^3}{2 PEA_1}\right)^2\right] = 0.34$$

Daily intercepted radiation equivalent area (REA, m^2) may be calculated with Eq. 3.22 and 3.23. Required inputs include mean solar radiation in July ($R_s = 29.9$ MJ m^{-2} day^{-1}; Table 43.3), mean extraterrestrial radiation ($R_A = 40.4$ MJ m^{-2} day^{-1}), day length ($N_s = 14.3$ h, Table 43.4), PEA_1 (3.53 m^2), and c_1 (0.34):

$$\alpha' = 2\frac{R_s}{R_A} - 0.5 = 0.98$$

$$REA = 0.34 \times 3.53\left[1 - 0.98 + 0.98\left(1.84 - \frac{0.75 \times 40.4}{3.6 \times 14.3}\right)\right] = 1.50\,\mathrm{m}^2$$

For isolated trees, transpiration ($E_{p\,\mathrm{tree}}$) can be calculated as the product of REA (1.5 m^2), ET_0 (7.7 mm day^{-1}; Table 43.4), and the transpiration ratio for full interception (K_{tf}), which takes different values for different species (Eq. 9.19). Taking

K_{tf} = 1.1, reported for olive trees in Table 9.1, an evergreen species adapted to Mediterranean areas as cypresses, $E_{p\ \mathrm{tree}}$ is 12.7 L day^{-1}.

44.6 Calculation of *ET* for Designing an Irrigation System

Calculate the maximum *ET* that should be considered for designing the irrigation system assuming summer crops as maize or cotton.

The maximum ET_0 in our location (Belmez) occurs in July (average of 7.7 mm day^{-1}). At that time, summer crops have already achieved maximum cover, so expansion is no longer critical for crop productivity. Thus, an allowable depletion (*AD*) of 0.67 can be adopted. The soil is of medium texture, so a plant available water (*PAW*) of 120 mm m^{-1} is assumed. Maximum root depth is restricted by soil depth (1 m). Therefore, the critical *SWD* will be:

$$SWD_c = 0.67 \times 120 \times 1 = 80\,\mathrm{mm}$$

This will be the typical irrigation dose if the basic rule (Chap. 20) is adopted. On the other hand, the maximum K_c for summer crops is 1.2. Therefore, for an ET_0 of 7.7 mm day^{-1}, the daily *ET* will be 9.2 mm day^{-1}. The climate in our location is semiarid (climate type 1 in Sect. 10.6) so C = 1.21. Therefore:

$$\frac{ET_{75}}{ET_{avg}} = C - 0.06(C-1)\sqrt{I_a} = 1.21 - 0.06(1.21-1)\sqrt{80} = 1.097$$

where ET_{avg} is the average crop *ET* (9.2 mm day^{-1}), I_a the mean irrigation applied (80 mm), and ET_{75} the *ET* exceeded in 25% of the years only, which should be used for designing irrigation systems. Under our conditions, the latter will be 10.1 mm day^{-1}.

44.7 Calculation of *ET* Inside an Unheated Greenhouse

Calculate the *ET* of a tomato crop in May with full ground cover inside an unheated greenhouse with polyethylene cladding. Assume a transmissivity for solar radiation of 0.7.

Reference *ET* (ET_0) inside the greenhouse can be calculated using Eq. 10.10. In Belmez, during May, we have an average solar radiation (R_s) of 24.9 MJ m^{-2} day^{-1} (Table 43.3) so the solar radiation inside the greenhouse (R_{si}, MJ m^{-2} day^{-1}) can be estimated as:

$$R_{si} = 0.7 \times 24.9 = 17.4\ \mathrm{MJ\,m^{-2}\,day^{-1}}$$

The average temperature in May is 17.3 °C so the slope of the saturated vapor pressure versus temperature (Δ) is 0.12 kPa K^{-1} (Eq. 10.4). Under these conditions, Eq. 10.10 leads to an ET_0 of:

$$ET_0 = \frac{1}{2.45} 0.7 \frac{0.12}{0.12 + 0.067} 17.4 = 3.1 \text{ mm day}^{-1}$$

The maximum crop coefficient (K_c) for tomato in the open is 1.2 (Appendix C in Chap. 10). In a greenhouse, crop coefficients tend to be 10–20% higher. Assuming an increase of 15% in K_c (i.e., K_c = 1.38), crop *ET* would be 4.3 mm day^{-1}.

