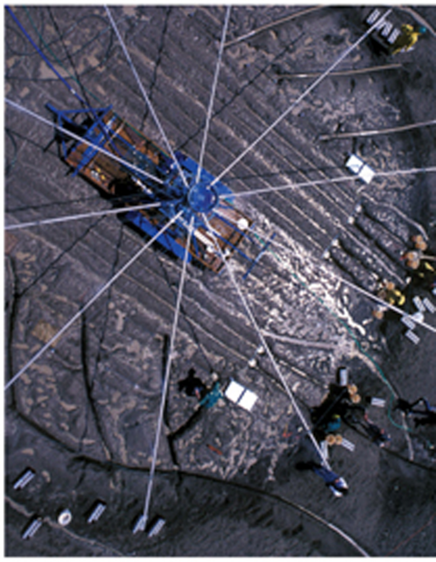
Soil Science & Management

SIXTH EDITION



Edward J. Plaster

Soil Science
& MANAGEMENT

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Soil Science and Management, 6th Ed.
Edward J. Plaster, M.Ed.

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PREFACE

Conceptual Approach

This sixth edition of *Soil Science and Management* continues the primary objectives of earlier editions, with the following four main purposes: (1) to acquaint the reader with the soil and water resources of the United States to enable a full appreciation of the importance of these resources; (2) to present soil science theory tied to the practice of those who use soil, mainly for growing plants; (3) to stress the sustainable management of soil and water resources by devoting detail to such subjects as soil and water conservation, conservation tillage, nutrient management, Best Management Practices, and sustainable agriculture; and (4) to relate soils to natural ecosystems.

New to the Sixth Edition

The major change to the sixth edition is an enhanced focus on horticultural soil use, particularly landscape horticulture. This change results from reviewer comments. Recognizing that many of the readers of this text do attend horticulture and landscaping programs, and that the majority of Americans live in cities and experience urban horticulture, I decided to follow the reviewer's request. Examples include coverage of landscape irrigation and drainage practices, expansion of greenhouse fertilization practices, and many others. Several mentions have also been made to LEED certification, a system for certifying "green" building construction that influences the landscape trade. It is hoped that the alterations will clarify the applicability of soil science to horticulture and engage student interest.

Since I did not wish this sixth edition to achieve doorstop weight, some coverage of agronomic practices has been condensed to make room for the new material. I feel this was achieved by deleting unnecessary details rather than weakening coverage of important ones.

Other, smaller changes are scattered liberally throughout the text. This includes updating various bits of data, expanding coverage of soil biology and geology, and providing more information on soils in the natural world. Also, since the effects of climate change have become even more pronounced, a bit more is added to that topic.

A more detailed chapter-by-chapter summary of changes follows:

Chapter 1: The section on soil uses was reworked to put greater emphasis on horticulture and landscape soil use, including an introduction to LEED certification, a third-party certification program for energy- and resource-efficient construction relevant to landscapers and landscape architects. It is also referred to elsewhere in the text. The section also introduces urban agriculture as a soil use, a topic of growing interest for many.

Chapter 1 includes a lot of data on land use and other details; most of these have been updated. Other smaller alterations appear throughout the chapter, including a bit more about Best Management Practices (BMPs) and soil's relationship to climate. An image of a rain garden was added to illustrate a BMP and an image of a staked palm to illustrate the concept of anchorage; to make room, the figure of the earth's cross section was dropped. There were minor changes in the review questions and enrichment activities.

Chapter 2: Chapter 2 now features an expanded discussion of rocks and minerals and their weathering, including an illustrative sidebar about weathering of Mount Rushmore. The accompanying drawing demonstrating the rock types was replaced by photos of actual rocks. Also new is a drawing of slope effects on soil. There are also several new review questions.

Chapter 3: There are no major changes. A sidebar was added about Histosols and climate, and a paragraph warning about some problems with published soil surveys. Some data on lands of the United States are updated, and some review and enrichment activities have been modified.

Chapter 4: Chapter 4 now exhibits more examples of soil physical properties related to horticultural soil use, including a sidebar about protecting soil from compaction around trees and a new photograph of what the soil in a yard looks like during building construction—such an indignity for soil to suffer. The section on soil temperature has been expanded because it is so important in horticulture. For example, frost heaving of plants and preventing it has been added. Also included in this section is the effect of fire on soil temperatures in natural ecosystems with an accompanying new figure; I felt it was timely given the great increase in wildfire incidence climate change is imposing on nature.

Numerous other smaller additions appear in this edition. The chapter calls out important simple practices for managing physical conditions of the soil, referring to them as axioms or cardinal rules, like "avoid bare soil." The intent is to focus student attention on certain simple, almost universal sustainable practices. There are several new review questions, including a couple applying soil science to the landscape industry.

Chapter 5: I reworked the coverage of the soil food web,expanding it and aligning it more with classical ecological knowledge of trophic levels. A well-known United States Department of Agriculture (USDA) graphic of the soil food web has been added to illustrate the principles, and the student is invited to refer back to it as a context for the rest of the chapter.

This edition puts more emphasis on the rhizosphere, even including material on rhizosphere effects on natural plant communities. That discussion continues with the effects on soil biology from the invasion of natural ecosystems by exotic plants like buckthorn. Numerous other smaller changes are also scattered throughout the chapter, like the introduction of intercropping as a practice to increase biological diversity in a garden or field. A couple of new enrichment activities are also added, as well a couple of new figures.

Chapter 6: There are no major changes in this chapter. A sidebar was added of some interest to those who work with plants in containers concerning the water-holding capacity of their growing media. I have expanded the concept of allelopathy, adding examples from landscaping and nature. The value of permanent vegetative cover for improving soil organic matter content is stressed a bit more, as well as its use in permaculture.

There are a couple of new images and little additions scattered throughout the chapter, especially of matters related to horticulture. One reviewer asked for a photo of an organic soil profile to augment the drawing I have, and I was lucky to find a photo of peat harvesting in Ireland that shows a profile.

Chapter 7: The main change to this chapter is the addition of material on elevation contours on the land and how they affect overland water flow. I added this partly because it is very important information for a diligent landscape designer, but also because it helps understand the soil conservation practices presented in Chapter 18. There are also several new review questions.

Chapter 8: In the past, this chapter has been pretty focused on water conservation in agricultural settings. In this edition, I have added some new basic material on water conservation in urban settings. To make room, the coverage of conservation in agricultural areas is slightly less detailed.

There is some updating of data used in the chapter and a couple of new images as well.

Chapter 9: In this edition, Chapter 9 expands coverage of drainage and irrigation in landscape settings. The new material certainly cannot substitute for classes dedicated to those subjects, and anyone wanting to design and install landscape irrigation needs to take a class on the subject. The same for stormwater management. This new material should help prepare for such classes.

To make room for this new material, I condensed the material on agricultural irrigation, which probably has been more detailed than needed in a basic text. Other bits were also edited out to avoid chapter size growing larger. This also meant losing a few figures and adding a few new ones.

I also expanded the discussion on controlled drainage, with a new drawing.

Chapter 10: This edition of Chapter 10 has relatively few changes. A photomicrograph of kaolinite clay particles has been added to assist students in visualizing clay structure.

Chapter 11: The biggest alteration is the treatment of soil acidification. This topic has been expanded to accommodate those who need to acidify soils—often landscapers and gardeners who want to grow acid-loving plants. Soil acidification is a less well-developed practice than liming.

As in many chapters of this edition, there are additional examples of the chapter topic applied to horticulture and natural ecosystems; for example, effects of acid rain on some forests, seaside salt issues, or natural plant communities that grow on salted soil. To make room, I slightly condensed material on salted and sodic soils. I hope this does not inconvenience some readers too much.

There are several new review questions, all using horticultural examples.

Chapter 12: Numerous smaller additions have been made to this chapter. The subject of nitrogen leakage into the environment has been introduced in greater detail, and will be developed more in later chapters. This topic also introduces the dramatic nature of the discovery of the Haber–Bosch process. More detail is added about phosphorus, and iron and manganese toxicities are discussed in more depth—these are common problems in some horticulture applications. Many of the changes relate to horticulture.

Chapter 13: In this edition, only a few minor changes were made to this chapter. I added some references to practices in horticulture, and stressed a bit more the importance of soil testing to avoid applying fertilizers in excess of plant needs.

Chapter 14: I expanded the material on slow-release fertilizers and the Haber–Bosch process. There are new comments about materials suitable or not suitable for organic growing. As in most chapters, there are more horticultural references. To keep the text from growing ever larger, I deleted or condensed some material, including that on blending calculations and pop-up fertilizers. There is a new image of a greenhouse injector and fewer images of field application equipment. There are also a few changed review questions.

Chapter 15: The material on manure has been modified with some information added and some deleted. The benefits, and potential problems, of these amendments have been stressed more. I condensed the material on manure handling systems while emphasizing manure's potential for phosphorus loading into the environment. Composting and anaerobic digestion are mentioned as ways to handle manure. I condensed the treatment of biosolids, mainly to save space. A new brief mention of small-scale composting appears. This edition also expands on the topic of human alteration of the nitrogen cycle and its effect on the environment and human health.

Chapter 16: In keeping with my desire to keep this text from developing gigantism, I condensed this chapter. Some detail and a couple of figures have been deleted. I added a section on the concept of intercropping as a cropping system.

Chapter 17: The sections of this chapter on fruit, vegetable, and nursery production are largely unchanged. The sections on greenhouse production and landscaping have been altered with changes scattered throughout. A major addition is a sidebar on the use of fertilizer injectors, including fertilizer calculations that are different from those standard calculations in Chapter 14. Minor changes include such matters as drawbacks of horticultural peat, water-quality issues, the use of low-ammonia and low-phosphorus feeds in container production, and others.

Chapter 18: This new edition updates some erosion data. I altered the text mainly in the section on water erosion control practices, with additional material throughout. Here I also refer back to the new material in Chapter 6 on the direction of water flow over land. There are also new references to soil conservation in landscape settings, including observing that landscaping *is* a soil conservation practice. The use of polyacrylamide polymers as a soil protectant is also mentioned for the first time. There are several new review questions.

Chapter 19: Some data are updated. There is additional new material on managing urban soils, like some detail about practices for LEED certification. Two new sidebars compare and contrast two ways of installing pavers: the traditional compacted base method and the newer permeable paving method. These provide examples of both purposeful compaction and a low-impact practice. Both also illustrate what is really an engineering use of soil.

Chapter 20: To make room for other additions in the text, I condensed this chapter. It also updates content for a couple of changes in the 2008 farm bill. Unfortunately, the 2012 farm bill was sitting in Congress at the time this edition was being prepared, so the content should be augmented by the instructor when the bill is passed.

In the Enrichment Activities section at the end of the chapters, some old or defunct Web sites have been deleted or updated, and I have a added a few sites of interest that I encountered while preparing this edition. I, along with the publisher, can affirm that the Web site URLs referenced were accurate at the time of printing. However, due to the fluid nature of the Internet, we cannot guarantee their accuracy for the life of the edition. Each activity attempts to provide the user with enough information to locate the Web site even if the link becomes out of date.

Ancillary Support Materials

The following supplements provide instructors with comprehensive resources for teaching the materials found in the textbook.

Lab Manual to accompany* Soil Science and Management, *Sixth Edition

By Philip G. Gibson

ISBN-13: 978-0-8400-2434-3

The Lab Manual provides activities related to the text material in each chapter. Each chapter contains a purpose, an overview, activities along with a list of equipment and materials, and follow-up questions to challenge the students. Students can complete all or selected portions of each chapter's activities. In addition, many of the activities can be modified to allow students to complete them off-campus or at home. In fact, the lab activities can be easily adapted to an Internet-based soils course.

New to this edition, content has been updated to correlate with the updates made to the core textbook. In particular, Chapter 1 incorporates updates to two activities. The third activity now relates to determining the pH of vinegar using litmus paper, and the last activity provides an updated activity related to the structural support of soil. Chapter 5 now includes a new Internet-based activity and corresponding Challenge Question related to conducting a survey of soil organism genetics. Chapters 7 and 19 contain new information related to water movement and the Soil Erosion and Control Act and LEED certification, respectively.

Instructor's Resource CD-ROM to accompany* Soil Science and Management, *Sixth Edition

ISBN-13: 978-08400-2436-7

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With Delmar Cengage Learning's Instructor Resources to Accompany *Soil Science and Management,* Sixth Edition, preparing for class and evaluating students have never been easier! As an instructor, you will find this CD-ROM offers invaluable assistance by giving you access to all of your resources—anywhere and at any time.

Features

- The **Instructor's Manual** contains various resources and answers for each chapter of the book; it is available in Microsoft Word® format and/or Adobe Acrobat PDF® format.
- The **Computerized Testbank** in **ExamView®** makes generating tests and quizzes a snap. With over 1,000 questions and different styles to choose from, you can create customized assessments for your students with the click of a button. Add your own unique questions and print rationales for easy class preparation.

- Customizable instructor support slide presentations in **PowerPoint®** format focus on key points for each chapter; these can also include video clips, animations, and photos.
- Use the hundreds of images from the **Image Library** to enhance your instructor support slide presentations, insert art into test questions, or add visuals wherever you need them. These valuable images, which are pulled from the accompanying textbook, are organized by chapter and are easily searchable.
- The **Lab Manual Instructor's Guide** offers instructor guidance for each lab activity found in the Lab Manual along with answers to the Challenge Questions.

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ACKNOWLEDGMENTS

Author's Acknowledgments

I continue to be indebted to the U.S. Department of Agriculture for the many photographs that appear in this text and the volumes of information it makes available. The Minnesota Geological Survey, which has been of assistance before, provided a fine image of kaolin clay crystals, and the Minnesota Landscape Arboretum supplied a photo of some of its display flower beds planted to a cover crop in the fall. I appreciate the input of reviewers in providing ideas for this new edition.

I want to especially thank my wife, Sue, and family. Since the last edition, a new granddaughter, Mya, joined Elena and Carrie as the younger members of the family, and all three give me great joy. I apologize to them for the time that preparing this edition has taken from my time spent with them.

Reviewers

I extend my appreciation to the reviewers who took the time to provide valuable feedback that informed the creation of this new edition.

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HOW TO USE

Soil Science & MANAGEMENT

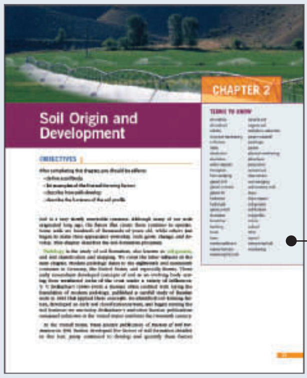
SIXTH EDITION

Objectives

Learning objectives at the beginning of each chapter introduce you to the key concepts you should understand upon completion of the chapter.

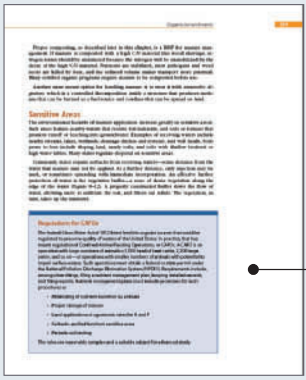
Terms to Know

Each chapter begins with a list of important key terms to know. Study this list as you prepare for tests and quizzes. Key terms are emphasized in color throughout the text so you can easily identify where they are discussed in the chapter. A definition accompanies the key term in the text and each term also has a corresponding glossary definition.



Informational Sidebars

Throughout the textbook, additional information about topics discussed in the chapter is highlighted in a sidebar feature that discusses a current event, pertinent regulation or legislation, or other relevant information related to the topic.



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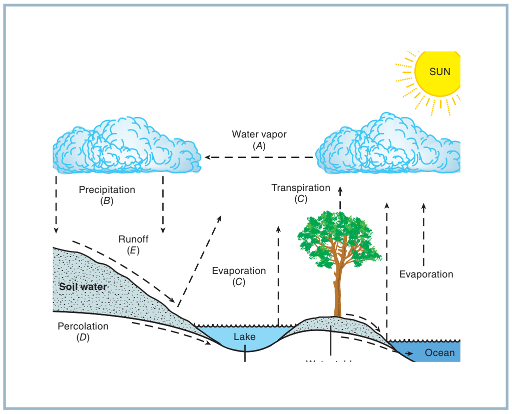

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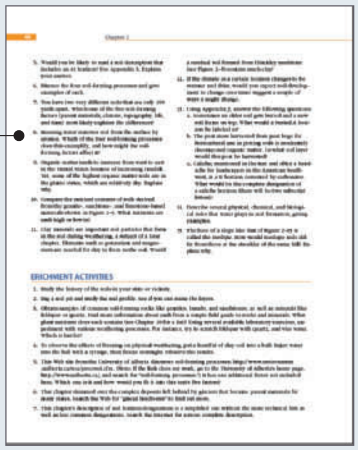
Photographs and Illustrations

Full-color photographs and illustrations are used throughout the textbook to help you visualize important aspects of soil science and management.

End-of-Chapter Recap

Each chapter concludes with a summary that recaps important concepts discussed in the chapter. Review questions quiz your knowledge and recall of the chapter's concepts, while Enrichment Activities use the Internet to provide you with additional resources for information about concepts discussed in the chapter, including websites with simple demonstrations, research studies, and other suggestions as well.



CHAPTER 1

The Importance of Soil

TERMS TO KNOW

aeration pore
anchorage
Best Management Practice (BMP)
carbon sequestration
carbon sink
cropland
desertification
hardpan
hydroponic crop
load-bearing capacity
macropore
micropore
nutrient
photosynthesis
pore space
respiration
shrink–swell potential
soil aeration
soil air
soil degradation
soil matrix
soil quality
soil solution
waterlogged soil

OBJECTIVES

After completing this chapter, you should be able to:

- summarize ecological functions of soil and its role in recycling resources needed for plant growth
- describe four ways plants use soil
- explain how soil is a three-phase system
- list and explain uses of soil
- discuss the concept of soil quality
- describe briefly the role of soil in climate change

Life and human civilization depend on the planet's limited soil and water resources. We have ample historical proof. Most early civilizations in the Old World grew and thrived on the rich soil and waters of major river floodplains. Early Chinese culture, for instance, began to develop 6,000 to 7,000 years ago on floodplains of the Yellow River, where periodic flooding deposited fresh soil for agriculture and canals could carry river water to fields for irrigation. Similarly, farming began to flourish some 10,000 years ago in the Mideast along major rivers.

The famous Greek historian Herodotus left us his notes about the dependence of Egypt on soil supplied by flooding of the Nile. In 340 B.C.E., in *The History of Herodotus*, he observed that black, crumbly, silty river deposits were easy to work and productive—these soils could produce plentiful food with less toil. These soils, he noted, were the foundation for Egyptian civilization.

North America too depends on its soil and water, and our history was influenced by its soils. Part of its success stands on rich soil and water resources; those of the United States are described later in this chapter

Figure 1–1

A Dust Bowl "roller" moves across a Colorado landscape, carrying off soil and damaging everything in its path. Events such as this have reappeared with recent prolonged drought in the Great Plains. Photos of such a roller over Phoenix appeared in the news as this edition was being prepared.

and throughout the text. But we have often not been wise in their use. The Dust Bowl of the 1930s, caused by drought, soil misuse, and widespread wind erosion, drove farmers out of several middle plains states. At its peak, severe wind erosion damaged some 150,000 square miles of prairie farmland (Figure 1–1). By 1940, 2.5 million people had moved out of the Great Plains, forced out by drought, unsustainable land-use practices, and depression. Photographs from that era create striking and poignant images of people driven off their land by the destruction of the Dust Bowl and scattered to new lives elsewhere (Figure 1–2).

Soil and water resource problems also cross national borders, sometimes in ways hard to imagine. For instance, North and South America and Europe receive dust blown from desert lands of Africa. As soils of Africa degrade, that movement of dust has been increasing. More obviously, shortages of soil and water resources cause conflicts and migration of refugees.

In the future, soil will become even more crucial. As this edition was being prepared, the earth's population reached 7 billion; some estimates expect it to reach 9 billion by 2050, well within the lifetime of most students reading this text. Yet only about 7 percent of the earth's surface is suitable for agriculture, and that figure is not going to increase. Of that land, some is being lost to degradation and urbanization. A late-2011 report by the United Nations Food and Agriculture Organization (*The State of the World's Land and Water Resources for Food and Agriculture 2011*) found a quarter of the world's land to be highly degraded. It further noted that the world's growers will need to provide 70 percent more food by 2050. Unfortunately, soil cannot easily be replaced: Soil is a nonrenewable resource within the time frame of a human generation.

Many experts have noted that part of the rhythm of human history is the rise and fall of cultures founded on the use, abuse, and final exhaustion of soil and water

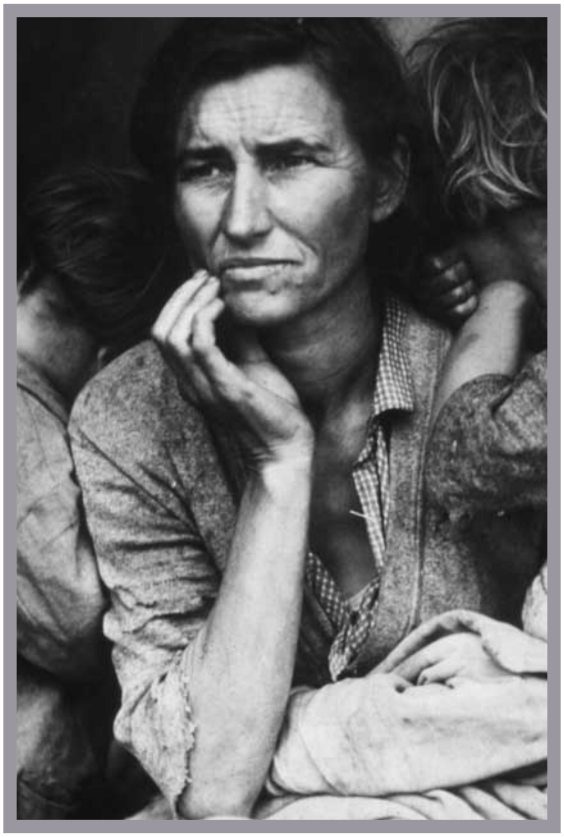


Photo by Dorothea Lange, USDA Natural Resources Conservation Service

Figure 1–2
A famous Dorothea Lange photograph of a migrant worker in California displaced by the Dust Bowl.

resources. Some once-productive land of the ancient Fertile Crescent, in modern-day Iraq, now lies barren because of salts built up from centuries of irrigation from the Tigris and Euphrates rivers. This is not simply a problem of the past, but of today.