44.8 Optimum Seasonal Irrigation

Calculate the optimum seasonal irrigation for your crops in the last season with weather data. Consider prices of water 0.05 € m^{-3} and 0.50 € m^{-3}. Assume that the average yields of your crops under no water stress are 80% of the maximum (calculated in Sect. 43.4). Distribution uniformity is 0.70. Assume that soil evaporation is 25% of *ET*.

We will apply Eq. 23.12 for estimating the optimum irrigation amounts (I_{opt}). This equation requires data on the price of water (Q_I), total crop evapotranspiration (*ET*), soil evaporation (E_s), distribution uniformity (DU_{lq}), price of the crop at harvest (P_H), maximum yield (Y_x), and net irrigation requirements (I_{req}):

$$I_{opt} = \frac{3 I_{req}}{\sqrt{480 \frac{Q_I (ET - E_s)}{P_H Y_x} (1 - DU_{lq}) + (4 DU_{lq} - 1)^2}}$$

80% of potential dry yields are 6550 and 6316 kg ha^{-1} for leek and pepper, respectively. After searching for prices for the farmer, we found selling prices of harvest of 0.255 € kg^{-1} for leek and 0.25 € kg^{-1} for pepper. Considering the fractions of dry matter in the harvested organ reported in Appendix in Chap. 35 (0.17 for leek and 0.125 for pepper), P_H was estimated as 1.5 € kg^{-1} for leek and 2.0 € kg^{-1} for pepper.

Seasonal *ET* (calculated in Sect. 43.6) is 398 mm for leek and 619 mm for pepper. As E_s represents 25% of total *ET*, the seasonal E_s is 99.5 mm for leek and 155 mm for pepper. I_{req} (calculated in Sect. 43.6) was 120 mm for leek and 504 mm for pepper in the 2012/2013 campaign.

Results for the two prices of water and the two crops are reported in Table 44.2. In summary, with cheap water, we should apply a gross amount of 194 mm to leek and 808 mm to pepper. With expensive water, the gross amounts should be 155 (leek) and 623 mm (pepper).

Table 44.2 Optimum irrigation requirements (in mm) for leek and pepper using cheap (0.05 € m^{-3}) and expensive (0.5 € m^{-3}) water price scenarios.

Crop	Cheap water (Q_I = 0.05 € m^{-3})	Expensive water (Q_I = 0.5 € m^{-3})
Leek	194	155
Pepper	808	623

44.9 Comparison of Alternative Water Qualities and Prices

The cost of pumping (energy + depreciation cost) is 0.10 € m^{-3}. You have two offers of irrigation water. Water A has EC_w = 1 dS m^{-1} and a price of 0.10 € m^{-3}. Water B has EC_w = 1.5 dS m^{-1} and a price of 0.05 € m^{-3}. Select the best option for your crops. Assume that the average yields of your crops under no water stress are 80% of the potential values (calculated in Sect. 43.4).

The maximum benefit is obtained for

$$I_{opt} = I_{req} + \sqrt{\frac{P_H \times Y_x \times B' \times EC_w \times I_{req}}{5Q_I}} < \frac{I_{req}\left(5\dfrac{EC_{eu}}{EC_w} - 1\right)}{5\dfrac{EC_{eu}}{EC_w} - 2}$$

where $B' = B_s/100$, P_H is the selling price of harvest (€ kg^{-1}), Y_x is maximum yield (kg ha^{-1}), I is irrigation applied (m^3 ha^{-1}), I_{req} is net irrigation requirement (m^3 ha^{-1}), Q_I is the price of water (€ m^{-3}), and EC_{eu} is the threshold electrical conductivity for maximum yield (dS/m).

As the inequality indicates, the solution is valid below the value of I at which maximum yield is achieved. According to the statement, $Y_{\max}$ is 80% of the potential dry yield, 6550 kgha^{-1} for leek and 6316 kg ha^{-1} for pepper. After searching for prices for the farmer, we found selling prices of harvest of 0.255 € kg^{-1} for leek and 0.25 € kg^{-1} for pepper. Considering the fractions of dry matter in the harvested organ reported in Appendix in Chap. 35 (0.17 for leek and 0.125 for pepper), P_H (dry matter basis) was estimated as 1.5 € kg^{-1} for leek and 2.0 € kg^{-1} for pepper. I_{req} (calculated in Sect. 43.6) was 1200 m^3 ha^{-1} for leek and 5040 m^3 ha^{-1} for pepper in the 2012/2013 campaign.