Human society—indeed, most life—is possible only because earth's crust is dusted with a bit of soil where we can grow food. Most of the world's soils capable of being farmed without causing great environmental damage are already being farmed, thus the importance of making productive and sustainable use of those soils. This book is dedicated to describing those soil and water resources and how we can use them wisely. We begin by looking at soil's ecological functions in supporting life on the planet, its role as a medium for plant growth, and its use by humans.

SOIL IS A LIFE-SUPPORTING LAYER OF MATERIAL

Although we take soil for granted, it is a very thin and often fragile layer of life-supporting material. We all stand on the rocky solid surface of the earth, the continental crust, which is generally about 50 miles thick. We breathe the air of the atmosphere, which is about 22 miles deep (though there is no measurable edge). Soil forms a very thin interface between the two.

The atmosphere, crust, and soil interact to provide plants and animals with the resources they need. Living things need proper temperature, oxygen, water, carbon (the basic element of all living bodies), and other nutrients. These factors are exchanged in the soil, as shown in Figure 1–3, usually in cycles that allow elements to be recycled and stored rather than lost. Although later chapters will discuss the cycles in greater detail, this chapter previews them briefly.

Temperature

Plant roots grow best in certain soil temperature ranges. For instance, most plant roots in temperate climates grow at soil temperatures above 40°F to 50°F. The cool-season grasses grown in northern states cease root growth at soil temperatures above 85°F. Seed germination also depends on soil temperature; wheat seed, for example, germinates between 40°F and 50°F, while sorghum needs temperatures above 80°F. Soil temperature, and to some degree the air above the soil, is controlled by a heat-exchange mechanism.

Pedestrians standing on a tar road on a hot summer day sense how heat is exchanged as the road both gains and loses heat. Feet in contact with pavement get

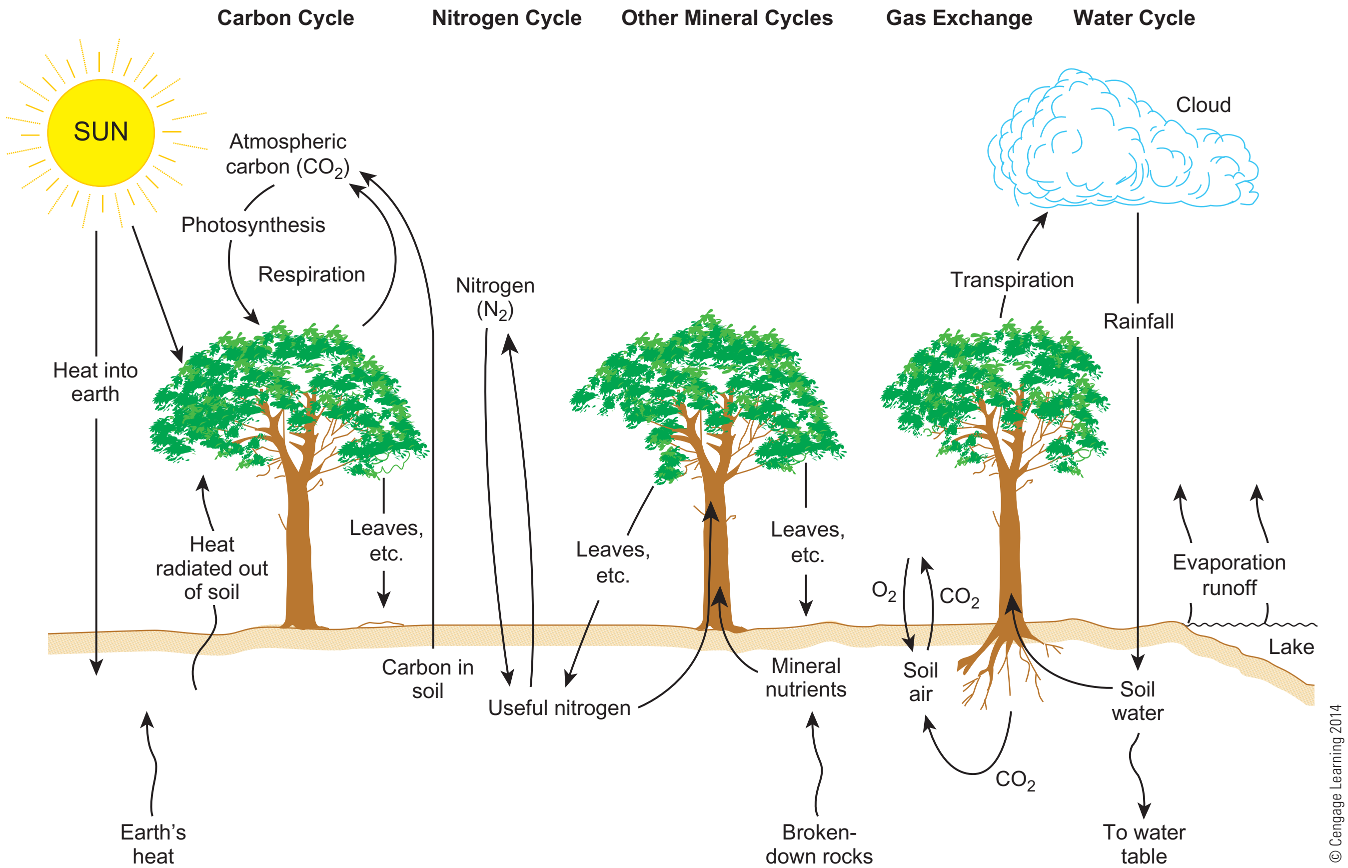


Figure 1–3
Cycling and exchange between atmosphere, crust, and soil. The soil temporarily stores resources needed for plant growth.

hot because the road is absorbing energy from the sun. Looking down the road, one sees heat waves rising from the tar, an effect of the road losing excess heat to the air. Energy is also radiating away as light in a wavelength that humans cannot see. In the same way, soil maintains temperatures for growing plants. On a larger scale, this heat exchange influences air temperature, weather, and even global climate.

Gases

Plant roots and other soil organisms need oxygen and give off carbon dioxide as they respire. Some important soil bacteria need nitrogen gas as well. Figure 1–3 shows that these gases pass into and out of the soil to maintain proper amounts of each. In this process of air exchange, soil also acts to filter and purify the earth's atmosphere.

Water

Water seldom stays in one place long, always being on its way to the next stage of its cycle. Water evaporates from land, lakes, and oceans and forms clouds in the atmosphere. Rain falls from the clouds, moistens the soil, and fills streams and lakes. Most of the water finally reaches the oceans, where evaporation begins the cycle again. Some water seeps deep into the ground where it is held as groundwater. When moisture falls on the soil, however, some water is temporarily stored for plant use. In the process, soil filters water as it moves through the soil, purifying it.

Carbon

Plant leaves collect sunlight to use the sun's energy in the process known as **photosynthesis**, which involves converting atmospheric carbon (carbon dioxide) to biological carbon (simple sugars). In the process, light energy is converted to chemical energy usable by plants and creatures that eat plants. Some of the carbon is recycled directly back to the atmosphere by plant and animal **respiration**, while other carbon is recycled by organic matter decay in the soil. In this process, some carbon is retained in the soil as organic matter. Soil acts as a vast carbon reserve keeping carbon dioxide out of the atmosphere, where it would contribute to the greenhouse effect.

Nutrients

Plant **nutrients** (chemicals a plant needs to grow) also cycle through the soil. Two kinds of nutrient cycles are shown in Figure 1–3: the nitrogen cycle and other mineral cycles.

Nitrogen comes entirely from the atmosphere, where it occurs as a gas, a form that plants cannot use. Soil organisms convert gaseous nitrogen to forms that plants can use. Some nitrogen recycles as once-living material decays in the soil, while water carries some nitrogen deeper into the ground. Some nitrogen returns to the air when other microbes change it back to its original form.

Other nutrients are released from rocks in the earth's crust when the rocks are broken down by weather, plants, and other factors. These nutrients are continuously reused by plants until some return deep into the ground by leaching, get washed into the ocean, or are removed by cropping.

SOIL IS A MEDIUM FOR PLANT GROWTH

In the broad view, soil has important ecological functions in recycling resources needed for all life. In the narrow view, an individual plant depends on soil for four needs: **anchorage**, water, oxygen, and nutrients. Let us look at these four needs.

Anchorage

In deep soil, where roots grow freely, plants are firmly supported, or anchored, so they can grow to reach for sunlight. When people grow plants in ways that deprive plants of soil support, artificial support is often required. Growers of **hydroponic crops** (roots growing not in soil but in fertilizer solutions) support plants with a wire framework. Landscapers may stake or "guy" a newly planted tree until the tree is firmly rooted (Figure 1–4), though staking weakens or even damages the trunk and is no longer recommended for regular use except in special cases like palms. Poorly anchored trees can even cause serious safety or economic issues, as they may topple in windstorms and damage cars or buildings, or even land on people.

Water

Because roots are a plant's water-absorbing body, soil supplies the water a plant uses. For each pound of dry matter produced by growth, plants obtain between 200 and 1,000 pounds of water from the soil for photosynthesis, sap flow, and other

Image courtesy of Ed Plaster

Figure 1–4

Because of the way palm trees are transplanted, the soil cannot function well to anchor the tree, so they need to be staked, as in these trees in Florida.

uses. It is obvious that water-holding capacity of a soil is important in its agricultural and horticultural use.

Oxygen

Except for some microscopic organisms, all living creatures, including plants, need oxygen. Plants release oxygen during photosynthesis, but consume it during respiration. The parts of a plant above the ground, suspended in an atmosphere that is 21 percent oxygen (Figure 1–5), have all the oxygen they need. Underground, plant roots and soil organisms use up oxygen and give off carbon dioxide. As a result, **soil air** has less oxygen and more carbon dioxide than the atmosphere. The resulting concentration gradients between soil and atmosphere cause oxygen to diffuse into the soil and carbon dioxide to diffuse out.

In the absence of factors that limit it, this process, known as **soil aeration**, exchanges soil and atmospheric air to maintain adequate oxygen for plant roots. Aeration varies according to soil condition. Saturated, or **waterlogged soil**, which is completely soaked with water, is an example of a soil with poor aeration. The oxygen content near the surface of a well-aerated soil rarely drops below 20 percent, but may approach 0 in a saturated soil.

Nutrients

Of 17 nutrients usually considered to be needed by most plants, plants absorb 14 from soil. Carbon, oxygen, and hydrogen come from air and water; the rest are from the soil. Nitrogen comes indirectly from the atmosphere via the soil. While leaves are able to absorb some nutrients, roots are specialized for the purpose. Root hairs absorb plant nutrients dissolved in soil water (called the **soil solution**) by an active process that moves nutrients into root cells. The energy that powers this process is produced by respiration in the roots.

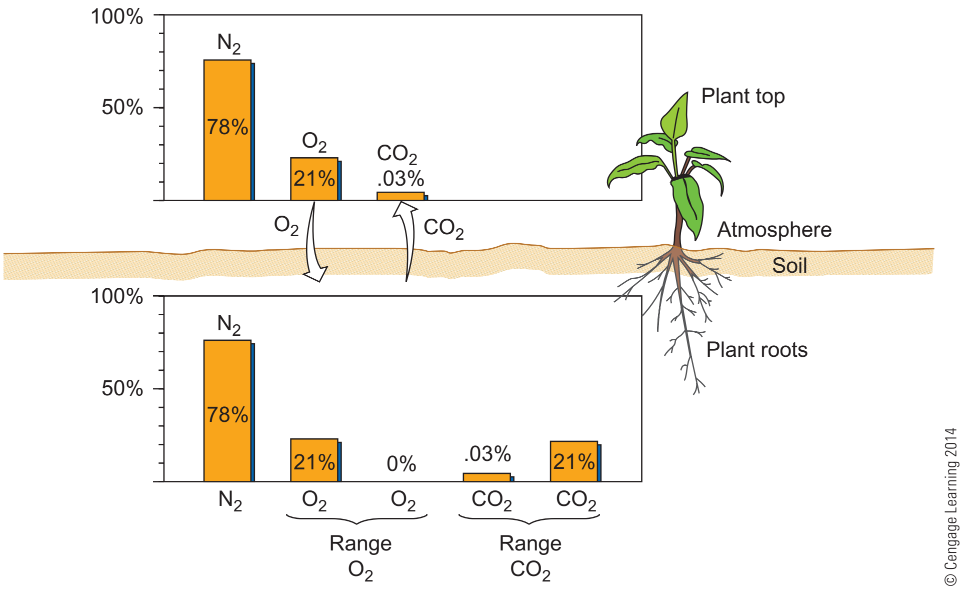


Figure 1–5
Soil air and aeration. Most of the gas in air and soil is nitrogen. Above the soil, air is about 21 percent oxygen. In the soil, respiration of living things replaces oxygen with carbon dioxide. Aeration is the process by which carbon and oxygen are exchanged.

SOIL: A THREE-PHASE SYSTEM

How does soil fulfill the four functions described? Any grower knows that soil is made of solid particles. In most soils, solid particles largely consist of mineral matter with about 1 percent to 10 percent organic material. Between these solid particles are open spaces, or voids, which we call **pore spaces**. This arrangement of solid particles and pore spaces is called the **soil matrix**. Commonly, about half the volume of soil is solid material and half is pore space, and we consider this a good composition for plant growth.

Pore space is always filled with some combination of air and water (Figure 1–6). Chemists call solids, liquids, and gases phases of matter, so we can describe soil as a three-phase system. A combination of about half air and half water in the pores provides an excellent supply of both for roots, but the actual ratio varies dramatically over time. Right after a heavy rain, pores may be filled almost entirely with water and have almost no air. As soil dries, air replaces water in the pore spaces, and pores in a very dry soil may contain almost entirely air and very little water. These soils are too wet or too dry for good plant growth. We generally consider equal amounts of air and water as ideal for plant growth.

The amount and composition of soil air varies not only over time, but in space as well. That is, it varies greatly from spot to spot within the soil matrix. A large pore may be rich in oxygen, while a small pore a fraction of an inch away contains water and is devoid of oxygen. Those large pores, called **macropores** or **aeration pores**, are largely responsible for easy movement of air and water in the soil, and for providing space for air, while smaller **micropores** retain water for plant use.

Generally, soil is richest in oxygen near the surface, while deeper layers may be very low in oxygen because the atmosphere is farther away and pathways for diffusion are much longer. This, in turn, influences distribution of roots in soil.

Because roots require oxygen, lack of aeration poses a serious problem for plant health. Plant growth suffers greatly if air-filled porosity falls below 20 percent, or if 80 percent to 90 percent of pore space fills with water.

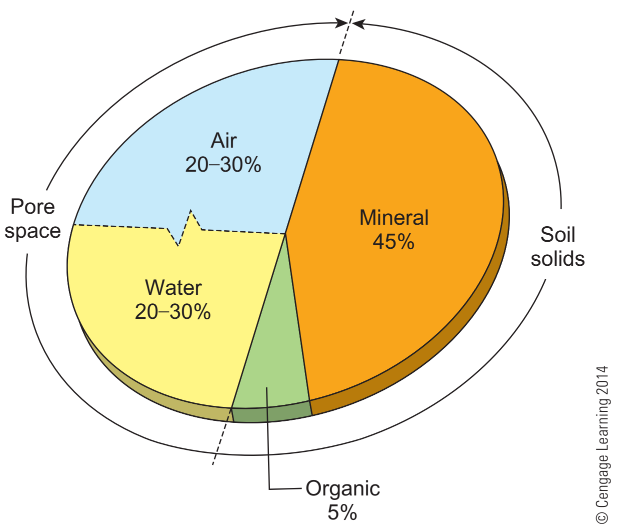


Figure 1–6
Composition of a typical soil desirable for plant growth. It contains equal proportions of solid particles and pore space, and air and water occupy equal proportions of the pore space. The proportions of air and water vary, as shown by the broken line, but ideally are within the range shown. These measurements are by volume.

Root Growth

Plants need a sufficient volume of quality soil to host roots and supply needed resources. Figure 1–7 shows two rows of urban trees. The row on the left was planted in small tree pits surrounded by pavement; the trees are stunted. The row on the right, planted at the same time, enjoys open soil where roots have room to grow; the trees are much larger and darker green.

From a root's point of view, it is pores that matter. As roots grow into the soil, they follow continuous pore spaces between solid particles, absorbing water and nutrients from the soil solution. Root tips easily penetrate pores larger than themselves. Behind the root tip, the diameter of the root increases, pushing aside or deforming the soil to make room for itself. Root tips may also enter smaller pores if the root can exert enough pressure to deform soil ahead of the tip. If pores are too small or discontinuous, or if soil particles are too difficult to push aside, root growth suffers. Such conditions can result if soil is severely compressed or compacted; in such soil, roots may only be able to follow cracks or other channels in the soil.

Water reaches roots in two ways: either water flows toward the root, or the root grows into moist soil. Roots spread to contact as much soil as possible; for trees, they typically extend up to three times the spread of the canopy (Figure 1–8). One authority estimated that a mature oak tree has about 1 million live root tips. Alfalfa roots grow to a depth of 5 or 6 feet and may go much deeper in loose soils. However, roots do not grow below the depth of aeration, unless they are specially adapted to do so, so most roots do not extend below 5 or 6 feet.

While roots try to grow widely or deeply, they grow best and the thickest where oxygen, water, or nutrients are present in optimal amounts. Roots are able to sense

Image courtesy of Ed Plaster

Figure 1–7

Street trees in St. Paul, Minnesota. The stunted trees on the left grow in small tree pits, surrounded by concrete, while the larger trees on the right grow in a turf area with plenty of soil for roots. The trees are the same age.

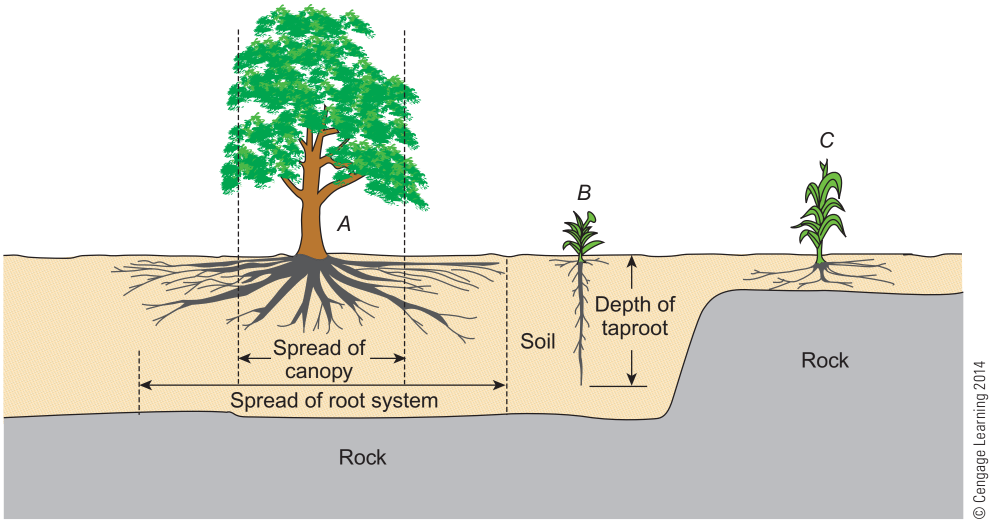


Figure 1–8
Plant roots spread far from the plant, seeking water and nutrients. (*A*) Most roots spread laterally near the soil surface where the oxygen content is highest. (*B*) A few plants, like alfalfa, send roots deep into the soil. (*C*) Conditions that limit the spread of roots, like solid rock near the surface, also limit plant growth.

soil gradients of resources they need and grow toward concentrations of those resources. Where roots find rich supplies of resources, be it oxygen, water, nutrients, or warmth, they branch and fill that area with numerous roots. For instance, a city tree growing in a narrow boulevard may grow a few ropelike roots under the sidewalk, where the soil is dry and low in oxygen, to the lawn on the other side, where the tree develops lush fans of absorbing roots. This pattern of root growth allows plants to exploit soil resources most efficiently.

Oxygen levels especially determine where roots grow. Most roots—even those of large trees—occupy the upper 12 inches of soil, where the greatest amount of oxygen is found.

Different soil types can affect how roots grow. For instance, some soils have hard layers under the surface, called **hardpans**, which prevent roots from growing deeply. As a result, the plant has less soil to draw on for water and nutrients. The same effect results from bedrock or waterlogged soil near the surface. Numerous other conditions inhibit root growth as well, including low oxygen, nutrient deficiencies, high soil salts, pH extremes, toxic materials, compaction, and temperature extremes. All of these are covered in later chapters.

Health of the entire plant depends on the health of its root system. Healthy turfgrass roots, for example, lead to turf that resists damage from golf or baseball shoes, diseases, or drought, and hosts fewer weeds. Poorly rooted turf is difficult and expensive to maintain, and requires much greater use of chemicals such as pesticides.

To summarize, only where a soil has the proper proportion of solid, liquid, and gas can roots grow actively to obtain good anchorage and sufficient water and nutrients.

AGRICULTURAL USES OF SOIL

Human societies depend on soil to grow food, fiber, timber, ornamental plants, and increasingly, biofuels. Different agricultural uses require different soil management practices. *Agriculture* is an umbrella term that traditionally includes agronomy and other farming enterprises, horticulture, and forestry.

Figure 1–9
Row crops like this corn in Iowa present management challenges, including preventing erosion and preserving soil organic matter.

Cropland

Cropland is land on which soil is worked and crops are planted, cared for, and harvested. Worldwide, the greatest acreage of cropland is devoted to annual crops—those planted and harvested within one growing season. Annual crops include agronomic products such as corn (Figure 1–9) and soybeans, fiber plants such as cotton, and horticultural crops such as vegetables. Annuals require yearly soil preparation. This activity gives growers a chance each year to control weeds and to work fertilizer and organic matter into the soil. Because the soil surface is often bare much of the time, growers must be careful to keep soil from washing away, and repeated tillage degrades soil and water in ways to be described later. Managing annual crops must be done with great care to reduce the environmental consequences.

Perennial forages, such as alfalfa, are in the ground for a few years. They may be harvested as hay to feed animals, or be used for grazing. These crops cover the soil completely and so keep the soil from washing away. Because the soil is not worked each year, fertilization is different than for annual crops. Perennial crops also tend to build up and improve the soil, and are better than annuals for maintaining or enriching soil organic matter. Perennial crops, especially grasses, offer numerous environmental and soil-quality advantages over most annual crops.