Results for the two waters and the two crops are reported in Table 44.3. In both cases, the second term of the equation above is lower, so the maximum yield will be reached. For both crops, we get a higher benefit using the cheaper water (B).

44.10 Leaching Fraction to Maximize Crop Water Productivity

Calculate the leaching fraction to maximize crop water productivity for the two crops.

Table 44.3 Optimum irrigation amounts and net benefit for leek and pepper under two scenarios of quality and price of the water

Water	EC_w (dS m^{-1})	Q_I (€ m^{-3})	Crop	I_{opt} (m^3 ha^{-1})	Benefit (€ ha^{-1})
A	1	0.2	Leek	1500	9525
A	1	0.2	Pepper	5956	11441
B	1.5	0.15	Leek	1800	9555
B	1.5	0.15	Pepper	6720	11624

The optimum leaching requirement (LF_{opt}) can be calculated with Eq. 24.14, valid whenever it is lower than that the LF required for maximum yield (LF_{limit}). The electrical conductivity of irrigation water (EC_w) is 1.7 dS/m (Table 43.2).

44.10.1 Leek

Appendix in Chap. 24 does not include leek so we adopt the parameters of a closely related species, onion. The threshold EC_{eu} is 1.2 dS m^{-1} and the slope B_s is 16.1% (dS/m)$^{-1}$, so $B' = 0.161$. Using these values:

$$LF_{limit} = \frac{1}{5\frac{EC_{eu}}{EC_w} - 1} = 0.40$$

$$LF_{opt} = \sqrt{\frac{0.2\,B' EC_w}{1 + B'\left(EC_{eu} - 0.2\,EC_w\right)}} = 0.22$$

As $LF_{opt} < LR_{limit}$, the optimum LF will be 0.22.

44.10.2 Pepper

According to Appendix in Chap. 24 the threshold EC_{eu} is 1.5 dS m^{-1} and the slope B_s is 14% (dS/m)$^{-1}$, so $B' = 0.14$. Using the same equations, $LF_{opt} = 0.20$ and $LF_{limit} = 0.29$ are deduced. Therefore, the optimum LF will be 0.20.

44.11 Sulfur Exports in a Rotation

Calculate the exports of sulfur in your rotation. Modify the fertilizer program to compensate for these exports. Assume that the average yield of your crop is 80% of the estimated maximum. The concentration of S is 4 g/kg for leek and 1 g/kg for pepper.

Sulfur exports (S_{export}) can be calculated by considering dry yield (Y), the fraction of residues left in the field (F_{res}), and sulfur concentrations in the harvested organ (SC_{yield}) and residues (SC_{res}):

$$S_{export} = Y \times SC_{yield} + \left(1 - F_{res}\right)\frac{\left(1 - HI\right)}{HI} Y\, SC_{res}$$

In our leek-pepper rotation, residues are left in the field ($F_{res} = 1$), so the exports are directly calculated from the product of Y and SC_{yield}. The results are presented in Table 44.4.

Table 44.4 Dry yield (Y), S concentration in the harvested organ (SC_{yield}), and S exports (S_{export}) for the leek-pepper rotation

Crop	Y (kg ha^{-1})	SC_{yield} (kg S kg^{-1})	S_{export} (kg S ha^{-1})
Leek	6550	0.004	26.2
Pepper	6316	0.001	6.3
Crop rotation			16.25

To compensate for the exported sulfur, we have several alternatives to the fertilization plan proposed for our leek-pepper rotation in Sect. 43.8. For instance, we may:

(a) *Use superphosphate instead of triple superphosphate*
The P requirement for the rotation was 16.5 kg P ha^{-1} (Table 43.6) that may be supplied by 206 kg/ha of superphosphate (8% P, 12% S; Table 25.2). With this amount, we are adding 24.75 kg S ha^{-1}. This is 8 kg S ha^{-1} above the S requirement.

(b) *Use potassium sulfate instead of potassium chloride*
The K requirement for the rotation is 111 kg K ha^{-1} (Table 43.6), equivalent to 267 kg ha^{-1} of potassium sulfate (41.5% K, 17% S; Table 25.2). Therefore, we will supply 45.5 kg S ha^{-1}, almost 30 kg S ha^{-1} above the S requirement.