Perennial horticultural crops include fruits, nuts, and nursery stock. Plants stay in the ground for 3 to as many as 20 years. Many crops are clean-cultivated to keep the ground bare and weed-free, while others are grown on sod or other soil cover. Challenges to the grower of such horticultural crops are controlling weeds, reducing erosion, preventing soil compaction, and keeping organic matter levels stable.

Growers are also beginning to assume a new task: growing crops for fuels. Farms are essentially large living solar energy collectors to produce food; increasingly solar energy collected by crops will be converted to fuel. These currently include corn for alcohol and soybeans for biodiesel, but as biofuels develop, new plants from our native switchgrass to willows may be grown. Besides that, in many locations wind turbines are being placed on farmland to generate electricity. The project to produce energy on farms can succeed only if there is a large net energy yield—that is, the energy produced greatly exceeds the energy consumed in the process. Efforts to harvest fuel energy from farmland may have serious implications for maintaining soil quality and management.

Grazing Land

Much land in the United States is grazed by cattle and sheep. In the eastern half of the country, pasture is planted to perennial forage (Figure 1–10). In the western half of the country, which has a drier climate, most grazing is on rangeland. Range consists largely of native grasses and shrubs, with some nonnative grasses planted through existing vegetation. Partly because of the size of much rangeland, it is usually loosely managed. The environmental consequences of grazing depend largely on how land is managed. Overstocked land suffers damage to soil and water; proper grazing practices can be quite sustainable.

Forest

Foresters probably disturb soil the least, but soil management is still a concern. When trees are harvested after many years' growth, logging equipment tears up the vegetative cover and compacts the soil. Increased erosion results, and the soil is a less desirable medium for growth of newly planted seedlings. Other concerns of forestry include choosing the best trees for each soil type and ensuring good conditions for newly planted seedlings.

Photo by Bob Nichols, USDA Natural Resources Conservation Service

Figure 1–10

Pasture is one common use of soil, as in this beef operation in Wisconsin.

Landscape Horticulture

Crop production horticulture, the culture of fruits, vegetables, and nursery stock, is similar to the agriculture described earlier. Landscape horticulture, including landscaping and growing plants in containers, is also similar but has its own distinct challenges and practices.

People often refer to landscape horticulture as "ornamental horticulture," suggesting it's all about making land pretty. This devalues the valuable contribution that the discipline makes to human and environmental well-being. For instance, urban landscapes greatly reduce the heat buildup typical of cities, making life tolerable and reducing air-conditioning and energy costs.

From the point of view of this text, landscape horticulture is *the* set of practices we use to sustain soil and water resources in urban areas where most Americans now live. For instance, trees intercept and absorb substantial amounts of stormwater. This text will suggest ways to enhance sustainability of those practices.

Landscapers install and maintain plants in soils that have often been heavily modified by construction. Their activities conserve soil in urban areas, but until a landscaping project is complete, soil erosion can be severe. Landscapers should know not only the soil, but how hundreds of different plants respond to the soil. For instance, a yew (*Taxus* species) planted in soil that stays wet will surely die. All too often, landscapers must plant in soil heavily disturbed by construction or in rocky fill. Landscapes stay in place for decades, during which time soil can be subjected to injury from deicing salt, and foot and equipment traffic.

Some crops such as flowers, houseplants, and nursery stock are grown in pots. Plants growing in the tiny root zone of a pot require great care. Growing media for containers may be highly modified to improve their properties or be entirely soilless mixtures of peat, perlite, and other materials, but they follow the same principles of soil science as field soils.

Urban Agriculture

There is increasing interest in growing food in or very near cities. This *urban agriculture* or *urban farming* is something greater than small-scale gardening but different than typical rural commercial production. Urban farming seeks to provide food,

LEED and Landscaping

In recent years, efforts to make construction greener and more sustainable have become more prominent. Part of that effort includes Leadership in Energy and Environmental Design (LEED) certification, an effort of the U.S. Green Building Council. While most of the requirements of LEED certification concern buildings themselves, a number relate to soil and water issues, and thus are a matter of great interest to the landscape industry. LEED certification calls for accumulating a sufficient number of points accrued by meeting a series of standards, some of which relate to the grounds around a building. These "grounds" standards aim to reduce erosion losses from building sites, off-site sedimentation, water use, and export of pollutants in runoff water. These are topics taken up throughout this text, and references will be made to LEED standards.

especially for poorer people, near where it will be consumed. It is also partly recreational for some. The most common crops are horticultural ones like vegetables or fruits, but other products may also be grown where zoning permits—even poultry and eggs.

Being that urban farmers occupy relatively small pieces of land—vacant lots, large yards or grounds, and the like—it must be a highly intensive form of agriculture using practices like intercropping (Chapter 16). Urban farmers typically favor sustainable or organic practices (also discussed in Chapter 16). Practitioners face the problems common to urban soils covered in Chapter 19, such as soil contamination.

NONAGRICULTURAL USES OF SOIL

Other human activities—in addition to growing plants—require soils. At its most basic, soil is a surface that people inhabit. Specific nonfarming soil uses include recreation and engineering projects such as building foundations and waste disposal. Let us look at a few of these uses.

Recreation

Recreational uses of the soil surface are important. Sit in an urban park and you will see children in the playground, softball teams on the field, and runners on jogging paths. Golf courses (Figure 1–11), parks, and campgrounds are examples of large areas used for recreation. The design of recreational facilities is a specialized skill that requires knowledge of soil properties. Since recreational facilities are completed and

Courtesy of Deep Tine, LLC

Figure 1–11
Recreational soils, as in this golf course, have their own management challenges. Here a worker cultivates a new area with an aerator, a device specific to turf management.

maintained using horticultural practices, one could also include recreational facilities as agricultural.

Sport-playing fields may be the most demanding of all soil uses. To grow turf that withstands the punishment of football cleats or soccer shoes challenges even the best of managers. Soils in the best playing fields are highly engineered mixes of loam, specific sizes of sand, and other ingredients. They may even include a plastic mesh to hold the soil together. Fields generally have several soil layers, are carefully graded and drained, and are well maintained. These and other considerations require a knowledge of soil science.

Engineering

Before constructing a home, laying a road, or installing sewer lines (Figure 1–12), soils must be tested and sometimes modified to make sure they are suitable for supporting the structure. People know that structurally sound buildings depend not only on the builder's skill but also on the soil under the house. Building foundations, for instance, crack if soil settles under the building. In some towns, landscapers require an engineer's service in designing retaining walls to ensure that they hold firmly in the soil. Civil engineers also need firm soils that settle little for the roadbeds of highways and foundations of bridges.

Examples of important engineering properties include **shrink–swell potential** and **load-bearing capacity**. Many soils swell when wet and shrink as they dry, cracking walls, destroying foundations, and breaking or dislodging buried pipes, like those of the sewer line being installed in Figure 1–12. Soils high in clay or organic matter have low load-bearing capacity. Foundations of buildings constructed on such soils may shift and crack, as happened to numerous homes during the great drought of 2012

Image courtesy of Ed Plaster

Figure 1–12
New sewer line being excavated near the author's college. Soil traits are important to the safety of this line. Here, the line is buried in deep deposits of outwash sand (Chapter 2).

when bone-dry soils shrank away from foundations. Roads and other structures built on such soils may also have structural problems. In 1989, San Francisco shook to a major earthquake that brought down many buildings—most located on a loose "fill" soil that could not support structures when the earth began to shake.

Waste Disposal

Newspaper headlines about hazardous waste disposal focus attention on the difficulties of safely handling wastes generated by society. Soil has long been used for waste disposal, sometimes with unfortunate results.

Treatment of human sanitary waste often relies on soil because it filters out some of the material, while microorganisms break down organic portions into less dangerous compounds. The common home septic drain field is an example.

One way for sewage treatment plants to handle their end products is to spread them on soil (Chapter 15). Sewage sludge may be useful to farmers as a source of nutrients and organic matter, as long as possible harmful materials in the sludge are taken into account. To avoid problems from sludge, its use is regulated by government agencies.

Sanitary or especially hazardous waste landfills require soils that will not allow hazardous materials to leach into the water table or run into neighboring streams or lakes. The search for landfill sites often arouses conflict in a community. Many people feel landfills cannot be entirely safe, and even those who agree that landfills are necessary do not want them nearby.

Building Materials

Before long-distance shipping of building materials became practical, people built their homes with locally available materials, including soil. Early settlers in the Great Plains built huts out of sod, a thick carpet of grass, its roots, and soil. Adobe, a sunbaked mixture of three parts sandy soil to one part clay soil, has been used as a building material for thousands of years and continues to be used in the American Southwest.

Modern applications of soils are being developed in the search for energy-efficient housing. Buildings can be built underground, into hillsides, or even with soil piled over them. These earth-sheltered buildings are warm in winter and cool in summer, lowering both heating and cooling costs. A few homes have been built of packed earthen walls, constructed by tamping earth into erected forms.

LAND USE IN THE UNITED STATES

Figure 1–13 shows how nonfederal land was used in 2007, but land use does not remain static. In any given year, some forest is cleared for cropland, while somewhere else cropland returns to forest. Market forces such as land or grain prices, technological change such as irrigation, and government programs spur changes in land use.

Figure 1–13 displays data gathered during a United States Department of Agriculture (USDA) inventory of nonfederal land in the United States (excluding Alaska) called the 2007 National Resource Inventory (NRI). NRIs were also conducted in 1982, 1987, 1992, 1997, and 2003; together they show trends in land use in the nation.

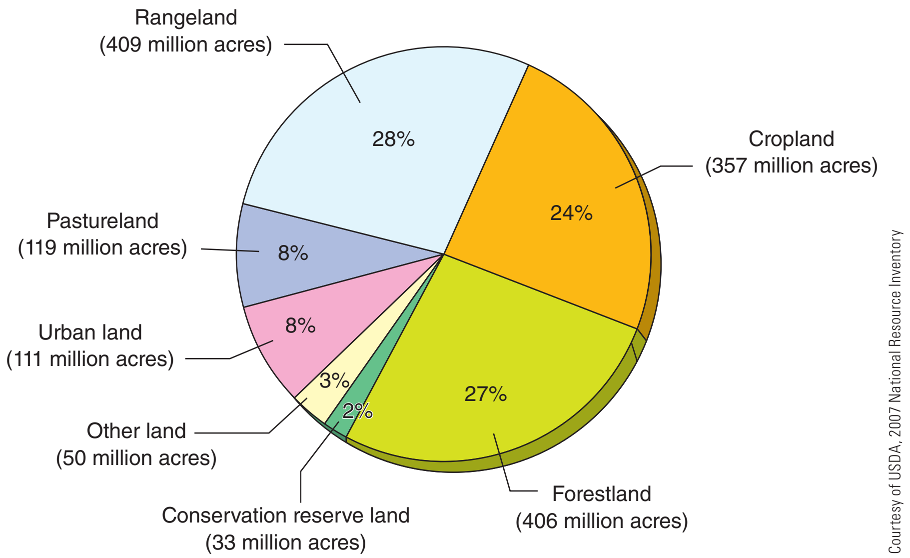


Figure 1–13
Use of nonfederal land in the United States (excluding Alaska) in 2007. Urban land includes built-up and rural transportation.

The 2007 NRI shows that about 80 percent of nonfederal land is evenly divided among crop, forest, and rangelands as the major uses of our soils. Because much of the 402 million acres of federal land is forest or range, they cover a larger proportion of the total U.S. land surface than shown here.

During the 1982–2007 period, nonfederal rangeland declined by about 6 million acres, cropland decreased by 63 million acres, pastureland shrank by 12 million acres, and forestland grew slightly. About 32 million acres of what had been marginal cropland were enrolled in the Conservation Reserve Program in 2007 (Chapter 20); some portion of that could later be returned to its prior use.

One land use continues to grow at the expense of other uses—urbanization (Figure 1–14). This includes the building of cities, towns, factories, and roads. Comparisons with the 1982 NRI show that during the years 1982–2007, 38 million acres of rural land were developed for urban uses. Fourteen million of these acres were classified by the USDA as *prime farmland*—land best suited for agricultural use. Recognizing the drawbacks of urbanizing prime farmland, LEED standards (see earlier sidebar) discourage development on such land.

SOIL QUALITY

Soil quality, also called soil health, is the capacity of a specific soil to provide needed functions for human or natural ecosystems over the long term. That is, it can sustain plant and animal growth and productivity, maintain air and water quality, and support human health. Quality soil helps keep a forest healthy and grows excellent crops or effective landscapes; in short, it performs the functions described in this chapter.

The concept of soil quality has been used as an educational tool and as a way to assess soil. To do the latter, various soil-quality indices based on important soil characteristics such as organic matter content have been devised. Such indices have been

Figure 1–14
One land use continues to grow at the expense of the others—urbanization. Here see new subdivisions outside Las Vegas, Nevada.

questioned in the soil science community, but here we will use the general concept as a useful umbrella for soil traits and soil-use practices covered in this text.

Soil degradation is the loss of soil quality. Because soil connects intimately to water, soil degradation also means water-quality problems. A United Nations report, *Global Environment Outlook 2000,* estimates degradation of some 4.7 billion acres (1.9 billion hectares) of land worldwide. Examples of soil and water degradation include:

- water erosion of soil from the land, particularly a problem in the eastern half of the country
- wind erosion of soil from the land, particularly a problem in the western half of the country
- pollution by industrial chemicals, oil spills, and many others
- conversion of dry grasslands to desert, called **desertification**
- changes in soil chemistry, such as severe changes in soil acidity
- increases in soil salt levels, or salinization, a common problem in California and the American Southwest
- loss of soil organic matter

A major goal of this text is to present ways to prevent such problems and to conserve soil quality. While preserving soil and water quality involves understanding basic soil processes and management, it also includes specific practices that preserve our soil and water resources while being practical and profitable for a soil user. We call these practices **Best Management Practices (BMPs)**. For example, an

Figure 1–15
BMPs are effective and useful practices that preserve our soil and water resources. Here, a small rain garden in a residential yard intercepts some of the runoff filling the street gutter, preventing it from entering the storm sewer system (see Chapter 19). The curb cut routes water into the specially designed "sunken garden", where the water will quickly filter into the ground.

entire set of BMPs involves practices that keep the soil covered as much as possible, employing management methods such as mulching, cover cropping, or conservation tillage. Conservation tillage dramatically reduces erosion and polluting runoff, stores more moisture in the field, and improves soil organic matter content without being difficult or expensive. Figure 1–15 shows a BMP for capturing runoff from residential settings before it can enter lakes or streams, called a *rain garden*.

Use of these BMPs is part of being a good citizen for those who use soil, and the population of every nation has the right to expect its soil users to understand the soil, to follow BMPs, and to stay abreast of new methods for soil-quality preservation.

SOIL AND NATURE

So far, this chapter has largely focused on human uses of soil. Indeed, human usage strongly informs the entire discipline of soil science. If soil science developed with a focus on natural ecosystems, it might look slightly different. Nevertheless, soil plays a critical role in natural ecosystems, and much of the information in this text is applicable. The reader will find references to natural systems scattered throughout the text.

For instance, which living things reside where depends on soil and climate, because these two define availability of resources such as proper temperature, moisture, and nutrients. In a local area, water and nutrients largely control the nature of plant communities, and it is soil that delivers those resources. Figure 1–16 shows an "ordination diagram" of wooded communities in Minnesota. Each colored patch represents a group of related plant communities; each code represents a specific

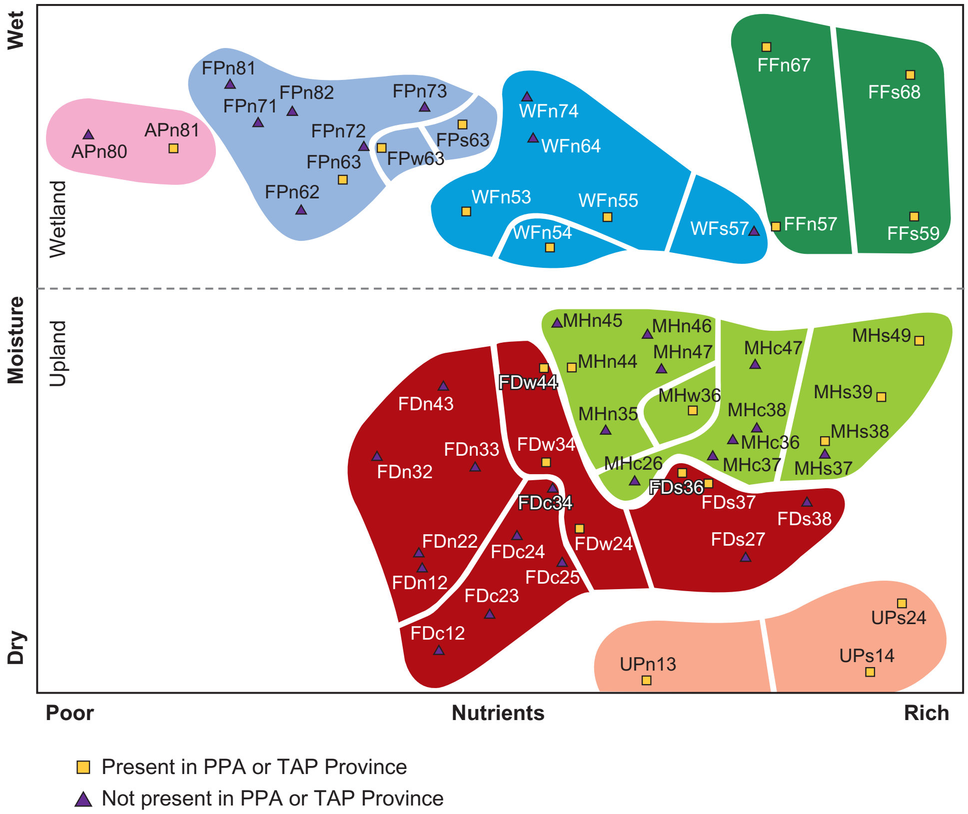


Figure 1–16

Ordination diagram of some Minnesota forest communities. Each character codes for a type of plant community, and the shaded shapes contain related communities. The diagram shows that soil moisture and nutrients partially define what plant communities grow where. Sugar maple-basswood forest (light green MHs39) grows in nutrient-rich, moist uplands, while jack pine woodland (red FDc12) is found in very dry, less-nutrient-rich locations and black spruce/sphagnum bog (pink APn80) is found in very nutrient-poor wetlands.

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community. Note the axes of the diagram: moisture level and nutrient availability, both strongly influenced by soil.

We have already posed the problem of growing populations and the limited area of quality soil to support them. We might similarly ask: In the face of growing populations, how do we make room for nature? Natural ecosystems deliver important services to society, such as watershed functions of collecting, purifying, and storing water. Surely part of the answer is to preserve our best farmlands and forests, and to make the most productive and sustainable use of them. As one soil scientist put it more eloquently: “The sustainable soil management strategy is to cultivate the best soils by best management strategies to produce the best yields so that surplus land can be saved for nature conservancy.”[1]

SOIL AND CLIMATE

Our changing global climate will affect growers and other soil users in ways we are only beginning to understand. Climate affects how we use the soil, and in turn, how we use the soil affects the climate. Because this is so, future public policy will certainly influence soil usage.

[1]Rattan, L. (2009). Ten tenants of sustainable soil management. *Journal of Soil and Water Conservation, 64*(1), 20A–21A.

Courtesy of USDA

Figure 1–17
Carbon sequestration on land under grass cover while set aside in the Conservation Reserve Program (Chapter 20). Measurements showed a large increase in soil carbon.

Soils interact with the atmosphere by gas exchange, as described earlier in this chapter. Some of these gases are "greenhouse gases," or gases that trap heat in the atmosphere, such as carbon dioxide. What we do when we manage soil can increase or decrease concentration of these gases in the atmosphere, and thus the degree of climate change. According to 2007 data, the agricultural sector contributes about 6 percent of the world's greenhouse gas emissions.

Soil is one of the planet's largest reservoirs of carbon in the form of organic matter. If we lose soil organic matter from fields, more carbon dioxide goes into the atmosphere and climate change is promoted. If we increase soil organic matter, carbon dioxide is withdrawn from the atmosphere, and climate change is moderated. In practical terms, for instance, modern conservation tillage increases soil organic matter, while older conventional tillage reduces it. Or, because land covered with permanent grass cover holds more organic matter than land growing corn and soybeans, converting more animal production from feed to grazing or forage will also withdraw carbon from the atmosphere. Figure 1–17 shows a soil in Minnesota that stored large amounts of new carbon after the land was converted to permanent grass cover as part of the Conservation Reserve Program (see Chapter 20), visible as the deep black coloration of the topsoil.

The process of storing carbon in soils, plants, or elsewhere is called **carbon sequestration**, and locations where it is sequestered are **carbon sinks**.

Agricultural and horticultural lands offer great potential as carbon sinks. Most of the virgin lands of the world were brought under cultivation in the 19th and 20th centuries, causing large losses of soil organic matter and contributing to atmospheric carbon dioxide levels. Soil management with an eye toward carbon sequestration could put some of that back. Natural ecosystems, in contrast, remain largely in equilibrium with atmospheric carbon dioxide, so they cannot store much more carbon. Disturbing them, however, releases lots of carbon dioxide.

It is possible that the public will eventually ask growers to rent their land as carbon sinks. That is, while growers grow their crops, they will be asked to grow carbon in their soils as well. There could be a system of carbon credits offered to farmers. Chapter 20 discusses programs concerning soil erosion and water quality that affect growers; already carbon sequestration has begun to appear in these programs. Fortunately, increasing soil organic matter content will also improve soil quality and crop productivity for the grower.

Growers may also play a role in moderating climate change by growing biofuels and hosting wind-energy production to reduce the use of fossil fuels.

The reader will find throughout this text references to climate and soil interactions as they come up. If the reader is unfamiliar with the science of climate change, Appendix 1 summarizes the topic.

SUMMARY

The significance of soil is best explained by describing its function in three ways. First, soil serves ecological functions that support life on earth, including supporting plant growth, recycling and storing carbon and nutrients, and purifying air and water. These functions are often served through interactions between the earth's crust, soil, and atmosphere.

Second, soil supplies anchorage, water, and nutrients to the plant and oxygen to roots. Soil answers these plant needs because it is a three-phase matrix of solid particles with water and air in the pores between the particles. When the soil is healthy, roots can explore these pores to find the water and nutrients needed by the plant.