(c) *Use ammonium sulfate instead of urea*
The N requirement for the rotation is 135 kg N ha^{-1} (Table 43.5). Using ammonium sulfate (21% N, 24% S; Table 25.2), we need 643 kg ha^{-1} of the fertilizer, supplying also 154 kg S ha^{-1}, which implies a huge S excess.

(d) *Use ammonium nitrosulfate instead of urea*
Using ammonium nitrosulfate (26% N, 12% S; Table 25.2), we need 519 kg ha^{-1} of the fertilizer, supplying 62 kg S ha^{-1}, which is clearly above sulfur requirements.

Comparing the different alternatives, the first (superphosphate) is the one closest to the objective of compensating exported sulfur.

44.12 Selection of the Best Fertilizers

The prices of different fertilizers are shown in Table 44.5. (A) Calculate the best combination for your rotation assuming that around 30% of N and all P and K are applied before planting. (B) Repeat the calculations if sulfur exports have to be compensated with fertilizers.

For our crop rotation, annual requirements of P, K, and S were, respectively, 16.5 kg P ha^{-1} (Table 43.6), 111 kg K ha^{-1} (Table 43.6), and 16 kg S ha^{-1} (Sect. 44.11). N fertilizer requirements were 142 kg N ha^{-1} for leek and 128 kg N ha^{-1} for pepper (Table 43.5).

The amounts of fertilizers needed to satisfy these requirements are calculated considering their concentration of N, P, and K (Table 25.2).

Table 44.5 Prices of different fertilizers

Fertilizer	Price (€ t^{-1})
Superphosphate	297
Ammonium sulfate	325
Potassium chloride	401
Urea	423
Triple superphosphate (TSP)	448
Di-ammonium phosphate (DAP)	545
Potassium sulfate	1108

Table 44.6 Amounts of fertilizers and cost for two alternative fertilization plans

Alternative	Fertilizer	Amount (kg ha^{-1})	Cost (€ ha^{-1})	Total cost (€ ha^{-1})
1	DAP	83	45	244
	Urea	261	110	
	Potassium chloride	222	89	
2	TSP	83	37	250
	Urea	294	124	
	Potassium chloride	223	89	

A. In general, the most economical option is using straight fertilizers. For P, however, DAP is competitive with TSP as it includes some N. The best alternatives are shown in Table 44.6.
B. Table 44.7 below shows different combinations of three to four products that meet the sulfur requirements. The most expensive option is the one that includes potassium sulfate. The cheapest alternative includes ammonium sulfate, DAP, urea, and potassium chloride. In this case, ammonium sulfate, DAP, and potassium chloride would be applied before planting and all the urea would be applied as top dressing. DAP is slightly better than TSP (compare alternatives 2 and 4).

44.13 Leaching Index

Calculate the Leaching Index in your location.

The *LI* is calculated as the product of a Percolation Index (*PI*) and a Seasonal Index (*SI*). The former is calculated using Eq. 26.4. Inputs include annual rainfall (P = 533 mm in our location; Table 43.3) and a modified curve number (CN') that takes values of 28, 21, 17, and 15 for hydrologic groups A, B, C, and D, respectively (Chap. 8). Our soil is of medium texture, so we will assume that the hydrologic group is B ($CN' = 21$), which leads to:

$$PI = \frac{\left(P - 10160/CN' + 101.6\right)^2}{P + 15240/CN' - 152.4} = 20.55\,\text{mm}$$

Table 44.7 Amounts of fertilizers and cost for four fertilization plans that meet sulfur requirements

Alternative	Fertilizer	Amount (kg ha^{-1})	Cost (€ ha^{-1})	Total cost (€ ha^{-1})
1	Superphosphate	206	61	274
	Urea	294	124	
	Potassium chloride	223	89	
2	Ammonium sulfate	68	22	259
	Urea	263	111	
	Potassium chloride	223	89	
	TSP	83	37	
3	Potassium sulfate	96	106	324
	Potassium chloride	142	57	
	Urea	294	124	
	TSP	83	37	
4	Ammonium sulfate	68	22	253
	DAP	83	45	
	Urea	230	97	
	Potassium chloride	223	89	

SI represents the concentration of rainfall during the winter period, and it can be calculated using Eq. 26.5, which requires total rainfall during autumn-winter (P_w, October 1 to March 31 in N latitudes) and annual rainfall (P). In our location $P_w = 376.6$ mm and $P = 533$ mm, which leads to:

$$SI = \left(\frac{2P_w}{P}\right)^{1/3} = 1.12$$

Therefore, *LI* is 23 mm, which is rather low.