Third, people inhabit the soil surface and have both agricultural and nonagricultural uses for soil. Agricultural uses include the production of food, fiber, timber, and other plants, as well as landscaping. Nonagricultural uses include recreation, building of foundations and roadbeds, and waste disposal. Soil also provides a source of building material. Properties suitable for engineering uses, such as a low shrink–swell potential, often differ from those needed for agriculture.

This chapter stressed how important soil is and noted that the world's soil base is shrinking because of expanding urban areas and soil degradation, while the world's population continues to expand. At the same time, the necessity for making room for nature becomes more acute. These problems emphasize the need to use and conserve soil correctly.

Public expectations of soil users may rightfully grow more complex, to not only grow crops but also to preserve soil and water quality by the use of BMPs, to grow fuels for the nation, and to grow carbon in their soils to moderate climate change.

REVIEW

1. Is the need for maintaining good soil quality likely to increase or decrease in the years to come? Explain your answer.
2. In older homes, tile sewer lines have openings that are often invaded by tree roots, plugging the lines. Explain why this happens.
3. In building a home, an old tree has its roots covered with an additional foot of soil to make a flat, level area for a patio; the tree slowly dies. Explain why the tree died using information from this chapter.
4. In many city neighborhoods, boulevard trees are planted on a narrow strip of land with the street

on one side and a sidewalk on the other. Beyond the sidewalk lies a lawn. Explain why tree roots may damage the sidewalk and the possible consequences of cutting the roots while repairing the damage.

5. Prepare a list of six soil functions in our human and natural ecosystems. An example would be "medium for plant growth." Give examples for each.
6. Considering the four plant needs supplied by soil, speculate how these needs are supplied when plants are grown hydroponically.
7. Traditionally, landscapers mulched shrub beds by covering the soil with a sheet of black plastic and then laying a mulch such as rock chips on top. Now, they have mostly replaced the black plastic with porous landscape fabrics. Explain the advantage of the fabrics to shrub health.
8. Corn prices are high this year, so a farmer plows up an old pasture and plants it with corn. As a consequence, the organic matter content of the soil declines. Using information in this chapter and Appendix 1, explain why this would contribute (in a very small way) to an increase in average global temperatures.
9. Using the ordination diagram in Figure 1–16, describe the moisture and nutrient characteristics of the sites where savannas (codes beginning with *UP*) grow in Minnesota. Speculate what the soils might be like in these locations. You might answer this question again when you have completed your course, and compare answers.
10. A Case Study: The symbol of a town near the author's college was an old tree called the *Lone Oak*. When the nearby highway was completely remodeled and rebuilt, the health of the Lone Oak declined over several years and finally died. What factors might have led to its demise?

ENRICHMENT ACTIVITIES

1. Anybody whose career is in agriculture, horticulture, natural resources, or engineering needs a basic knowledge of soils. Some jobs we might consider soil science careers include soil surveyor or soil conservation specialist. The Internet contains many sites about soil science careers; check out these examples:
   - Canadian Soil Science Society career page, http://www.csss.ca. Go to "Students," then read the section titled "Picture Yourself . . . As a Soil Specialist."
   - Professional Soil Scientists Association of Texas career page, http://pssat.org. Go to "Careers."
   - Soil Science Society of America (SSSA) has a brochure that can be downloaded from its Web site, http://www.soils.org, in the career section. Also check out job listings there.
2. Part of being a professional is participating in professional organizations. Check out the home pages of the professional organizations listed previously, as well as the following:
   - Association for Women Soil Scientists, http://www.womeninsoils.org.
   - Soil and Water Conservation Society, http://www.swcs.org.

   You can find societies for many other nations on the Internet as well, such as the Mexican Society of Soil Science, the Indian Society of Soil Science, and others.
3. Internships are an important part of learning about soil use. For information on internships in soil science, browse the Internet for "internships in soils."
4. For further information on some of the topics discussed in this chapter, try these Web sites:
   - The Soil Quality Institute for more information on soil quality, http://soils.usda.gov/sqi.
   - The SSSA statement about carbon storage in soils, https://www.soils.org/files/about-society/carbon-sequestration-paper.pdf.

- The USDA document on climate change and agriculture and policy, http://www.nrcs.usda.gov/wps/portal/nrcs/main/national/climatechange.
- *The History of Herodotus*, http://classics.mit.edu/Herodotus/history.2.ii.html.

5. For a treatment of the place that soil degradation (as well as other factors) played in the collapse of earlier societies, see Jared Diamond's 2005 book *Collapse: How Societies Choose to Fail or Succeed* (Penguin Books).
6. Figure 1–1 shows a dust storm from the 1930s. In July 2011 a massive "historic" dust storm covered Phoenix and much of surrounding Arizona. Search the Internet for images of that storm.

CHAPTER 2

Soil Origin and Development

TERMS TO KNOW

alluvial fan
alluvial soil
caliche
chemical weathering
colluvium
delta
dissolution
eluviation
eolian deposit
floodplain
frost wedging
glacial drift
glacial outwash
glacial till
hydration
hydrolysis
igneous rock
illuviation
lacustrine
leaching
levee
loess
marine sediment
master horizon
metamorphic rock
mineral soil
organic soil
oxidation–reduction
parent material
pedology
pedon
physical weathering
plow layer
polypedon
residual soil
river terrace
root wedging
sedimentary rock
slope
slope aspect
soil genesis
soil horizon
soil profile
solum
subsoil
talus
topsoil
transported soil
weathering

OBJECTIVES

After completing this chapter, you should be able to:

- define a soil body
- list examples of the five soil-forming factors
- describe how soils develop
- describe the horizons of the soil profile

Soil is a very slowly renewable resource. Although many of our soils originated long ago, the forces that create them continue to operate. Some soils are hundreds of thousands of years old, while others just began to make their appearance yesterday. Soils grow, change, and develop. This chapter describes the soil-formation processes.

Pedology is the study of soil formation, also known as **soil genesis**, and soil classification and mapping. We cover the latter subjects in the next chapter. Modern pedology dates to the eighteenth and nineteenth centuries in Germany, the United States, and especially Russia. These early researchers developed concepts of soil as an evolving body arising from weathered rocks of the crust under a variety of influences. V. V. Dokuchaev (1846–1903), a Russian often credited with laying the foundation of modern pedology, published a careful study of Russian soils in 1883 that applied these concepts. He identified soil-forming factors, developed an early soil classification system, and began naming the soil horizons we use today. Dokuchaev's and other Russian publications remained unknown in the United States until into the twentieth century.

In the United States, Hans Jenny's publication of *Factors of Soil Formation* in 1941 further developed five factors of soil formation detailed in this text. Jenny continued to develop and quantify these factors throughout his career and connected them with ecological principles. Much of the information in this chapter comes from the work of Jenny and other soil scientists practicing in the United States in the twentieth century. Before describing how a body of soil forms, let us define what we mean by a soil body.

THE SOIL BODY

Soil is a collection of natural bodies of the earth's surface containing living matter that is able to support the growth of plants. It ends at the top where the atmosphere or shallow water begins. It ends at the bottom at the farthest reach of the deepest rooted plants. Soil varies across the landscape: In one area it may be mostly made of decayed plant parts, whereas in another place it may be mostly sand. It is not possible to learn everything about a soil just by standing on the surface. One must dig a hole to see what it looks like below the surface (Figure 2–1). Because a soil scientist cannot dig up acres of ground to study a whole body of soil, soil is divided into small parts that can be easily studied. This small body is called the **pedon** (Figure 2–2). A pedon is a section of soil, extending from the surface to the depth of root penetration, but generally examined to a depth of 5 feet. Generally, a pedon has dimensions of about 1 meter by 1 meter, and about 1.5 meters deep (about 3 feet × 3 feet × 5 feet). Soil scientists use the pedon as a unit of soil easily studied by digging a pit in the ground. The pedon is a human device for studying soil; it does not actually exist in nature. This soil body can be studied, classified, described in a soil survey report, and used.

The traits of a pedon are set by the combination of factors that formed it. In the landscape near the pedon being studied are other pedons that are very similar. As

Photo by Erwin Cole, USDA Natural Resources Conservation Service

Figure 2–1
One must dig into the ground to examine a soil, here the Clarion soil of Iowa. See Figure 2–17 to identify the layers.

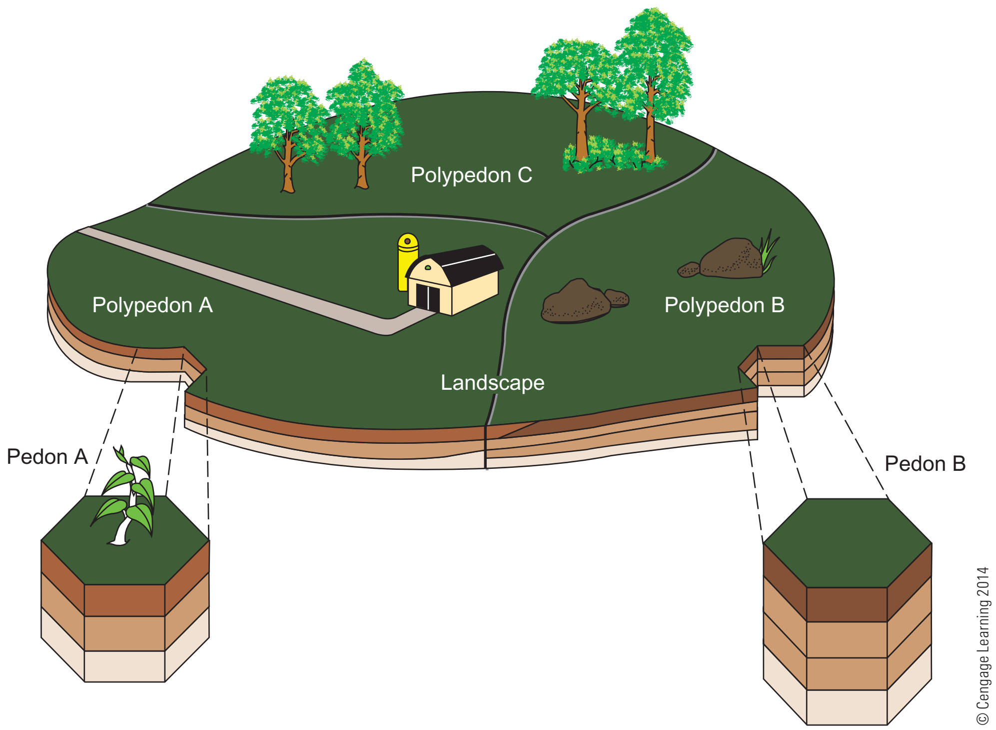


Figure 2–2
Two soil pedons show how each relates to polypedons and the total landscape.

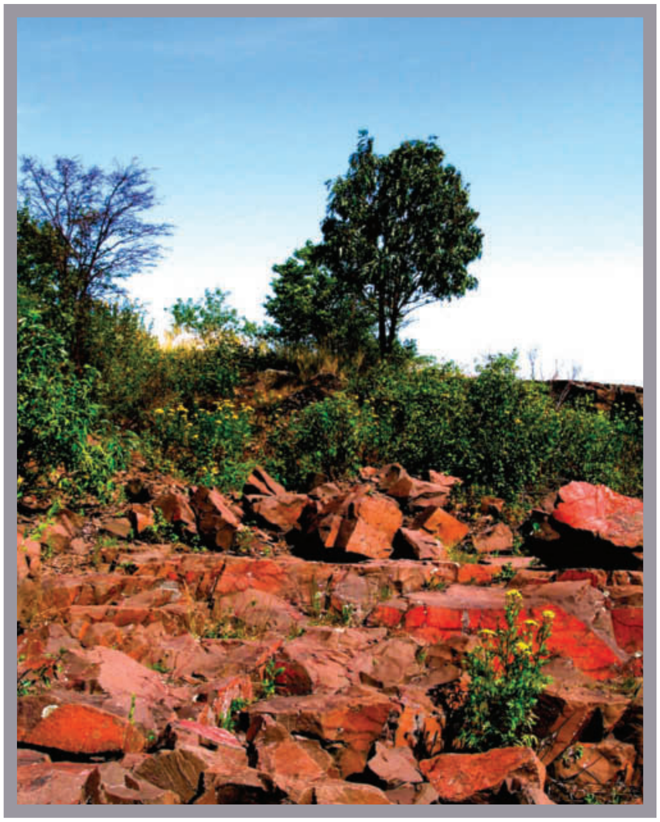
one moves across the landscape, however, one will reach a pedon that is different, because the combination of factors that formed it was different. A collection of pedons that are much the same is called a **polypedon**. Later in this text, we will learn how these polypedons are mapped into units called soil series.

How does a soil pedon form? Picture a section of bare rock that could someday become a soil pedon. In the process of soil formation, this rock is changed into a layer of small, tiny mineral particles with some organic matter mixed in. Weather and plants are the major agents responsible for forming soil from rock, and the process is called **weathering**.

Physical weathering is the disintegration of rock by temperature, water, wind, and other factors. Figure 2–3 shows bedrock being fractured by physical processes. Physical weathering reduces particle size; it does not alter the chemistry of the material. For instance, in cold climates, **frost wedging** occurs when water freezes and expands in rocks or in cracks in the rock, causing it to break apart. The alternate expansion and contraction of rock caused by heating and cooling cycles also stresses the fabric of rock. Both cause rock to fracture or outer layers to peel away. In some climates, salts may crystallize in cracks in rock, placing internal pressure on the rock and splitting it apart. Rain, running water, and wind-blown dust also wear away at rock surfaces.

Chemical weathering changes the chemical makeup of rock and breaks it down. A common process is **dissolution**. Some minerals simply dissolve slowly in water, as in the dissolution of gypsum:

$$caSO_4 + H_2O \rightarrow ca^{+2} + SO_4^{-} + H_2O$$



Courtesy of Maurice Northrup

Figure 2–3
Weathering bedrock that could be on its way to form residual soil. Physical and chemical processes are fracturing the rock.

Maintaining Mount Rushmore

The weathering processes described here work on all rock of the earth's surface. They also work on the presidential faces of Mount Rushmore. Periodically cracks are sealed to prevent water from entering and initiating freeze–thaw cycles. Lichens are removed by pressure washing to slow their contribution to erosion of the rock faces. Fortunately, the faces are carved in hard granite. Geologists estimate the rock loses about 1 inch per 10,000 years.

In **hydrolysis**, minerals react with the hydrogen that is in the water molecule, splitting the water apart. For example, the feldspar mineral orthoclase undergoes hydrolysis by replacing the sodium in the mineral with hydrogen, creating a new, softer feldspar:

$$NaAlSi_3O_8 + H_2O \rightarrow HAlSi_3O_8 + Na^+ + OH^-$$

Hydration also involves water, but here the water molecule itself joins the crystalline structure of the mineral, again creating a softer, more easily weathered material, as in the hydration of hematite to ferrihydrite:

$$5Fe_2O_3 + 9H_2O \rightarrow Fe_{10}O_{15} \cdot 9H_2O$$

Much of chemical weathering involves water interacting with crystalline minerals to create new materials by dissolution, hydrolysis, or hydration. Not surprisingly, moisture availability is an important variable in soil genesis.

Oxidation–reduction and other reactions are also important in chemical weathering. Refer to Appendix 1 if you need help understanding these reactions.

Plants also play an important role in rock crumbling. Roots can exert up to 150 pounds per square inch of pressure when growing into a crack in rock. **Root wedging** from the pressure pries apart stone. Lichens growing on bare rock form mild acids that slowly dissolve rock. When a lichen dies, its dry matter is added to the slowly growing mixture of mineral particles and organic matter. When a small bit of soil forms in a rock crevice, plants begin to grow from seed that has blown into the crevice, continuing the cycle. Roots themselves release mild acids that further the process of soil genesis. Plants themselves actively promote soil genesis.

Soil formation does not stop when a layer of young soil covers the surface. The new soil continues to age slowly and develop over thousands of years. Soil scientists state that five factors operate during the process of soil genesis and development: *parent material, climate, life, topography*, and *time*. One could say that over time, climate and living things act on parent material with a certain topography to create soil. Some have suggested that human activities might be named a sixth factor, because most soils have been modified to some degree by humans.

Soil formation begins with rock, which supplies the parent materials for most soils. Before studying the five factors, let us look at the rocks of earth's crust.

ROCKS AND MINERALS

The original source of most soils is rock—the solid, unweathered material of the earth's crust. Solid rock breaks into smaller particles, which are the **parent materials** of soil. Rock is a mixture of minerals that, when broken down, supply plant nutrients. Geologists classify rock into three broad types: igneous, sedimentary, and metamorphic.

Igneous Rock

The basic material of the earth's crust is **igneous rock**, created by the cooling and solidification of molten materials from deep in the earth. Igneous rocks, such as granite, contain minerals that supply 13 of the 17 required plant nutrients (listed in Chapter 10 of this text).

Igneous rock may be coarse grained, with grains and crystals large enough to easily see with the naked eye, such as granite. Basalt is an example of a fine-grained rock. Igneous rock can also be dark colored, like basalt, or lighter colored, like some granites. Darker-colored igneous rocks tend to weather more easily and contain more iron and calcium, important plant nutrients.

Granite (Figure 2–4A), which is mined for monuments and building material, is a hard, coarse-grained rock made of feldspar, quartz, and other minerals. Feldspar, a fairly soft mineral containing potassium and calcium, weathers easily to clay. Quartz, a very hard and resistant mineral, weathers slowly to sand. Figure 2–5 lists the nutrient content of two sample igneous rocks: a granite and a basalt. Granite tends

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A

© Tyler Boyes/www.Shutterstock.com

B

Figure 2–4

Two examples of rock discussed in the text. (*A*) Granite, a coarsely grained rock that weathers very slowly to sandier soils. (*B*) Gneiss, a metamorphosed granite. The banding forms during metamorphosis.

to weather slowly to create acidic parent materials high in sand, while basalt, a softer, darker, finer-grained rock, weathers more quickly to less-acidic materials low in sand.

Sedimentary Rock

Igneous rock comprises only about one-quarter of the earth's actual surface, even if most of the crust is igneous. This is because **sedimentary rock** overlays about three-quarters of the igneous crust. Sedimentary rock forms when loose materials such as mud or sand are deposited by water, wind, or other agents, slowly cemented by chemicals or pressure into rock. Much of the sedimentary rock covering North America was deposited in prehistoric seas.

Sand deposits can solidify to form the gritty but often loosely cemented sandstone, a light-colored, coarsely grained rock. Loosely cemented sandstone weathers easily to release sand grains. Mud deposits form shale, a fine-grained light-colored rock. Limestone forms when calcium-rich grains of calcite settle out of ocean water.

The parent materials of many American soils derive from sandstone and limestone. Sandstone, which consists of cemented quartz grains, weathers to sandy soils. Generally, these soils are infertile and droughty. Limestone is high in calcium and weathers easily to soils high in pH, calcium, and magnesium. Figure 2–5 lists the contents of a typical sandstone and limestone.

Minerals	Gray Granite	Basalt	Hinckley Sandstone	Platteville Limestone
% quartz	64	49	94	7.5
% feldspars, others	20	20	2	—
% calcite, dolomite	7	15	5	90
Elements		**Pounds/Ton of Rock**		
Calcium	69	150	—	704
Potassium	66	17	—	—
Magnesium	36	66	—	18
Iron	23	35	15*	
Phosphorus	5	5	—	—
Manganese	—	3	—	—

Adapted from Minnesota Geological Survey

Figure 2–5

Composition of several igneous and sedimentary rocks of Minnesota, according to the Minnesota Geological Survey. Dashes mean only trace amounts, and the starred number was estimated by the author.

Rocks			
Sedimentary	**Igneous**	**Metamorphic**	**Main Components**
Sandstone		Quartzite	Quartz sand
Limestone		Marble	Calcite
Shale		Slate	Feldspar clays
	Granite	Gneiss	Quartz, mica, feldspar
	Basalt	Schist	Feldspar, mica, olivine

Figure 2–6

Relationships of several common sedimentary, igneous, and metamorphic rocks. See Figure 2–4 for images of granite and gneiss.

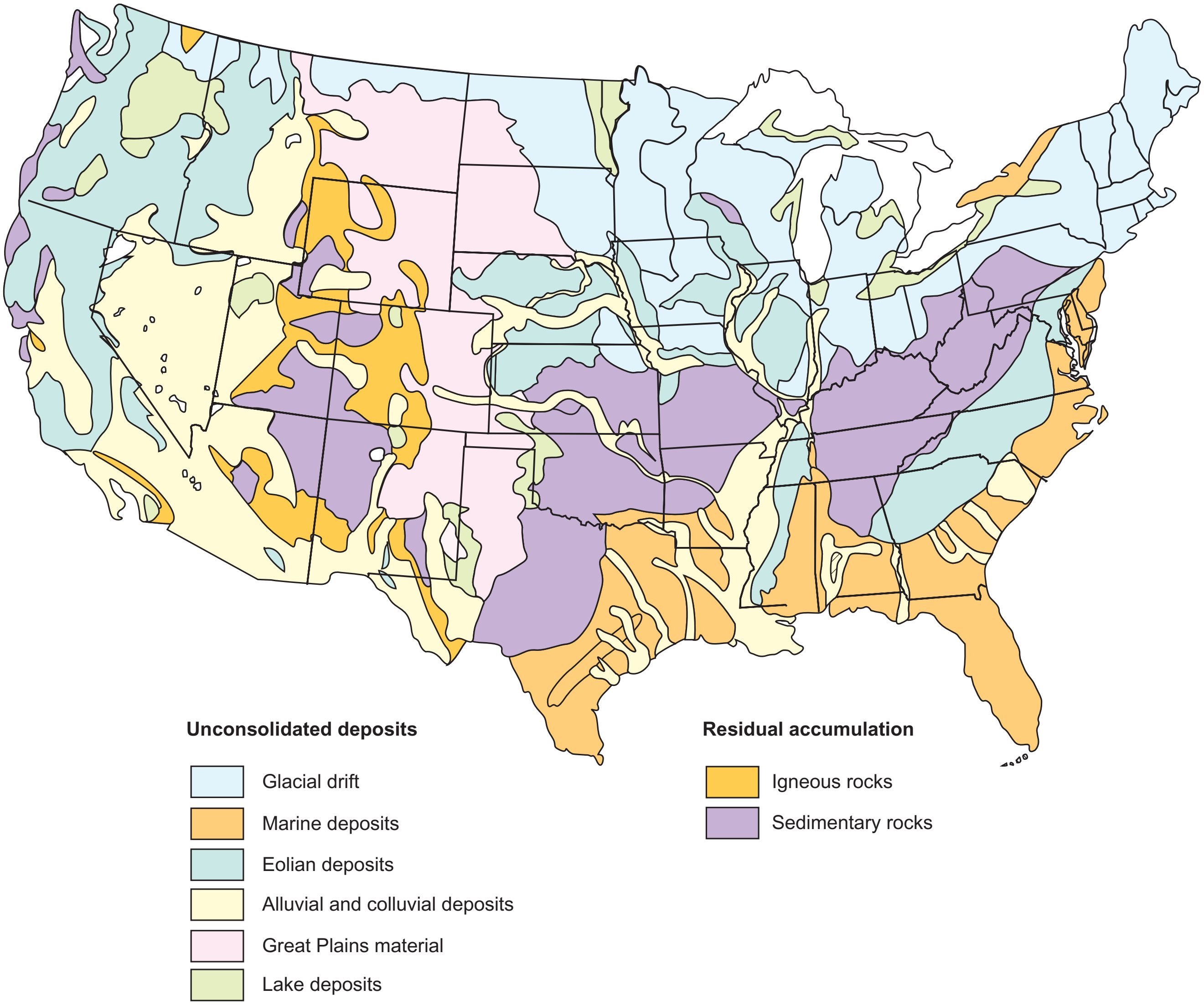
Metamorphic Rock

If igneous and sedimentary rocks are subjected to great heat and pressure, they change to form **metamorphic rock**. For instance, limestone is a fairly soft, gritty rock. When subjected to heat and pressure, it changes to marble, which is harder and can be cut and polished. Sedimentary rocks tend to become much harder when metamorphosed, becoming slower to weather. Sandstone, for example, changes to the far harder rock quartzite.

Figure 2–4B shows gneiss, a form of metamorphosed granite. While granite is speckled, gneiss tends to display banding that forms during metamorphosis. Soils arising from metamorphic parent materials resemble soils from the original sedimentary or igneous rock. Figure 2–6 shows the relationships between common sedimentary, igneous, and metamorphic rocks.

PARENT MATERIAL

Soil genesis is the process of creating soil from parent material. The description of soil origin earlier in the chapter was of soil formed directly from bedrock; such a soil might form from the rock in Figure 2–3. These **residual soils**, formed in place from the residuum of broken-down bedrock, are actually less common than soils of parent materials carried from elsewhere by such pervasive agents of transport as wind, water, ice, or gravity. Residual soils form slowly, as solid rock must be weathered first. **Transported soils** develop from already weathered material, so they develop more quickly. Figure 2–7 shows parent materials of the United States. Let us look at the agents of transport and the sorts of parent materials they carried.



Courtesy of USDA

Figure 2–7
Major parent materials of soils of the United States.

Glacial Ice

Glacial ice carried parent materials over the northern part of North America (Figure 2–8) during numerous glacial periods over the past 2 million years. The last four left the most evidence, and the most recent glacier, that of the Wisconsin period, reached its peak expanse about 18,000 years ago and melted back out the United States about 10,000 to 12,000 years ago. Most of the glacial deposits that cover the northern states come from the vast ice sheet of the Wisconsin glaciation.

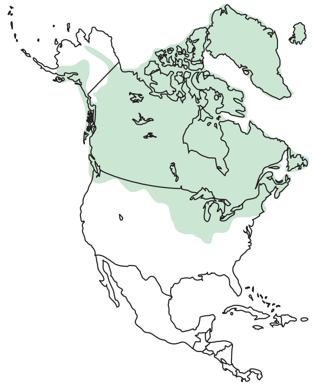


Figure 2–8
Glaciers have covered much of North America several times.

Glaciers that expanded out of Canada crushed and ground the earth; picked up and transported clay, sand, rocks, and other materials; and deposited them elsewhere to become the parent materials of new soil. We term these deposits **glacial drift**. In the process, the glaciers left behind a distinctive landscape over much of northern United States and Canada, often rich in wetlands, lakes, and ponds.

Glaciers deposited materials in many ways, so there are several kinds of glacial drift. During the melting process, some debris simply dropped in place to form deposits called **glacial till**. Some till dropped at the margins of the glacier, forming hills called moraines. Other kinds of till were deposited beneath advancing ice; these materials, crushed under the weight of the ice riding over them, are often extremely dense and compacted. In some areas such as parts of New England and Minnesota, they form dense hardpans. Because there was no sorting action in the deposition, glacial till is extremely variable, and so are the soils derived from it. Till soils often contain pebbles, stones, and even boulders.

Other materials carried by the glacier washed away in meltwater to form sediments in streams and lakes. During the process, materials were sorted by size. Coarser material, being larger and heavier, was deposited near the glacier and in nearby streams and rivers to form **glacial outwash**. Outwash deposits tend to be sandy and gravelly (see Figure 1–12 in Chapter 1), and are good sources of construction sands and gravels. Smaller particles often reached glacial lakes to form **lacustrine** deposits on the lake bottoms.

Wind

Some parent materials were carried by wind, leaving **eolian deposits**. For example, some soils in Nebraska formed from sand dunes, deposits of sand carried by rolling in the wind. Most eolian soils in the United States are actually a result of the last glacial period.

After the last glaciers melted and meltwaters subsided, large expanses of land were exposed to a dry climate with strong westerly winds. Winds picked up silt-sized (medium) particles and deposited them in the Mississippi and Missouri river valleys and elsewhere. These **loess** soils—wind-deposited silt—are important agricultural soils in much of Iowa, Illinois, and neighboring states. Loess often blankets other materials, so often forms the upper parts of a soil.

Unlike other materials, wind-blown dust is global. For instance, dust blown from the Sahara Desert of Africa makes a significant contribution to soils of the Caribbean Islands as well as Central and South America.

Water

Alluvial soils are soils whose parent materials were carried and deposited in moving freshwater to form sediments (Figure 2–9). Alluvial materials can be deposited in several ways. **Alluvial fans** form below hills and mountain ranges where

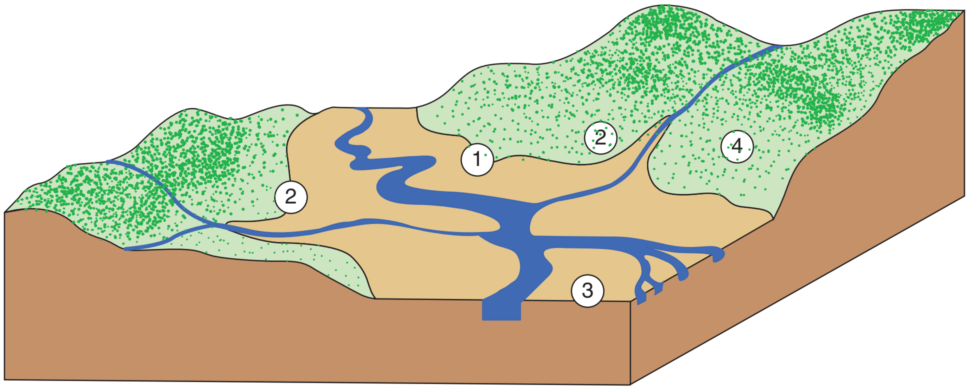


Figure 2–9
Water-and marine-deposited soils. (1) Floodplains form along rivers from materials deposited during flooding. (2) Alluvial fans are deposited at the base of slopes by running water. (3) Deltas form when smaller particles drop out as a river enters an ocean. (4) River terraces are old floodplains left above a new river level.

streams flowing down-slope deposit material in a fan shape at the base. As water speed slows abruptly at the foot of the slope, large particles drop out first. As a result, alluvial fans are generally sandy or gravelly. Finer materials are carried away in rivers.

Flooding rivers also leave behind deposits. Coarser materials may be deposited in low ridges, or **levees**, along the river bank. Away from the river, floodwaters spread over large flat areas called **floodplains**. Here water will be shallow and slower moving; fine particles settle out. Repeated flood events tend to create multiple layers in floodplain soils, and they can be excellent agricultural soils when flooding can be controlled and drainage improved. Levees, being coarser and elevated, dry more quickly. Floodplain soils are especially important along the Mississippi and its tributaries and along rivers that flow into the ocean on the East and Gulf coasts. Many important soils of California are from river alluvium.

Sometimes a river cuts deeply into its floodplain to flow at a lower elevation. This establishes a new riverbed and floodplain, while the old floodplain is left higher as a **river terrace**. An example of river terrace soil is some soil of the San Joaquin Valley of California.

Lacustrine deposits form under still freshwater. Most of our lacustrine soils remain from giant glacial lakes that have since dried up, including Glacial Lake Agassiz of northern Minnesota, North Dakota, and Canada, and Glacial Lake Bonneville of Utah. When glacial runoff water ran into the lake, the heaviest materials were left near the shore, while the smallest particles were carried to the center of the lake. Thus, lacustrine soils are sandy near the old shoreline and grade to soils with smaller particles toward the old lake center. Lacustrine soils, having flat terrain and being poorly drained, can host a rich agriculture with proper artificial drainage, but challenge the home and septic field builder.

Marine sediments form in the ocean. Many scattered soils of the Great Plains and the Imperial Valley of California are beaches of prehistoric seas that once covered the United States. Other beach soils are common along the Atlantic coastline and the Gulf of Mexico. All these tend to be sandy soils. **Deltas**, in contrast, have very small particles and tend to be wet. Deltas form when rivers flowing into an ocean deposit sediments at the mouth of the river. The Mississippi River Delta of Louisiana is a prime example, as is the Rio Grande Valley of Texas and Mexico.

Figure 2–10
Colluvium slides or rolls down a slope, here in Arizona.

Gravity

Some parent materials move simply by sliding or rolling down a slope. This material, called **colluvium**, is scattered in hilly or mountainous areas. An example of a colluvial material is a **talus**—sand and rocks that collect at the foot of a slope (Figure 2–10). Avalanches, mudslides, and landslides are other examples.

Volcanic Deposits

The ash blown out of a volcano and deposited nearby or carried some distance by wind forms a chemically distinct, dark, and lightweight parent material. The Pacific Northwest, Hawaii, and Alaska are areas of the United States where such deposits are common.

Organic Deposits

Characteristics of the soils formed from parent materials described so far are set by mineral particles in the soil. **Mineral soils** contain less than 20 percent organic matter, except for a surface layer of plant debris. **Organic soils**, containing 20 percent or more organic matter, form underwater as aquatic plants die. Low-oxygen conditions underwater retard decay of these dead plants, so partially decayed remains tend to pile up at the lake bottom. Eventually the lake fills in and is replaced by an organic soil. Organic soils are extensive in Minnesota, Wisconsin, Florida, Michigan, and Alaska.

CLIMATE

While climate is extremely complex, we are speaking here primarily of temperature and precipitation. There are whole vocabularies for naming temperature and rainfall regimes, but let us mention only the terms *arid, semiarid,* and *humid.* Most simply put, these terms refer to climates that experience very low, low, and higher rainfall, respectively.

Climate first affects soils by causing physical and chemical weathering of rock. However, climate continues to affect soil development long beyond this initial stage. The main effects are due to temperature and rainfall.

Temperature affects the speed of chemical reactions in the soil—the higher the temperature, the faster a reaction. Chemical weathering in soils occurs mostly when the soil is warmer than 60°F. Thus, in cold areas, such as tundra, soils develop slowly. In warm areas, such as the tropics, soils develop more rapidly.

Another result of temperature is its effect on organic matter. Warmth promotes greater vegetation, so more organic matter is added to the soil. However, warm temperatures also speed the decay and loss of organic matter. Thus, soils of warm climates tend to be low in organic matter.

In warm regions, warmth promotes dissolution of materials, so if climate is also humid, chemicals leach out of the soil more quickly. Warm climates also promote the weathering of clay minerals to forms that are less fertile.

Water is a critical factor in soil genesis. Much chemical weathering involves water in such reactions as hydrolysis and hydration. In cold regions, water is needed for frost wedging. Water moving down through the soil moves dissolved materials with it by **leaching**, and can even translocate (move) fine solid particles such as clay. Translocated materials include clays, lime, salts, plant nutrients, and other chemicals. Thus, soils in moist climates tend to be different than those in drier climates. For instance, desert soils (see Figure 2–14) tend to be enriched in salts that would leach out of the soil in humid climates.

Soils in high-rainfall areas also tend to grow more vegetation, so soils of humid areas tend to have more organic matter than soils of drier regions. However, this effect is often counteracted by vegetation effects discussed later in this chapter. As a broad summary of the effects of a higher-rainfall climate, soils tend to be deeper and have more organic matter in the topsoil. Clay particles and salts tend to move deeper into the soil, and the soil tends to be more acidic.

The United States is a good example of the effects of climate on soil (Figure 2–11). The climate of the United States cools from south to north. This is reflected in an increase in average organic matter content from south to north. Also, the most weathered soils in the United States are in the south. The average rainfall of the United States increases from west to east. As a result, the organic matter content of the United States' soils also tends to increase from west to east, though vegetation effects tend to mask the trend (see the next section).

Soil color also follows north–south trends. Because organic matter is black, soils tend to appear darker as one moves from warmer to cooler climates. Because of changes in chemical reactions involving iron, soils tend to appear redder as one moves from cooler to warmer climates.

ORGANISMS

Organisms that live in soil—such as plants, insects, and microbes—actively affect soil formation. The actual properties of a developing soil are influenced especially by the type of plants growing on it. Figure 2–12 shows the parent vegetation of soils of the United States.

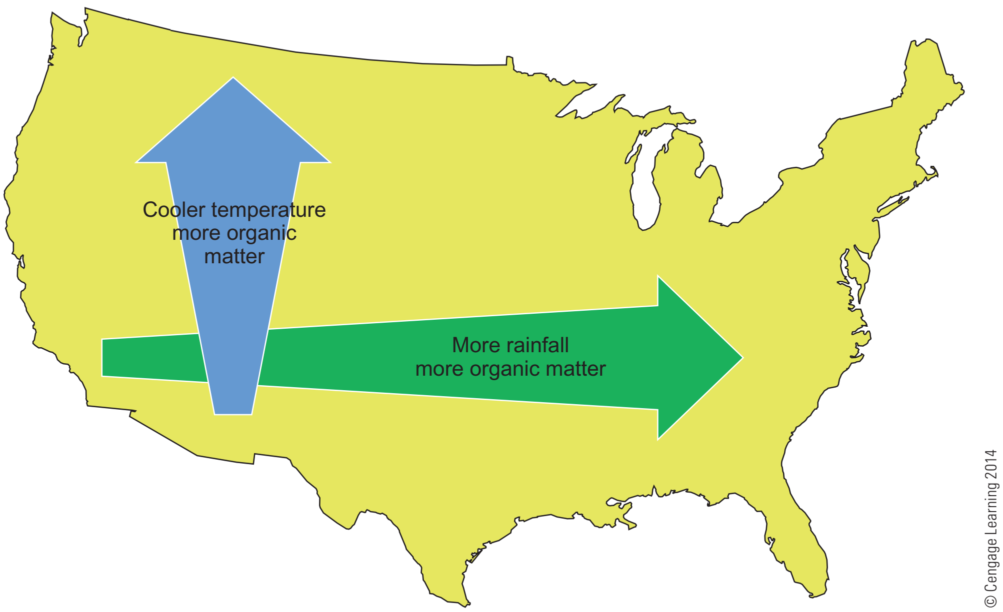


Figure 2–11

One effect of climate on soils. The average organic matter increases to the east and north because of higher rainfall or cooler temperatures. Other factors also affect organic matter, like vegetation, which alters these trends regionally.

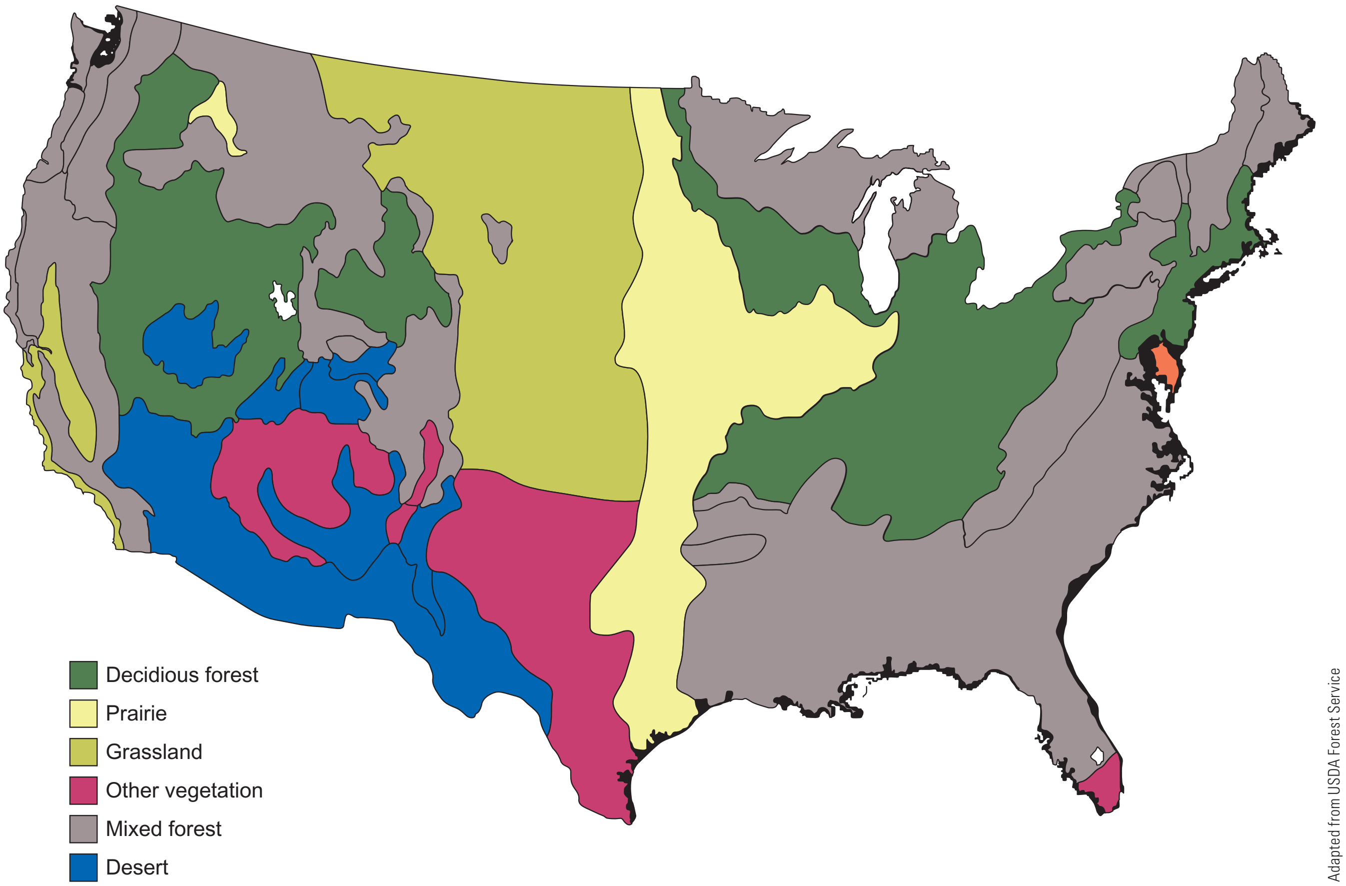


Figure 2–12

Native vegetation of the United States.

Mineral soils having the highest organic matter content form under grasslands (Figure 2–13). Grassland vegetation, mostly herbaceous, forms a deep, dense mat of fibrous roots, many of which die each year and contribute large amounts of organic matter to the soil. Indeed, most of the biomass of a prairie develops underground in the soil. This keeps the organic matter content high and the soil color dark. Prairie vegetation is the factor mentioned previously that masks the trend of higher moisture/organic matter soil content in North America. However, the fact that the moist eastern prairies of the Corn Belt display higher organic matter content than the dry western prairies of, say, Colorado, supports the association between higher rainfall and more organic matter.

In a forest, much of the biomass grows above ground in the trees. When leaves fall or the tree dies, the material falls to the soil where it creates a surface layer of organic matter that does not mix with deeper layers. As a result, forest soils have less organic matter than prairie soils and display shallower topsoils of lighter color. The type of trees also influences the soil. Compared to hardwoods (deciduous trees), softwood (conifer) foliage is acidic and resistant to decay; therefore their soils tend to be thinner, lower in organic matter, and more acidic. Deserts, with very sparse vegetation, have the least organic matter (Figure 2–14).

Vegetation also affects the location of nutrients and other ions in the soil. Plants absorb ions in the roots and carry them to the tops, where they are returned to the soil surface when leaves drop. This recycles ions from deeper in the soil to the surface and helps reduce their loss from leaching. Deep roots of deciduous trees, for instance, extract ions from deep in the soil, leaving the surface horizon of deciduous forest soils enriched in ions.

We tend to stress vegetation as the main living factor in soil formation, but other life impacts soil as well, such as burrowing animals that mix the soil; earthworms that create large, deep pores and speed organic matter decay; or nitrogen-fixing bacteria. These other organisms are covered in greater detail in Chapter 5.

Courtesy of Maurice Northrup

Figure 2–13
Grassland vegetation in Minnesota. Grassland soils tend to be high in organic matter (like the Clarion of Figure 2–1).

Figure 2–14
Soils of this piece of the Sonoran Desert near Phoenix are influenced by sparse vegetation and arid climate.

TOPOGRAPHY

Topography, or the soil's position in the landscape, influences soil development mainly by affecting water movement and soil wetness. Major changes in soil type can occur over very small differences in elevation and distance due to topography. Water runs off slopes, making them drier, and collects in low areas, making them moister. This, in turn, affects chemical weathering that depends on moisture, types of vegetation, and other factors that influence soil formation.

Two important features of topography are **slope** and **slope aspect**, or the direction the slope is facing. Slopes may be steep or shallow, long or short. Slope position strongly influences soil moisture. Soils on the shoulder of a slope mostly shed water and are dry; soils at the base of a slope mostly receive water from above, and tend to be moist. Soils at midslope shed water, but also receive water from above, and are in between in moisture content. Water tends to collect in depressions, creating a very wet position. In addition, the water table tends to be deepest near the shoulder and closest to the surface at the base of a slope and in depressions, also changing moisture content of the soil (Figure 2–15). The water table may even intersect the soil surface and create a wetland where organic matter accumulates. These differences affect chemical weathering of the soil. For instance, subsoil may be reddish high on the slope, the color of oxidized iron in a well-aerated soil, and gray at the base, the color of reduced iron in waterlogged soil (Chapter 4). Slope aspect determines the amount of solar energy the slope receives. South-facing, and to a lesser degree west-facing, slopes receive more intense sunlight than north- and east-facing slopes, and are thus warmer and drier. This effect is often visible by the types of vegetation occupying different slopes. For instance, in the author's area, sugar maple forest may develop on cool and moist north slopes while oak forest grows on hotter, drier south slopes.