44.14 Calculation of Soil Erosion

Calculate soil erosion for your rotation. Assume that the slope is 2% and the slope length is 100 m. Tillage is performed in the direction of the slope. Consider also that in your location, rainfall erosivity may be calculated as:

$$R = 12.6\sum\left(P_i^2 / P\right) - 250$$

where P_i is the mean monthly rainfall of month i and P is the total annual rainfall.

Considering the data reported in Table 43.3, $\Sigma(P_i^2/P) = 58.2$ mm so R = 483. The factors related to soil erodibility (K), to the effect of the cover and management (C), to soil steepness (NT) and tillage direction (P) can be taken from Table 18.1. We select $K = 0.027$ (sandy loam soil with low organic matter), $C = 0.37$ (mid value with plow), $NT = 0.3$ (slope of 2%), and $P = 1$ (tillage in the direction of the slope).

The slope steepness and length factor (LS) is calculated from Eq. 18.3 from the slope ($p_t = 2\%$), slope length ($l_t = 100$ m), and NT (0.3):

$$LS = \left[0.065 + 0.0456 p_t + 0.006541 p_t^2\right]\left(l_t / 22.1\right)^{NT} = 0.29$$

Soil loss by erosion (*SLE*) is subsequently estimated from *RUSLE* (Eq. 18.1):

$$SLE = R\,K\,LS\,C\,P = 483 \times 0.027 \times 0.29 \times 0.37 \times 1 = 1.4\ \mathrm{t\,ha^{-1}\ year^{-1}}$$

This value is very low, according to Table 18.2.

44.15 Calculation of Runoff

Calculate runoff for the first day with rainfall greater than 30 mm in your location starting on the first year of the weather data set. Consider separately the two crops of your rotation. Assume that the soil is very wet.

Our soil is medium texture, so we assume that the hydrologic group is B. In our location, Belmez, we have a rainfall of 51.8 mm on January 11, 2001. The farm is divided in two plots (one for leek, the other for pepper).

44.15.1 Leek Plot

At the time of the rainfall, the crop is in the field so the hydrologic condition is good. From Table 8.2, we take row crops in straight rows for hydrologic group B with good hydrologic conditions, so *CN2*=78. As the soil is wet, we assume that *CN* = *CN3*, which is deduced from Eq. 8.17:

$$CN3 = 78\,e^{0.00673(100-78)} = 90$$

Now *SMX* is calculated (Eq. 8.20):

$$SMX = 254\left(\frac{100}{90} - 1\right) = 28.2\,\mathrm{mm}$$

As *P* (51.8 mm) is higher than 0.2 *SMX* (5.6 mm), surface runoff is calculated from Eq. 8.21:

$$SR = \frac{(51.8 - 0.2 \times 28.2)^2}{51.8 + 0.8 \times 28.2} = 28.6\,\mathrm{mm}$$

44.15.2 Pepper Plot

At the time of the rainfall event, the crop is not in the field. In Table 8.2, we take bare soil for hydrologic group B, so *CN2* = 86. As the soil is wet, we assume that *CN* = *CN3*, which is deduced from Eq. 8.17:

$$CN3 = 86\,e^{0.00673(100-86)} = 94$$

Now *SMX* is calculated (Eq. 8.20):

$$SMX = 254\left(\frac{100}{94} - 1\right) = 16.2\,\text{mm}$$

As *P* (51.8 mm) is higher than 0.2 *SMX* (3.2 mm), surface runoff is calculated from Eq. 8.21:

$$SR = \frac{\left(51.8 - 0.2 \times 16.2\right)^2}{51.8 + 0.8 \times 16.2} = 36.4\,\text{mm}$$

44.16 Calculation of the Maximum Temperature Inside an Unheated Greenhouse

Calculate the maximum temperature on a clear day in May inside the unheated PE greenhouse, which has a height of 3 m and is occupied by a tomato crop with full ground cover. The air inside is renewed 25 times per hour.