Slope also affects erosion rates. Slopes tend to lose soil from erosion, while depressions tend to receive soil. Because soil particles are moved off slopes by erosion, such soils tend to be thinner and less well developed.

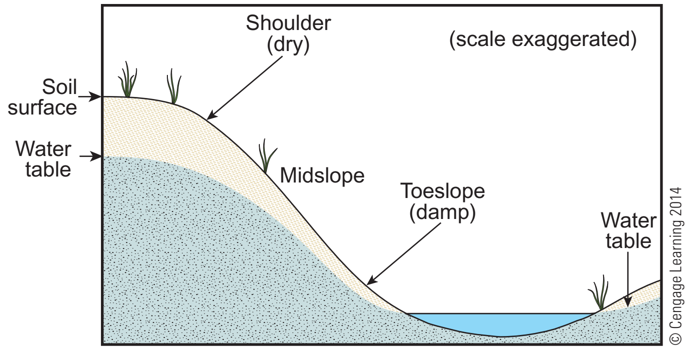


Figure 2–15

Common relationship between slope and soil moisture. Soil-water content of the soil is controlled by proximity of water table to the soil surface, runoff down the slope, and drying by exposure to the sun. The water table gets closer to the surface toward the base of the slope, and may even rise above the surface in a depression to create standing water. There may be very different soils at different positions on such a slope.

Because running water tends to carry off smaller particles, soils in lower areas may be finer than those of higher areas. Depressions may also intersect the water table at least part of the year, keeping them wet for long periods. One could say that level and depressional lands tend to have drainage problems, while sloping terrain often suffers from erosion and dryness. In natural ecosystems, these differences often determine what plant communities grow where (Chapter 9).

TIME

Soils change over time, undergoing an aging process. Initially, a thin layer of soil appears on the parent material. Such a young, immature soil takes as little as 100 years to form from well-weathered parent materials under warm, humid conditions. Under other conditions, it may take hundreds of years.

Weathering of the young soil continues, and many generations of plants live and die, so the young soil becomes deeper and higher in organic matter. If there is enough rainfall, leaching begins to carry some material deeper into the soil, creating the soil profile described later in this chapter.

As soils age, biological processes tend to increase the nitrogen content, while leaching tends to reduce phosphorus. Thus, young soils tend to be low in nitrogen but high in phosphorus, while older soils are the opposite. Mature soils are generally productive, but as soils continue to age, they become more severely weathered, more highly leached, and often less productive. In general, as soil ages it becomes deeper, develops distinct layers, and becomes more acidic and leached.

Over time, soils become less and less like their parent materials. Aging happens most rapidly in warm, humid climates, and most slowly in cold or dry climates, or where parent materials resist weathering.

However, the aging process is not static. Time zero for a soil usually begins when some dramatic event such as landslides, glaciers, or piling of mining spoil changes everything and resets the clock. Such events can happen at any time. A soil might age through the years until it reaches some steady state and remains unchanged thereafter, but this is rare. Soils can erode away, be buried, or even become the parent material for a new soil. If soil factors change, the direction of soil development can be deflected into a new path. For instance, if forest invades prairie, the soil embarks on a new path toward a forest-type soil.

We tend to think of soil development as progressive; that is, soil becomes deeper and more complex with more and better defined layers. But if the combination of soil-forming factors changes, soil can also regress, becoming shallower and less complex. Very old soils may have undergone repeated cycles of progression and regression.

HUMANS

Humans may be considered just another living entity that modifies soil, but their action can be so rapid, dramatic, and different from other life that they might be considered a separate, sixth soil-formation factor. Very few soils have been unaffected by human activities. Effects may be as subtle as the deposition of air pollutants distant from any human habitation to as massive as earthmoving during road construction. The latter resets the time clock for this new soil material to zero, and the earth moved by the machinery is the parent material for this new soil. Much of what people do to grow plants alters the soil, like cultivation or fertilization.

Humans also enrich soils around them in phosphorus by fertilization and disposal of refuse. This effect is distinctive enough that archaeologists use phosphorus enrichment as evidence of early human habitation. Our system of soil classification also recognizes such enrichment in some soils.

Chapter 19 describes traits of urban soils, those most modified by humans.

THE SOIL PROFILE

Soils change over time in response to their environment, represented by the soil-forming *factors*. Soil scientists have classified the causes of those changes into four soil-forming *processes:*

ADDITIONS:	Materials may be added to the soil; some examples are fallen leaves, alluvium, and human-made materials such as air pollutants and compost. Deposition of nutrient-rich dust is a major contributor to the fertility of many soils.
LOSSES:	Materials may be lost from the soil, as a result of such mechanisms as deep leaching, erosion from the surface, or gases filtering out of the soil.
TRANSLOCATIONS:	Materials may be moved within the soil, by leaching deeper into (but not out of) the soil, by being carried upward with evaporating water, by being moved by animals such as ants or earthworms, or by other action that moves soil material around.
TRANSFORMATIONS:	Materials may be altered in the soil; for example, organic matter decay, weathering of minerals to smaller particles, or chemical reactions.

For example, some soils contain **caliche**, a hard subsoil layer cemented by lime. Its formation has been explained this way. Over long periods of time, lime-laden dust is deposited on the soil surface (*addition*). It is leached downward by percolating water (*translocation*), and precipitates out as solid lime at some depth (*transformation)* where it cements a soil layer. This process requires the correct amount of rainfall—enough to translocate the lime downward, but not so much as to move it out of the soil altogether (*loss*).

Each of these processes occurs differently at different depths. For instance, organic matter tends to be added at or near the surface, not deep in the soil. Some material moves from high in the soil to be deposited lower. As a consequence, different changes occur at different depths, and horizontal layers develop as a soil ages (Figure 2–16).

These layers are known as **soil horizons**, visible wherever the earth is dug deep enough to expose them. The **soil profile** is a vertical section through the soil extending into unweathered parent material and exposing all the horizons. Each horizon in the profile differs in some visible physical or chemical way from other horizons.

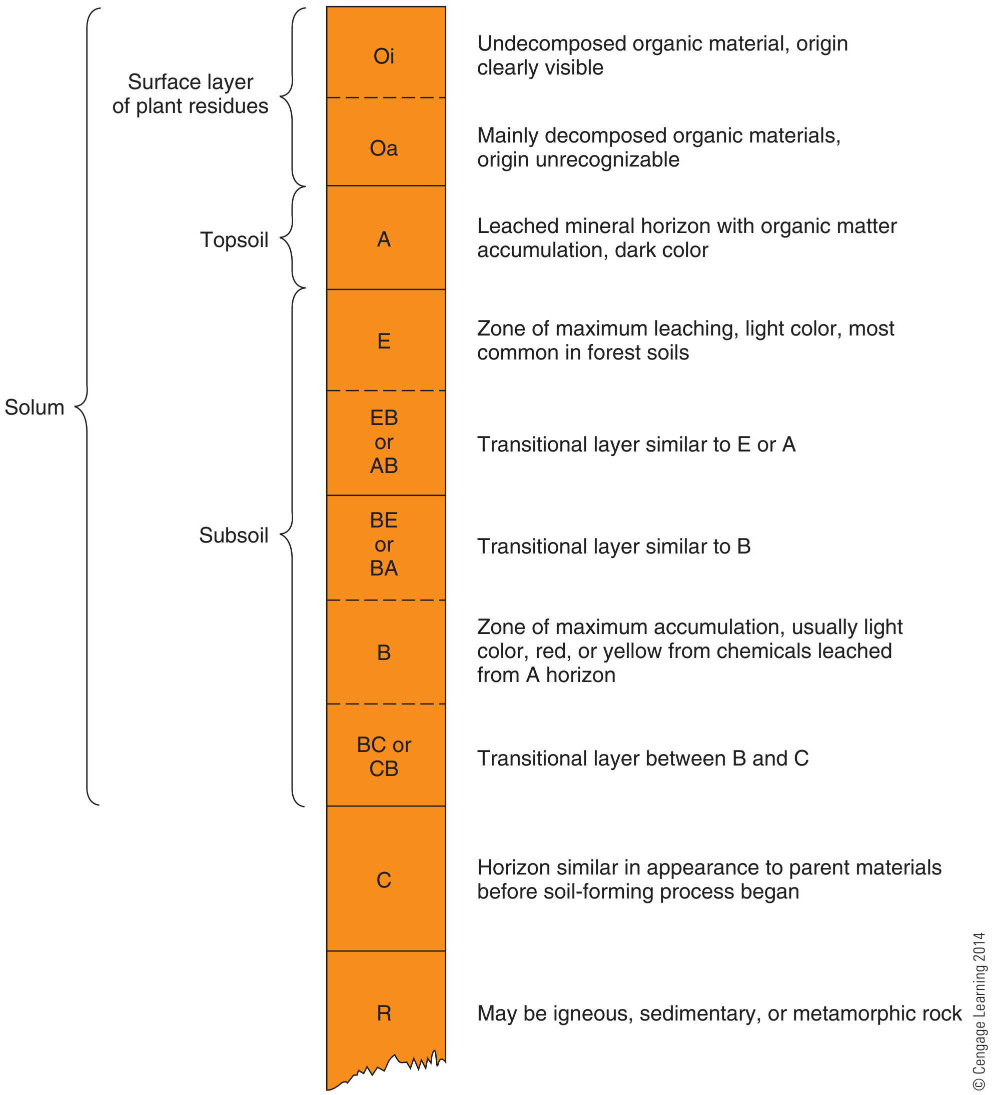


Figure 2–16
Main horizons of the soil profile, the O, A, E, B, C, and R are marked by bold lines. Also shown are some sample transitional horizons, marked by dotted lines.

In a very young soil, weathering and plant growth produce a thin layer of mixed mineral particles and organic matter atop parent material. The thin layer of soil is labeled the A horizon, a surface mineral horizon enriched with organic matter. The parent material below the A horizon of this young soil is termed the C horizon. It is defined as a subsurface mineral layer only slightly affected by soil-forming processes. Thus, this young soil has an AC soil profile.

As the young soil ages, the soil increases in depth, and new horizons appear. For instance, clay-sized particles and certain chemicals may leach out of the A horizon, moving downward in the profile to create a new layer, the B horizon.

Master Horizons

The A, B, and C horizons are known as **master horizons**. They are part of a system for naming soil horizons in which each layer is identified by a code: O, A, E, B, C, and R. These horizons are shown in Figures 2–16 and 2–17, and are described as follows.

O The O horizon is an organic layer made of wholly or partially decayed plant and animal debris. The O horizon generally occurs in undisturbed soil because plowing mixes the organic layer into the soil. In a forest, decaying fallen leaves, branches, and other debris make up the O horizon.

A The A horizon, called **topsoil** by most growers, is the surface mineral layer where organic matter accumulates. It is darker than the horizons below. Over time, this layer loses clay, iron, and other materials in downward-moving water, a loss called **eluviation**. Materials resistant to weathering, such as sand, tend to remain in the A horizon as other materials elluviate out. The A horizon provides the best environment for the growth of plant roots, microorganisms, and other life.

E The E horizon, the zone of greatest eluviation, is very depleted in clay, chemicals, and organic matter. Because chemicals that color soil have been leached out, the E layer is very light colored. Many soils have no E horizon; it is mostly likely to occur under forest vegetation in sandy soils in high-rainfall areas.

B The B horizon, or **subsoil** (though associating the A horizon with topsoil and the B horizon with subsoil is not always, strictly speaking, accurate), is often called the “zone of accumulation” where chemicals leached out of the A and E horizons accumulate. The word for this accumulation is **illuviation**. The B horizon has a lower organic matter content than the topsoil and is often enriched in clay deposited by illuviation.

C The C horizon lacks the properties of the A and B horizons. It is the soil layer little touched by soil-forming processes and is usually the parent material of the soil. It may also include very soft, weathered bedrock that roots can penetrate.

R The R horizon is underlying hard bedrock, such as limestone, sandstone, or granite. It may be cracked and fractured, allowing some root penetration. The R is identified only if it is near enough the surface to intrude into soil.

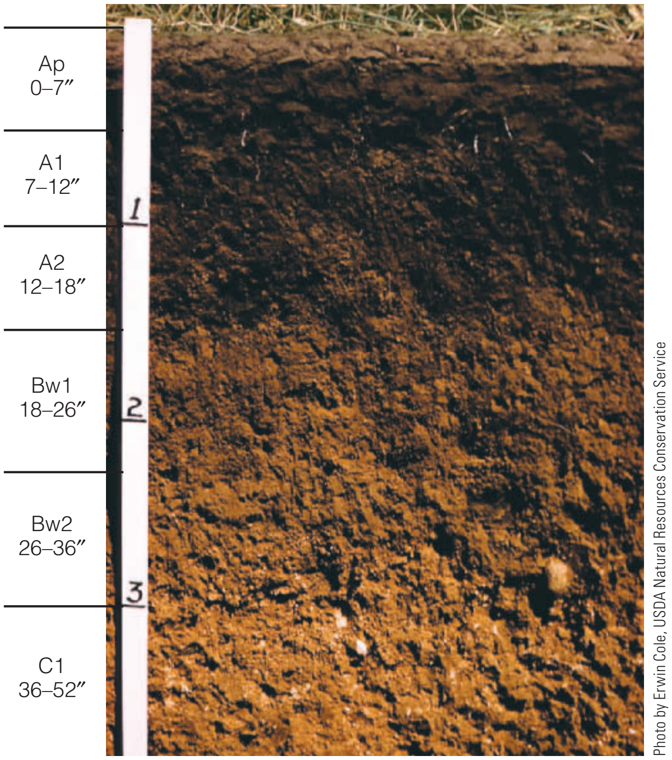


Figure 2–17
Clarion soil with horizons labeled.

The A, E, B, and O horizons together make up the **solum**, the portion of the profile that has actively participated in soil-forming processes and that is clearly soil. The C horizon below is either parent material or more closely resembles unaltered parent material than the layers above. Most often, the solum contains plant roots.

Subdivisions of the Master Horizons

As soils age, they may develop more horizons than the basic master horizons. Some of these layers are between the master horizons both in position and properties. These transitional layers are identified by the two master letters, with the dominant one written first. Thus, an AB layer lies between the A and B horizons and resembles both, but is more like the A than the B. Figure 2–16 shows some of these layers.

A soil layer can be further identified by a lowercase letter suffix that tells some trait of the layer. Appendix 3 lists these suffixes but three will serve as examples here—the Ap, Bt, and Ck. An Ap layer is a surface layer disturbed by humankind, so that the old layers were mixed up. For instance, plowing would mix up an O, A, and AB horizon if they were all in the top 8 inches. The Ap horizon is the same as the **plow layer**, the top 7 or 8 inches of soil in a plowed field. A Bt horizon is a B horizon in which clay has accumulated by illuviation. Soils in arid climates often exhibit horizons enriched in materials like lime (calcium carbonate). A C horizon enriched in carbonates will be labeled Ck.

Further subdivisions are noted by a number following the letters. Thus, one could have a soil with both a Bt1 and a Bt2 horizon. This means that the Bt horizon of the soil has two distinct layers in it, though they may be hard to separate by the untrained eye.

Now for an example. Figure 2–17 shows the top 42 inches of the Clarion soil found in Iowa and Minnesota—it is the same soil as Figure 2–1 with the horizons labeled. Clarion is a prairie soil with a deep, dark-colored A horizon. The top 7 inches are a plow layer from cultivation, hence labeled Ap. The thick A horizon extends below the plow layer, and is divided into an A1 and an A2. The differences between them are not readily visible in this photo. This makes the total A horizon 18 inches deep. At 18 inches, the Bw horizon appears, a weakly developed B horizon. It is lighter in color than the A above but darker than the C below. Again, there are two Bw layers, hard to separate in this photo. At 36 inches, the C1 horizon begins, and extends below the depth of the photograph to 52 inches. A C2 underlays the C1 at 52 to 60 inches. In this photograph, the C horizons are lighter in color than the B. This soil contains no E horizon because the soil-forming factors here do not favor development of one. Nor is there an R horizon, because bedrock is somewhere below the zone we study.

SUMMARY

Soils form from minerals broken up by the action of weathering and plant roots and from the addition of decaying plant parts. Young soils continue to age—growing deeper, being leached by rainfall, developing layers, and changing over time. This soil-forming process involves the addition, loss, translocation, or transformation of soil materials, and is governed by the five factors of parent material, climate, life, topography, and time. Some authorities would add humans as a sixth factor in soil formation. Over time soil deepens and develops recognizable horizons, and may finally become severely weathered and highly leached.

Residual soils develop directly from bedrock (igneous, sedimentary, or metamorphic). Most mineral soils come from parent materials moved from one area to another by ice, water, wind, or gravity. Organic soils are composed of decaying plants. Each type of parent material is responsible for a different soil.

Parent materials are acted on by climate and living organisms. Soils develop quickly in warm areas with high rainfall, then age into heavily weathered soils low in organic matter. In cooler regions, organic matter accumulates and weathering is less intense. In arid climates, sparse plant growth inhibits the formation of organic matter. Grassland soils tend to be high in organic matter, forest soils lower, and dryland soils lowest of all.

Topography affects soil formation by changing water movement and soil temperature. Low areas often have deep, rich soils that drain slowly. Erosion causes thin soils on slopes.

Time is a factor because soil development is a continuing process. Young soils tend to be thin with little horizon development. Mature soils are deeper and productive with several recognizable horizons. Old soils are severely weathered, highly leached, and less productive.

Soil profiles, which develop over time, are divided into master horizons. These, in turn, may also contain layers. Each layer is named by a code system that identifies its position in the profile and provides some information about it.

REVIEW

1. Name the five soil-formation factors and give an example of the effect of each on soil formation.
2. Draw a soil profile containing seven distinct horizons in the correct order, and label them. Indicate topsoil, subsoil, and solum. *Hint:* You will use more than just the regular master horizons, and there are many possible configurations.
3. Describe the major parent materials and vegetation as well as climate that contributed to the soils of your locality. Describe how they influenced your soils.
4. What do alluvial fans, floodplains, deltas, and terraces have in common? How are they different?

5. Would you be likely to read a soil description that includes an At horizon? Use Appendix 3. Explain your answer.
6. Discuss the four soil-forming processes and give examples of each.
7. You have two very different soils that are only 100 yards apart. Which one of the five soil-forming factors (parent materials, climate, topography, life, and time) most likely explains the differences?
8. Running water removes soil from the surface by erosion. Which of the four soil-forming processes does this exemplify, and how might the soil-forming factors affect it?
9. Organic matter tends to increase from west to east in the United States because of increasing rainfall. Yet, some of the highest organic matter soils are in the plains states, which are relatively dry. Explain why.
10. Compare the nutrient contents of soils derived from the granite-, sandstone-, and limestone-based materials shown in Figure 2–5. What nutrients are each high or low in?
11. Clay minerals are important soil particles that form in the soil during weathering, a subject of a later chapter. Elements such as potassium and magnesium are needed for clay to form in the soil. Would a residual soil formed from Hinckley sandstone (see Figure 2–5) contain much clay?
12. If the climate in a certain location changes to be warmer and drier, would you expect soil development to change over time? Suggest a couple of ways it might change.
13. Using Appendix 3, answer the following questions:
    a. Sometimes an older soil gets buried and a new soil forms on top. What would a buried A horizon be labeled as?
    b. The peat moss harvested from peat bogs for horticultural use in potting soils is moderately decomposed organic matter. In what soil layer would this peat be harvested?
    c. Caliche, mentioned in the text and often a headache for landscapers in the American Southwest, is a B horizon cemented by carbonates. What would be the complete designation of a caliche horizon (there will be two subscript letters)?
14. Describe several physical, chemical, and biological roles that water plays in soil formation, giving examples.
15. The base of a slope like that of Figure 2–15 is called the *toeslope*. How would toeslope soils differ from those at the shoulder of the same hill? Explain why.

ERICHMENT ACTIVITIES

1. Study the history of the soils in your state or vicinity.
2. Dig a soil pit and study the soil profile. See if you can name the layers.
3. Obtain samples of common soil-forming rocks like granites, basalts, and sandstones, as well as minerals like feldspar or quartz. Find more information about each from a simple field guide to rocks and minerals. What plant nutrients does each contain (see Chapter 10 for a list)? Using several available laboratory exercises, experiment with various weathering processes. For instance, try to scratch feldspar with quartz, and vice versa. Which is harder?
4. To observe the effects of freezing on physical weathering, pat a handful of clay soil into a ball. Inject water into the ball with a syringe, then freeze overnight. Observe the results.
5. This Web site from the University of Alberta discusses soil-forming processes: http://www.environment.ualberta.ca/soa/process6.cfm. (Note: If the link does not work, go to the University of Alberta's home page, http://www.ualberta.ca/, and search for "soil-forming processes.") It has one additional factor not included here. Which one is it and how would you fit it into this text's five factors?
6. This chapter skimmed over the complex deposits left behind by glaciers that became parent materials for many states. Search the Web for "glacial landforms" to find out more.
7. This chapter's description of soil horizon designations is a simplified one without the more technical bits as well as less common designations. Search the Internet for a more complete description.

CHAPTER 3

Soil Classification and Survey

TERMS TO KNOW

arable land
diagnostic horizon
family
great group
land capability class
mapping unit
phase
soil association
soil classification
soil order
soil series
soil survey
soil taxonomy
subgroup
suborder

OBJECTIVES

After completing this chapter, you should be able to:

- describe the current USDA soil classification system
- explain how soil surveys are prepared and used
- list soil capability classes

At the end of the 1800s, public leaders began to realize that land in the United States was being damaged by poor land policies. This realization led to public efforts to conserve soils—efforts that continue today. To preserve land one first needs to study it, and that study needs a system for describing, naming, and classifying soil. With these tools, soil professionals can survey the land and describe what they find. A start was made in the early 1900s when the government began to survey and classify the U.S. soils. This chapter will briefly review some history of soil classification, describe the current system, and then discuss soil surveys.

SOIL CLASSIFICATION

Soil survey depends on a system of grouping soils of like properties. **Soil classification** helps us understand, remember, and communicate knowledge about soils.

The Russian soil scientist V. V. Dokuchaev first suggested a way of classifying soils around 1880. He proposed that soils were natural bodies created by soil-forming factors. This proposal formed the basis of a classification system that soil scientists began using to survey the U.S. soils.

Over the years, the United States has used several, constantly evolving soil classification systems. In the 1920s C. F. Marbut, then chief of the Soil Survey Division of the USDA, began devising a soil classification system, later published in the *1938 Yearbook of Agriculture: Soils and Men.* This system was based on soil properties and the combination of soil-forming factors presumed to have created them, using terms such as *Podzol soils* and *Chernozem soils.* Students may encounter these names in older literature, and the terminology is still used in the classification systems of some other countries.

The USDA introduced the current classification system in 1960 with the publication *Soil Classification, a Comprehensive System.* Continued modifications led to its republication in 1975 as *Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys,* the basis for modern soil classification in the United States. We generally shorten the title of this system to simply the *Soil Taxonomy.* This system too continues to evolve, with changes such as the addition of a 12th soil order, the Gelisols, in 1998.

The Soil Taxonomy

Earlier soil classification systems were generally based on the presumed history of a soil, that is, its process of formation under the five soil-formation factors. The system of the *Soil Taxonomy* is based, rather, on properties of the soil as it can be observed in the field or laboratory.

It resembles the way plants and animals are grouped according to a system known as a *taxonomy*—a hierarchical grouping of objects at several levels to show how they relate, where the lowest level is the most specific and the highest level the broadest grouping. Figure 3–1 compares the taxonomy of plants with that of soils. This comparison can be deceptive; there is no real correlation between the levels of soil and biological taxonomy. However, conceptually they are similar in both being taxonomies.

Unlike taxonomy for plants and animals, soil classification is not universal. While the USDA's soil taxonomy can be universally applied to the soils of the globe, outside the United States, many nations employ their own systems to serve their own purposes. Canada, for instance, needs a finer-textured system for describing soils of cold climates than does the United States, while having little need of classifying soils of warmer climates. So while the Canadian system resembles that of the United States, it does not, for instance, have equivalents to the American soil orders

Soil Classes	Plant Classes
Order (12)	Kingdom
Suborder (66)	Division
Great Group (>320)	Class
Subgroup (>2,000)	Order
Family (>8,000)	Family
Series (>19,000)	Genus and species
(Phases)	(Variety)

Figure 3–1
The USDA soil classification lists six levels of soil classes. The approximate number of each is provided but continues to increase. The classes of the more familiar plant taxonomy are listed for comparison, but there is no direct correspondence between the levels.

Ultisol, Oxisol, or Aridisol (described later in the chapter), generally soils of warmer climates. The Enrichment Activities section of this chapter provides a Web site for the Canadian system.

As shown in Figure 3–1, the system has six levels of classification. The highest rank, the **soil order**, is the broadest group. The system recognizes 12 soil orders, based mainly on presence or absence of certain key layers in the soil profile, called **diagnostic horizons**, as well as on average temperatures and rainfall. *Diagnostic* horizons are not the same as the soil horizons described in Chapter 2, which are called *genetic* horizons because they are formed during soil genesis. An example of a soil order is an Entisol, a soil showing few signs of soil and horizon development. The name for all soil orders ends with the suffix *sol.* The 12 soil orders are described later in the chapter. Appendix 2 presents a map of the soil orders of the United States.

Each order is divided into several **suborders**, the next highest level of the soil taxonomy. Suborder members of the same order differ most often in soil moisture or temperatures but may differ by other factors. A Psamment, for instance, is a suborder of Entisols that is highly sandy. The name of a suborder includes a Latin or Greek root that provides information about the suborder and ends in several letters that identify the order to which it belongs. A Psamm*ent,* for instance, is an *Ent*isol. The letters *psamm* come from the Greek word for sand. These suffixes are named in the descriptions of soil orders later in the chapter.

Suborders, in turn, are divided into **great groups**, often based on the presence of certain key horizons, but may differ by other traits such as soil moisture and temperature. A great group is named by adding a prefix to the suborder name. A Udipsamment is a Psamment (sandy Entisol) that is usually moderately moist, expressed by the prefix *udi*.

Great groups are further divided into **subgroups**, based on how close a soil is to the "central concept" of its great group. That is, there is a core image of what that great group should be, but there are gradations within it. A subgroup that matches the central concept is called Typic, while other words express variations. We affix the subgroup name as a separate word before the great group name, for instance, a Typic Udipsamment.

Subgroups are themselves divided into **families**, units of a subgroup with similar properties important to the growth of plants and soil use, such as subsoil particle sizes or the minerals found in the soil. Family names are composed of a string of descriptive words placed before the subgroup name, for example, a *frigid, mixed Typic Udipsamment.* This is now the full, taxonomic name of this soil, and you will find such names in soil surveys. The naming system for families is quite complex and will not be further discussed here.

All the words and syllables used to create these names are listed in *Soil Taxonomy,* and the reader should refer to that publication for further details. Those who use soils at the local level, such as growers, builders, or county-extension agents, are more concerned about the lowest soil grouping, called the **soil series**.

Soil Series

Soil scientists divide soil families into smaller units called soil series. The soil series is the taxonomic unit with the narrowest range of features, and all pedons within a series have very similar soil profiles. Each of these units is distinct from other units and is the same as the polypedon described in Chapter 2.

Each series is given the name of the town, county, or other location near where the series was first identified. The Mahtomedi soil is named after a town in east central Minnesota and is an example of the soil family just classified earlier. Other examples of soil series include Saybrook (a Mollisol), found near the central Illinois town of Saybrook, or Ontario (an Alfisol), named after a town in New York. A series name may be followed by the surface texture of the soil, as in Saybrook silt loam.

The series is the lowest official category in the soil taxonomy. However, in practice, a series may be subdivided further into **phases**. A phase is a variation of a series based on some factor that affects soil management, such as slope, degree of erosion, or stoniness. One might have, for example, an Ontario loam, 3 percent to 6 percent slope phase. Soil series with their phases become mapping units for the most detailed soil surveys.

Soil Orders

As described earlier, soil scientists currently divide soils into 12 soil orders. While each of these orders carries a technical, formal definition, here we will provide a simple description of each.

Alfisols

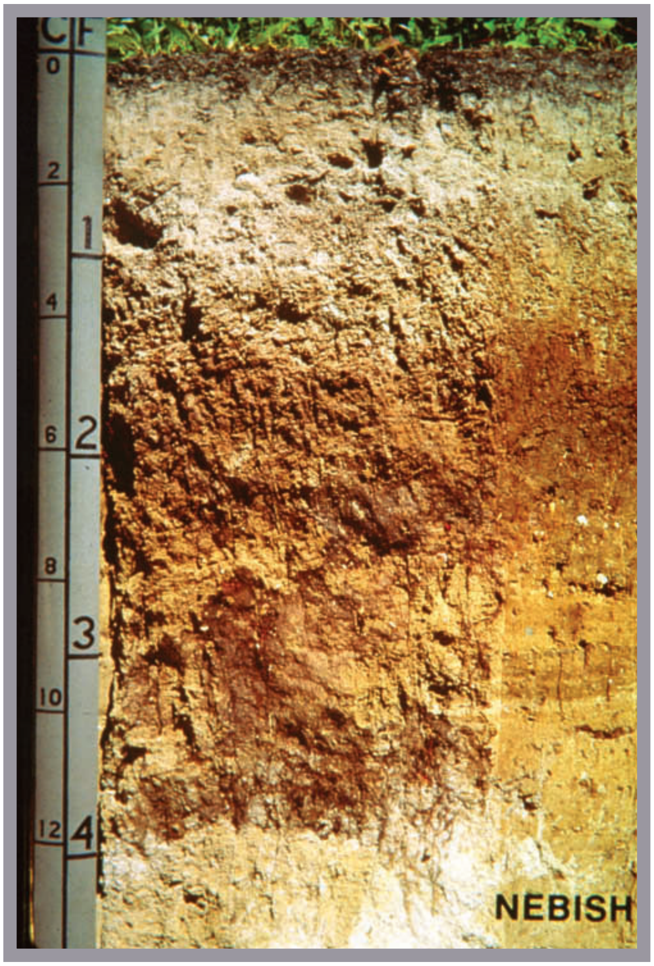
Alfisols usually are soils of deciduous forests of temperate moist climates. The A horizon is typically light colored, and in undisturbed soils, O horizons often occur at the surface. Surface horizons may be acidic. The B horizon contains some illuviated clay, and the soil has moderate to high base saturation, meaning certain cations have accumulated in the soil (Chapter 2 describes the ion pumping of trees). A typical profile could be O-A-E-Bt-C. Alfisols are generally good agricultural soils and constitute about 13 percent of U.S. soils, especially in the north central states. In the suborder name, the element *alf* is used. Figure 3–2 shows the Nebish series, a Hapludalf (moist Alfisol with minimum horizon development) of central Minnesota. It has the profile A-E-Bt1-Bt2-C.

Andisols

Andisols form in geologically recent volcanic materials; the parent materials are weathered particles of volcanic glass, which provide a very distinctive soil. The soil is lightweight, typically dark colored, high in organic matter, easy to till, with a high water-holding capacity. The soil binds phosphorus tightly, often making it less available to plants. A typical profile is A1-A2-Bw-C. These also make good agricultural soils, and make up about 2 percent of U.S. soils, mostly in the Pacific Northwest, Hawaii, and Alaska. In the suborder name, the element *and* is used.

Aridisols

Aridisols are soils of arid climates of cool to hot deserts and shrublands (see Figure 2–14 in Chapter 2), often with alkaline and salted horizons. Lack of water limits soil development. A typical profile would be A-Bt-Ck or Ckm, Cy, Cz. Aridisols are not productive for agriculture unless irrigated, as many are in the western United States. Aridisols comprise about 12 percent of U.S. soils, mostly in the West. In the suborder name, the element *id* is used.



Courtesy of Natural Resources Conservation Service

Figure 3–2
The Nebish series, an Alfisol. At the subgroup level, Nibish is a Typic Hapludalf.

Entisols

Entisols lack well-developed horizons. They may be young, or form under conditions that inhibit soil development, such as climatic extremes or resistant parent material. They may also form where erosion or deposition prevents horizon formation. Entisols are the least developed of the soil orders. A typical profile is A-C. They are extremely variable, scattered throughout the country, and sometimes difficult to use. Entisols make up about 8 percent of U.S. soils. In the suborder name, the element *ent* is used. Figure 3–3 shows the Zimmerman soil of Minnesota, a Udipsamment (sandy Entisol of moist climate) formed in glacial outwash. Notice the weak horizon development.

Gelisols

Gelisols are very cold soils of the tundra, cold desert, or high peaks. There is permafrost in the subsoil; often the surface is peat because the cold, wet conditions inhibit decay. There may be evidence of soil disturbance from freeze–thaw cycles. A typical profile is O-Bg-Cf. Gelisols are very fragile, and any human disturbance heals slowly. Gelisols are also a very large carbon sink. In the United States they are found mostly in Alaska.

Courtesy of USDA Natural Resources Conservation Service

Figure 3–3
The Zimmerman soil, an Entisol. At the subgroup level, Zimmerman is a Typic Udipsamment, and is described in the text. Notice the lack of strong horizon development.

Histosols

Histosols form from decaying organic matter in wetlands. The lack of oxygen slows decay so organic materials accumulate, reaching contents greater than 20 percent to 30 percent. These materials are often called peats and mucks (Chapter 6). They are of very low density. Histosols can be drained for growing certain crops, but suffer from subsidence or even fire. A typical soil profile is O1-O2-O3-C. Like Gelisols, Histosols function as large carbon sinks. Histosols comprise less than 1 percent of U.S. soils, found especially in the northern Midwest and Atlantic/Gulf coastal areas. In the suborder name, the element *ist* is used. Chapter 6 describes these organic soils.

Inceptisols

Inceptisols are another "young" soil, but slightly better developed than Entisols. Weakly developed horizons appear, with a typical soil profile of A-Bw-C. Quite variable in nature and scattered throughout the United States, Inceptisols comprise about 16 percent of U.S. soils. In the suborder name, the element *ept* is used.

Histosols and Climate Change

According to a report in an issue of *The Economist* (December 18, 2010), drained wetlands and peatlands emit a worldwide total of 1.3 billion tons of carbon dioxide annually—6 percent of total global emissions. Presumably these are Histosols and perhaps Gelisols. "Rewetting" wetlands is now being considered as one more strategy for reducing worldwide carbon dioxide emissions.

Mollisols

Mollisols are rich, dark soils of the grasslands. There must be a deep, dark A horizon with high base saturation. They typically form under conditions of moderate to low rainfall. Mollisols are considered the richest of agricultural soils, but lack of rainfall may be limiting for agriculture. Mollisols comprise about 25 percent of U.S. soils, mostly of the plains states and some areas of the Pacific Northwest, but extending through Iowa into Illinois. In the suborder name, the element *oll* is used, as in the Udoll (moist Mollisol) Clarion series of Figure 2–17 in Chapter 2. Notice the deep, dark A horizon.

Oxisols

Oxisols are highly weathered soils of the tropics. The A horizon is low in organic matter, and the soil is largely comprised of granules of iron oxide clays that behave like sand. Oxisols are often red to yellow in color because of iron oxides. The typical soil profile is A-Bo1-Bo2-C. In the suborder name, the element *ox* is used. Oxisols are challenging to manage for agriculture. Less than 1 percent of U.S. soils are oxisols, found only in Puerto Rico and Hawaii.

Spodosols

Spodosols most often form under coniferous forest conditions in cool, moist regions. They are light-colored, acidic, coarse soils, often lacking an A horizon, but usually with an E. The soil has low base saturation. The subsoil must contain accumulations of iron or aluminum compounds complexed with humus that stain the subsoil, making it darker than usual. The typical profile is O-E-Bs-C. Spodosols make very poor agricultural soils, useful for acid-loving plants such as potatoes, blueberries, or forests. About 5 percent of U.S. soils are Spodosols, mostly in the northern tier of midwestern and northeastern states. In the suborder name, the element *od* is used.

Ultisols

Ultisols are highly weathered soils of warm, humid climates, but not as weathered as Oxisols. There is low base saturation, and the topsoil can be quite acidic. Acidic subsoils often inhibit crop growth. The subsoil usually has illuviated clay, and is often reddish in color. The typical soil profile is A-E-Bt-C. Ultisols are not naturally fertile soils, but are used for agriculture with proper fertilization and liming. About 13 percent of U.S. soils are Ultisols, found mostly in the Southeast. In the suborder name, the element *ult* is used.

Courtesy of USDA Natural Resources Conservation Service

Figure 3–4

The Fargo soil, a Vertisol. At the subgroup level, Fargo is a Typic Epiaquert. Notice the extensive cracking.

Vertisols

Vertisols form from parent materials very high in clays that shrink and swell during drying and wetting cycles, such that large soil cracks form. This causes a churning of the soil that mixes the upper soil; they are said to be self-inverting. They can form only in locations with the proper parent materials and a climate that supplies strong wetting and drying cycles. The typical profile is A1-A2-A3-C. Vertisols are unstable for engineering uses, but can make good agricultural soil. They are fertile, but challenging to till properly. Vertisols make up about 1 percent of U.S. soils, most commonly in south central states. In the suborder name, the element *ert* is used. Figure 3–4 shows the Fargo series of the Red River Valley of Minnesota and North Dakota. Notice the soil cracks and tongues of dark soil extending into the B horizon; this is topsoil that has fallen into deep soil cracks.

SOIL SURVEY

The USDA developed the soil classification system for use in soil surveys. Soil surveys classify, locate on a base map, and describe soils as they appear in the field. Soil surveys tell what soils are in a given location, what the properties of those soils are, and how they can be used.

Photo by Jeff Vanuga, USDA Natural Resources Conservation Service

Figure 3–5
This soil scientist conducting a soil survey in Virginia observes surface features, probes the soil, and records field observations on a small handheld computer for geographic processing. Notice the GPS unit on her back.

Soil surveys are performed under the auspices of the National Cooperative Soil Survey Program, a joint effort of the USDA Natural Resources Conservation Service, or NRCS, and state Agricultural Experiment Stations (see Chapter 20). Most of the actual surveying is done by NRCS soil scientists.

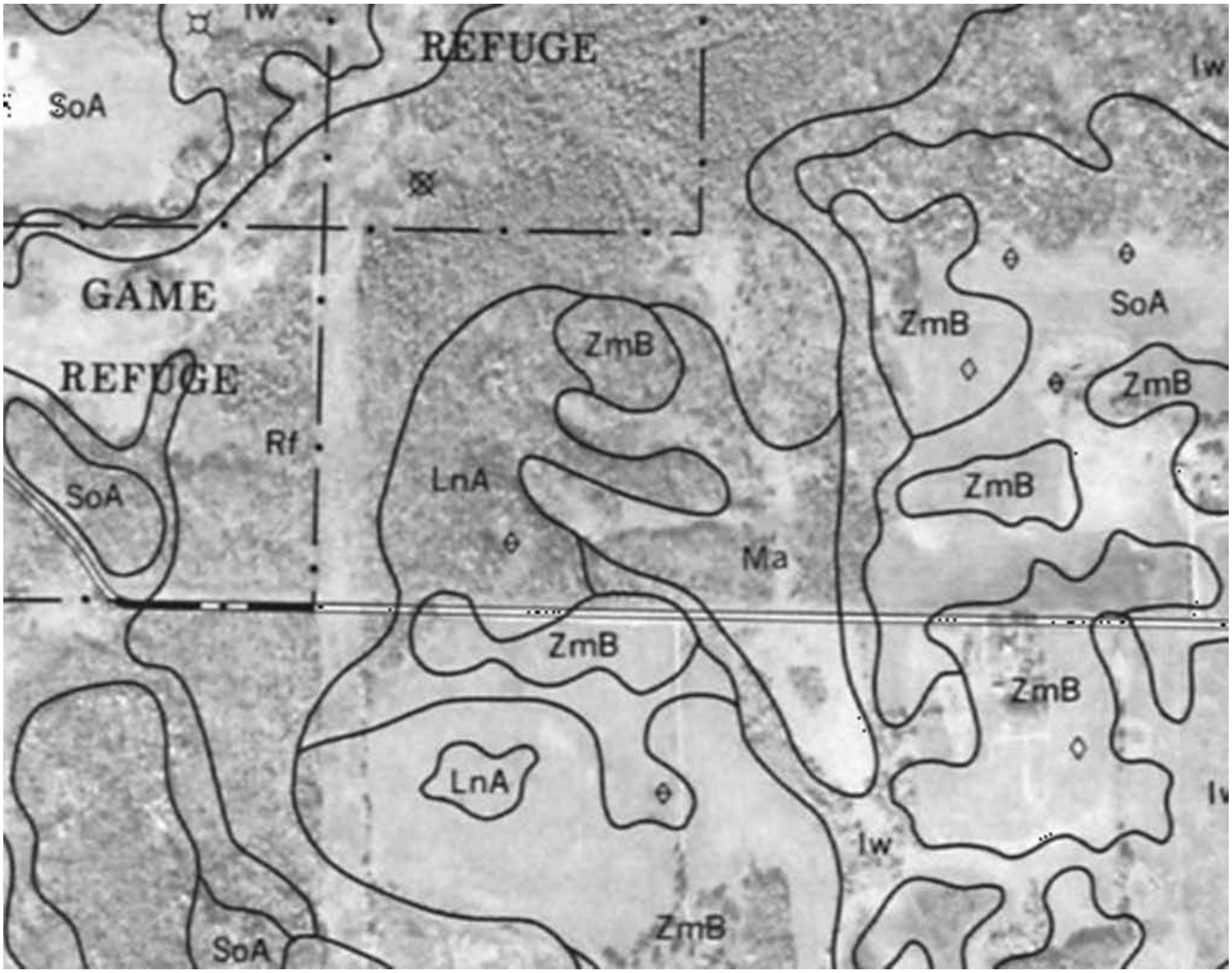
Field Mapping

Mapping a soil typically begins with preliminary study of older soil surveys, if they exist, and documents such as aerial photographs. The survey then moves out into the field. For detailed mapping, a soil scientist traditionally walks the land to survey it (Figure 3–5). Frequently the surveyer stops to probe the soil. By studying the soil profile, that spot can be placed in the correct series. The surveyor also notes slope, evidence of erosion, and other interesting features. With this information, the surveyor draws the soil series or phase on a base map.

The NRCS uses aerial photographs as a base map. Aerial photographs make good base maps because they show landscape features, including ponds, woods, and sand pits. Features visible on the aerial photograph may also indicate the boundaries of various soils.

When the survey is complete, the resulting map is copied neatly. Maps show the boundaries of the mapping units, with each unit identified by codes that vary from state to state (Figure 3–6). Note the codes shown in Figure 3–6. These codes may have one, two, or three parts. The first group of digits or letters (in this instance, letters) refers to the soil series. In addition, a unit may be labeled with codes to indicate the slope and erosion. If the latter two codes are absent, one assumes a nearly level relief with no erosion. Figure 3–7 gives the common codes and other symbols that indicate different features in the field.

Studying Figure 3–6, you will see some units labeled “ZmB.” In this excerpt from the soil survey of Anoka County, Minnesota, “Zm” stands for the Zimmerman soil,



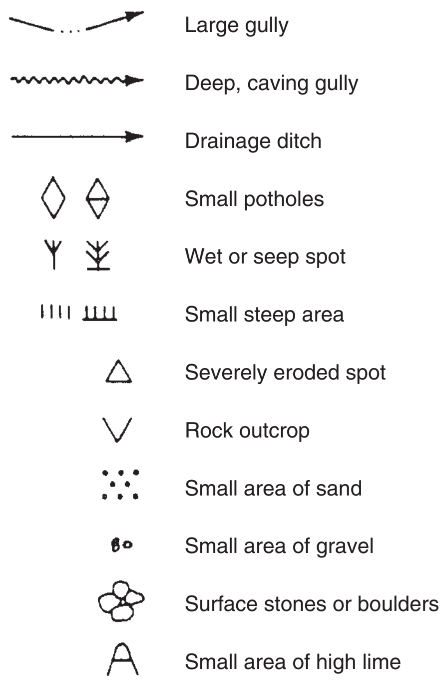
Courtesy of USDA

Figure 3–6

A section of map 28 of the soil survey of Anoka County, Minnesota. Notice areas of Zimmerman soil mentioned in the text, keyed here as *Zm*. This map, like many others, is now available on the Internet.

mentioned earlier in this chapter. The "B" means a gently sloping phase with a slope of 2 percent to 6 percent. There is no third part of the code, so there is no noticeable erosion.