The maximum temperature in May is 24.9 °C (Table 43.3) and solar radiation on clear days is 29.8 MJ m^{-2} day^{-1} (Table 43.4). For transmissivity of 0.7, R_{si} on a clear day in May will be:

$$R_{s\,in} = 0.7 \times 29.8 = 20.86\ \text{MJ m}^{-2}\ \text{day}^{-1}$$

At the time of maximum temperature, solar radiation may be deduced from Eq. 15.2:

$$R_{sx\,in} = 0.84\frac{\pi}{2}\frac{10^6 R_{s\,in}}{3600 N_s} = 0.84\frac{\pi}{2}\frac{10^6 \times 20.86}{3600 \times 14.1} = 543\,\text{W m}^{-2}$$

where N_s is the day length (Table 43.4). Now, we will use Eq. 31.3 to deduce the temperature inside the greenhouse (T_{in}) as a function of the temperature outside (T_{out} = 24.9 °C). For a temperature of 24.9 °C, Δ is 0.19 kPa K^{-1} (Eq. 10.4). As vapor pressure in May is 0.89 kPa, assuming P_{at} = 101 kPa, ρC_p will be 1207 J m^{-3} K^{-1} (Eq. 5.9). k_{RN} is the ratio of net radiation/solar radiation inside the greenhouse, which may be taken as 0.7 (Sect. 31.14). As the crop has reached full cover, we assume that *ET* is the equilibrium evaporation so their ratio, k_L, is 1. Greenhouse height (h_g = 3 m) and renovation rate (*RR* = 25 times h^{-1}) are known. All this leads to:

$$T_{in} = T_{out} + \frac{\left(1 - k_L\right)\Delta + \gamma}{\Delta + \gamma}\frac{3600}{\rho C_p}\frac{k_{RN} R_{si}}{h_g\,RR} = 24.9 + \frac{0.067}{0.19 + 0.067}\frac{3600}{1207}\frac{0.7 \times 543}{3 \times 25} = 28.8°C$$

which is around 4 K warmer than the air outside.

44.17 Shading by a Windbreak

If you establish a windbreak using a plastic mesh with E-W orientation and height of 3 m in your location, calculate the shade width at solar noon on December 21 and June 21.

The zenith angle (θ) can be calculated from the latitude ($\lambda = 38.27°$), solar declination ($\delta = 23.45°$ on June 21 and $-23.45°$ on December 21), and solar time (when expressed as an angle, $h_a = 0°$ at solar noon) using Eq. 3.3. The width of the shade (w_{shade}) is given by:

$$w_{shade} = w + h \tan\theta$$

where w and h are the width and height of the structure (w is negligible, h = 3 m). The results are shown in Table 44.8.

44.18 Frequency of Days Suitable for Pesticide Applications

Calculate the frequency of days suitable for applying pesticides in your location. Assume that wind speed during the daytime can be calculated as

$$U_d = \frac{2}{N_s/24 + 1} U_{avg}$$

where U_{avg} is the average daily (24-h) wind speed and N_s is the daylength (hours).

The application of pesticides is not recommended on rainy days, when wind speed exceeds 2.5 m s^{-1} or when air temperature is higher than 32–35 °C. We will consider as days not suitable for applications those that have rainfall and/or with daytime wind speed greater than 2.5 m s^{-1} and/or with maximum temperature exceeding 35 °C. Calculations for our location (Belmez) were performed with Microsoft Excel. The frequency of days suitable for pesticide treatments for each month is shown in Table 44.9.

Table 44.8 Shade width of an E-W-oriented 3-m high windbreak at solar noon on December 21 and June 21 in Belmez, Spain

Date	λ (°)	δ (°)	h_a (°)	θ (°)	w_{shade} (m)
December 21	38.27	–23.45	0.0	61.7	5.58
June 21	38.27	23.45	0.0	14.8	0.79

Intermediate variables used in the calculations are λ (latitude), δ (solar declination), h_a (solar angle), and θ (zenith angle)

Table 44.9 Monthly frequency of days suitable for applying pesticides in Belmez, Spain

Month	1	2	3	4	5	6	7	8	9	10	11	12
Frequency	0.24	0.27	0.28	0.34	0.46	0.40	0.16	0.21	0.48	0.40	0.28	0.23

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