While soil surveyors still walk the land, modern technology has become an essential tool of the trade. Global Positioning Systems (GPSs) (Figure 3–5) allow the surveyor to identify precisely his or her location much more readily and accurately than by landmarks on an aerial photograph. With GPS, each piece of data taken in the field can be recorded with a precise geographic location. Geographic Information Systems (GISs) process and organize the data recorded in the field as well as other sources, and can then generate a variety of maps and reports. Various remote-sensing systems can be used for initial reconnaissance and for gathering certain



Slope		
Legend	**Percentage of Slope**	**Description**
A	0–2	Nearly level
B	2–6	Gently sloping
C	6–12	Sloping
D	12–18	Strongly sloping
E	18–30	Very strongly sloping
F	30–60	Steep
	More than 60	Very steep

Erosion	
Legend	**Description**
0	No erosion
1 or P	Slight, 0 to 1/3 topsoil gone
2 or R	Moderate, 1/3 to 2/3 topsoil gone
3 or S	Severe, 2/3 or more topsoil to 1/3 subsoil gone
4	Heavy subsoil erosion, deposition of eroded soil

Courtesy of USDA Natural Resources Conservation Service

Figure 3–7
A sample of soil-mapping symbols that give information about slope, erosion, and landscape features.

types of useful data, such as type or health of vegetation, from which one can infer soil information, or even some soil traits directly. Modern soil survey is a combination of traditional feet-on-the-ground observation and modern technology. See the sidebar for information on these technologies.

Mapping Units

Different **mapping units** are used in soil surveys, depending on how large an area the map or survey covers. For small areas, mapping units are detailed phases of soil series. For larger-scale maps, the units may be higher levels of the soil taxonomy, like families or great groups. Soil orders are the mapping units on the national soil map in Appendix 2, suborders the mapping units on some state maps. For most county maps, phases of soil series are the basic mapping unit.

For some land in surveys, there are pockets of soils, or inclusions, that are too small in area to show up on the scale of the map. Thus, most mapping units actually contain more than one series, with the major series being the one identified on the map and the others as small inclusions not identified. Where soils are mixed up enough to be difficult to separate on the scale of the map, mapping units may be **soil associations** or other mapping unit combinations. A soil association consists of one or more major soils and one or more minor soils, for instance, the Zimmerman–Isanti–Lino association of the author's home state. This association is dominated by Zimmerman with smaller inclusions of Isanti and Lino soils.

Soil survey maps are drawn to scale appropriate to the area and detail needed. The larger the scale, the larger the area covered but the less detail offered. Most county

Technology and Soil Mapping

GPSs, GISs, and remote sensing are technological tools available to today's soil surveyors. GPS relies on 24 satellites in orbit about the earth, positioned such that any point on the earth's surface receives a signal from at least four satellites. Using the signal, a GPS unit determines its distance from each satellite; with readings from four satellites, it can determine its precise position on the earth's surface. Simple units may be handheld, larger units carried like backpacks or mounted on vehicles.

Remote sensing gathers information about a site from a distance by using sensors mounted on planes or satellites. Standard aerial photographs, one form of remote sensing, are black and white, using visible light that we all can see. Other sensors can see other wavelengths of energy, such as infrared, that standard cameras cannot see. These reveal information about patterns or health of vegetation from which we can infer information about soil, color of visible soil, or other information.

GISs are powerful computer software programs that organize and integrate data from a variety of sources, such as soil data from GPS points, remote-sensing data, and all sorts of other relevant data such as zoning information or watershed boundaries. GIS software can then integrate all the data and generate a variety of reports and maps.

surveys are drawn to scales of 1:12,000 to 1:31,680. At the smaller scale, there are about 0.2 mile per map inch (5.28 inches per mile), and the smallest size area that can be practically noted is about 1.5 acres. Therefore, small pockets of soil may well differ from what is mapped, a warning to be considered when interpreting a map. Where finer-textured detail is needed, a more exhaustive survey and a map drawn to finer scale may be required.

Soil Survey Reports

A completed soil map becomes part of a soil survey report, typically for a county. A soil survey report has four major parts: a set of soil maps, map legends that explain the map symbols, descriptions of the soils, and use and management reports for each soil. All these parts provide much useful information about the soils, including:

- Taxonomy of the soil—telling the order, suborder, and other classes.
- Descriptions of the soil. For instance, to quote a bit of one description: "The Cathro series consists of very poorly drained soils formed in deposits of herbaceous organic material over loamy sediments in depressions. This soil is black muck 23 inches thick. The substratum is a grayish brown sandy loam. Slopes are less than 2 percent. Most areas are used for woodland."
- Soil properties of each horizon, including texture, bulk density, permeability, available water, pH, salinity, and other features that will be discussed in this text. Engineering properties are also listed. (Note to reader: The Cathro is discussed in this listing only as an example.)

- Suitability for urban landscape uses such as turf, ornamentals, and gardening. Problems are severe for the Cathro because of ponding and excess soil humus. Tables should also provide information useful for designing and installing "hardscape" features such as retaining walls.
- Rating of suitability for engineering projects such as landfills, buildings, and roads. Problems are mentioned; for instance, the Cathro is listed as poor for most projects because of ponding.
- Suitability for water-management projects such as reservoirs, drainage, and irrigation. Problems are mentioned. The Cathro, for instance, is poor for digging aquifer-fed ponds because of a low refill rate.
- Suitability for recreational development such as playgrounds and campgrounds. Problems are mentioned. The Cathro is listed as poor because of ponding.
- Potential for cropping, including capability class and projected yields for common crops grown under high management. Cathro soil, for instance, cannot be cultivated unless drained. If drained, one can expect 50 bushels of corn per acre, or 55 bushels of oats per acre.
- Woodland suitability, including problems and suggested trees to plant. The Cathro is rated as poor for woodlands, but certain trees that are tolerant of wet soil may be planted.
- Information about good plants for windbreaks.
- Potential as a habitat for wildlife. The Cathro is rated as good for wetland plants and animals, but poor for others.

Finding a given location on a soil map in a county survey report can challenge those unfamiliar with the system. Soil survey maps in most states use the *township-range* system, a legal survey system employed in the United States for identifying location. An Enrichment Activity at the end of this chapter identifies Internet resources for learning about the system.

Survey Report Uses

Soil maps are the heart of good land-use planning. Soil maps give the information needed to make good land-use decisions—whether the decision maker is a national planner or a farmer, home builder, or landscape designer. At the national level, for instance, the USDA has inventoried soil resources of the United States and kept track of them from soil maps.

Civil engineers need soil maps. Civil engineers planning a new road will study maps to find routes with good soils for roadbeds. Planning commissions searching for new landfill sites will begin with soil maps.

New growers or growers planning to expand find soil maps useful for choosing new land. Instead of driving all over a region searching for the right land, one can target certain prime areas on soil maps.

Growers can use soil maps in many ways, such as creating a conservation plan (Figure 3–8). The information in soil surveys helps in planning irrigation or other projects. For instance, a grower dug a pond in the wet Cathro soil, cited earlier,

Courtesy of USDA Natural Resources Conservation Service

Figure 3–8
A soil conservationist works with a landowner in Georgia to prepare a conservation plan using a soil map.

with hopes of irrigating out of the pond. Had he read a soil report first, he would have known that the pond would refill too slowly for this purpose. Growers can also use the maps to create field maps of their own land, used as planning and record-keeping tools, even digitized into computers for precision agriculture (described later).

A word of warning about county soil surveys. Many of them unavoidably are somewhat out of date; there is no way to keep them all current with the resources available. For instance, some former rural land may now be developed land. They may lack information needed for newer practices like rain gardens. Some older advice may be best avoided, like recommendations of exotic invasive species, such as honeysuckle, in shelter belts. Soil users should keep their own knowledge up-to-date and apply common sense to soil surveys.

LAND CAPABILITY CLASSES

Soil surveys and maps provide the basis for placing soils into a variety of capability and limitation classes. These are systems for classifying soils according to their suitability for various uses, such as agriculture, forest, drain fields, landscaping, or others. Best known is the USDA's **land capability class** system, which primarily rates soils according to their suitability for agriculture, and also for pasture, rangeland, timber, recreation, and other uses. The system indicates the best long-term use of land to protect it from erosion or other problems. For example, flat land with deep, rich soil can tolerate long-term heavy cropping without erosion.

Use	Class I	II	III	IV	V	VI	VII	VIII
Row crops	X	X	/					
Hay, small grains	X	X	X	/				
Pasture	X	X	X	X	X	X		
Range	X	X	X	X	X	X	/	
Woodland	X	X	X	X	X	X	/	
Recreation, wildlife	X	X	X	X	X	X	X	X

Figure 3–9

Suitable uses for soil capability classes. The higher the class number, the fewer the number of suitable uses. A single slash indicates that very careful management is needed and that the soil cannot be safely used for this purpose every year.

Capability Classes

The NRCS recognizes eight land capability classes. These are numbered by Roman numerals I to VIII. Class I soils have the fewest limitations and Class VIII soils are so limited as to be totally unsuitable for agriculture. Erosion hazard due to slope is the main criterion, but other criteria are used as well. Figure 3–9 shows sample uses for each class. Note that there are fewer safe uses for each succeeding class.

Class I soils (Figure 3–10) have few limitations for cultivated agriculture. They can be heavily cropped, pastured, or managed for woodlands or wildlife. Crop cultivation is the most profitable use of Class I soils. These soils are well drained and nearly level (0 percent to 2 percent slope). They have good water-holding capacity and are fertile. Ordinary cropping practices such as liming, fertilizing, and crop rotation keep these soils productive. As some of our best agricultural soils, it would be wise public policy to preserve such land for agriculture.

Class II soils are also suitable for all uses, but have mild limitations that need moderate soil conservation or other measures when cropped. Problems include:

- Gentle slopes (2 percent to 6 percent slope)
- Moderate erosion hazards
- Shallow soil
- Less-than-ideal tilth
- Slight alkali or saline conditions
- Slightly poor drainage

Class III soils can grow the same crops as Class I and II soils. However, serious problems need to be addressed, such as:

- Moderately steep slopes (6 percent to 12 percent slopes)
- High erosion hazards

Figure 3–10
This vineyard in California exemplifies Class I land—level land free of the hazard of erosion and suitable for all uses. While vineyards are generally clean cultivated, as is this one, leaving soil bare is damaging to soil quality, a subject taken up in the next chapter. This vineyard is drip irrigated (Chapter 9).

- Poor drainage
- Very shallow soil
- Droughtiness
- Low fertility
- Moderate alkali or saline conditions
- Unstable structure

Special conservation methods are needed. Growers should limit the number of row crops grown and favor close-growing crops. This is the lowest soil class that can be used safely for all crops, but only if used carefully.

Class IV soils are marginal for cultivated crops. Limitations are those listed for Class III but are more severe. Slopes may be 12 percent to 18 percent. Row crops cannot be grown safely, but close-growing crops may be. Crops that cover the soil completely, such as hay crops, are best. Careful erosion control measures must be practiced.

Classes I to IV make up **arable land**, land suitable for crop production, with Class IV land being most challenging for sustainable long-term use. The following Classes V to VIII are nonarable land—not suitable for crop production but available for other uses.

Class V soils are not suited to cultivated crops, but may be used for range, pasture, woodlands, and recreation. These soils are level, have little erosion hazard, but are limited by factors such as flooding, short growing season, rockiness, or wet areas that cannot be drained.

Class VI soils are unsuitable for cultivated crops, but may be used for pasture, range, wildlife, and woodland. Problems may include steep slopes (18 percent to 30 percent slope), severe erosion hazard, established severe erosion, stoniness, shallowness, or drought.

Class VII soils have the same problems as that of Class VI, but more severe. It is difficult to maintain high-quality pasture, but the land may be used for range, woodlot or forest, recreation, or wildlife if it is carefully managed. Slopes may be greater than 30 percent.

Class VIII soils cannot support any commercial plant production, even timber. They may be preserved only for recreation, wildlife, or for beauty. Sandy beaches, rock outcroppings, and heavily flooded river bottoms are examples of Class VIII land.

Land Capability Subclasses

All classes except Class I have one or more limitations. Land capability subclasses indicate factors that limit soil use by means of a single-letter code added to the class number. A Class IIe soil, for instance, is slightly limited by erosion hazards; a Class VIe soil is very limited by erosion hazards.

The letter codes are as follows:

- e—Runoff and erosion. Land with slopes greater than 2 percent are those that need some form of erosion control.
- w—Wetness. These soils may be poorly drained or occasionally flooded. Some such soils may be drained; others are classed as wetlands and are best left as is.
- s—Root zone or tillage problems. These soils are shallow, stony, droughty, infertile, or saline. Wind and water erosion may be problems.
- c—Climatic hazard. Areas of rainfall or temperature extremes make farming difficult. Examples include deserts or the Far North.

Soil Limitation Classes

Besides the USDA capability classes, soils can also be classified by their limitations for any use, perhaps for landscaping, or tree nurseries, or residential streets. In these schemes, soil carries limitations for a given application rated as slight, moderate, or severe. These ratings are based on criteria relevant to that use.

Land with slight limitation is favorable for a particular use without modification. Land with moderate limitations has mild problems that can be overcome with reasonable modification and prior planning. Land with severe limitations is unfavorable for the proposed use. For instance, high shrink–swell potential, low soil strength, and severe frost action all present severe limitations for road construction.

The USDA offers formal criteria for a number of uses, and the information needed to categorize a soil can be found in tables in county soil survey reports. Appendix 4 offers a simpler system that students can use for practice. Again, the data needed for rating a soil appear in soil survey tables, and some can simply be found by examining the soil profile on-site.

Land users can readily transfer the results of soil ratings for an area onto a soil map to graphically reveal lands suitable or unsuitable for various purposes. We might call these *land-use* or *interpretive maps.* On the soil map, mapping units are colored in, often with green (go) for areas with slight limitations, yellow (caution) for those with moderate problems, and red (stop) for unfavorable soils. The soil map of Figure 3–6 would then appear with color between the boundaries of the mapping units. For instance, one might create an interpretive map of Figure 3–6 for septic system suitability. People reading the map quickly locate areas most favorable for proper septic system operation and areas to be avoided. GIS software is particularly adept at creating such maps.

Lands of the United States and Elsewhere

The United States is fortunate to have a great deal of good farmland. Figure 3–11 summarizes the capability of nonfederal U.S. soils, excluding Alaska. Approximately 43 percent of our soil is rated in Classes I to III. This is soil on which nearly any crop can be grown. Most of the rest of U.S. land is suitable for some form of commercial production such as grazing or woodlands.

Good farmland is not evenly distributed over the United States. Corn Belt states have the highest percentage of good farmland, followed by northern plains states and delta states. Much of the land of the West is too mountainous to be useful for cultivated crops.

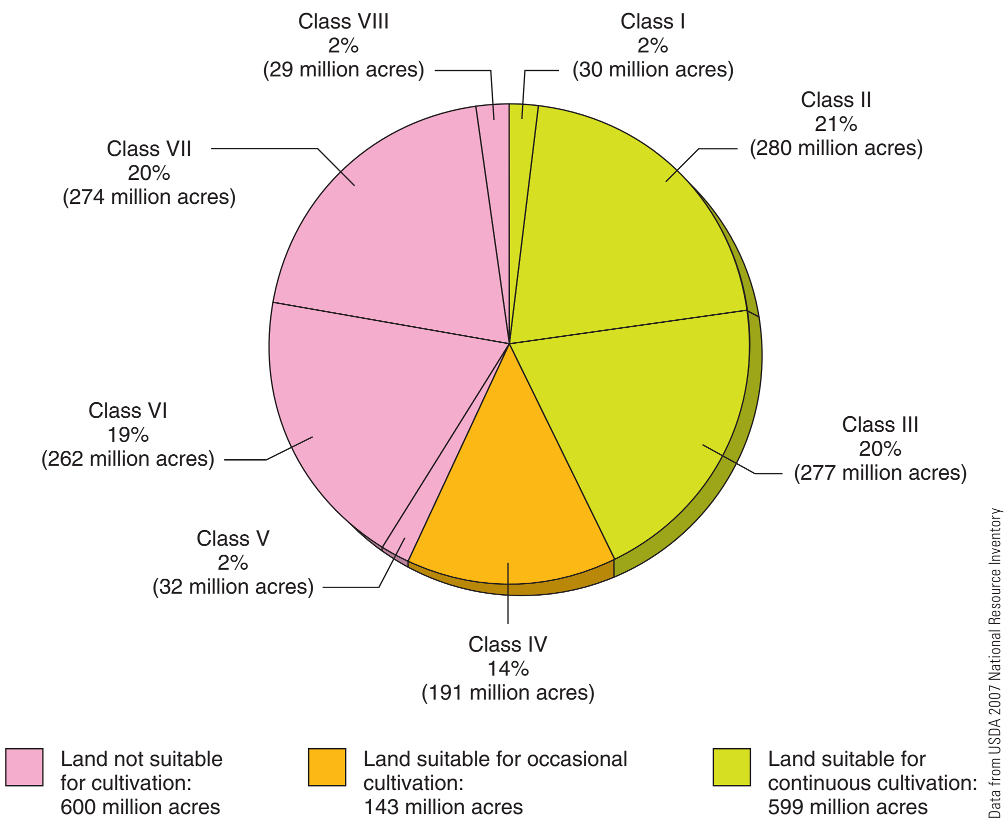


Figure 3–11

Land capability of nonfederal land in the United States, excluding Alaska.

The USDA figures mentioned previously are for nonfederal land, not the entire land surface of the United States. Much federally owned land is mostly rangeland, forest, or other nonarable land. According to the definition used by *The Economist* in its *2007 World in Figures,* 19 percent of the total land of the United States is arable, compared to about 11 percent of the world. By comparison, other selected countries include Saudi Arabia at 1 percent arable, Canada 5 percent, Mexico 13 percent, and Ukraine, a former territory of the USSR and its "breadbasket," 56 percent.

SUMMARY

Soil survey efforts in the United States began around 1900. At first, a simple soil class system based on soil-formation factors was used. This system was refined over time until the current system came into use.

Soil scientists presently classify soils according to their soil properties, profiles, and climate. This soil taxonomy has six levels. The top level consists of 12 soil orders. Each order is further divided into suborders, great groups, subgroups, families, and series. The most important level to an individual grower is the soil series and its subdivision, the soil phase.

Soil scientists survey land and prepare a soil map based on this classification system. The surveyor studies the soil profile and notes slope, erosion, and other features. A soil survey report includes the map plus printed information about the soils on the map and their suitable uses. These reports are then used by regional planners, engineers, growers, and others.

The information in a soil survey places the land into one of eight capability classes. Classes I, II, and III are suitable for cultivated crops. Class IV is marginally useful for cultivation. Classes V to VIII are restricted to noncultivated uses. A number of factors are used to classify the soil, principally erosion hazard. Other factors include drainage, droughtiness, and extreme climates. Soils can also be classified as to their suitability for other uses, and conventional soil maps may be colored to represent the suitability of each mapping unit.

Many soil surveys are now available on the Internet, and the number offered is growing. A following Enrichment Activity supplies the URL of a USDA site containing many county surveys.

REVIEW

1. How do the five soil-forming factors interact to produce an Alfisol?
2. Explain what a soil interpretive map is. How could you draw one from a soil survey map?
3. The Saybrook silt loam, mentioned in the text, is a "fine-silty, mixed, superactive, mesic Oxyaquic Argiudoll." Try to identify which syllables or words apply to family, subgroup, great group, suborder, and order. What soil order is it?
4. At the time colonists arrived in the New World, most of the northern New England states were covered by forests. They were cut down and replaced by farms. Later, forests grew back when the center of agriculture shifted to the Midwest. Explain differences in soil that could have contributed to this shift. *Hint:* Look at the soil map of the United States in Appendix 2.
5. As soils develop over time, they may move from one soil order to another. What might be examples of young, "middle-aged," and older soil orders? Explain.
6. What are soil survey maps drawn on? What are the advantageous of this as a base map?
7. What percentage of the nonfederal land of the United States is rated as arable land? What percentage is nonarable? Can you suggest why the percentage of arable land is low in Saudi Arabia and in Canada?

8. If the average temperatures of the northern latitudes rise, given enough time, what would happen to the percentage of the world's surface covered with Gelisols? Speculate what impact the effect might have on further climate change.
9. Using Appendix 4, list conditions that create moderate and severe limitations on land for establishing and maintaining home landscapes.
10. What are the major soil orders of your state? How did the soil-forming factors interact to put them there? To complete this question, you will need further information from your instructor.
11. It has been proposed to harvest crop residues as feedstock for producing energy. However, a good cover of crop residues is important for reducing soil erosion. In which soil capability class would it be safest to remove crop residues? Why?

ENRICHMENT ACTIVITIES

1. "The USDA Natural Resources Conservation Service soils website at http://soils.usda.gov has numerous resources related to this chapter, including:"
   a. The official Soil Series Descriptions of all the soil series of the United States.
   b. Online soil surveys for many of the counties of the United States.
   c. An online version of *Soil Taxonomy* (11th edition) that became available in 2010.
   d. Listings and images of the official state soils for each state.

   Also check under the Education tab for other resources, including a poster of the twelve soil orders.
2. In most states, parcels of land are located using the township and range system of land survey used in the Public Land Survey System. For a simple graphic display of the system, try http://www.landprints.com/LpRectangularSurveySystem.htm. Practice using this system on a soil survey map.
3. Using the previously mentioned resources, identify your state soil. Then, using the Soil Series Descriptions, find out what kind of soil it is. Write a short report describing the soil.
4. Photocopy and blow up an area of a soil map from a survey supplied by your instructor. Select a use you would like to put the land to in that area. Using the tables in the survey, and Appendix 4, color in the mapping units as having slight, moderate, or severe limitations.
5. A copy of the Canadian soil classification system is available online at Canada's Agriculture and Agri-Food website: http://sis.agr.gc.ca/cansis/references/1998sc_a.html.

CHAPTER 4

Physical Properties of Soil

TERMS TO KNOW

aeration pore
biopore
blocky structure
bulk density (BD)
caliche
clay
claypan
clod
coarse fragments
compaction
cone penetrometer
duripan
fine earth fraction
fragipan
friable
gley
granular structure
hydraulic conductivity
infiltration
loam
macropore
massive soil
mechanical analysis
micropore
mottling
Munsell color system
oven-dry soil
pan
particle density (PD)
ped
percolation
permeability
physical property
platy structure
plinthite
prismatic structure
puddling
redoxymorphic feature
sand
silt
single-grain soil
soil aggregate
soil consistence
soil porosity
soil separate
soil strength
soil texture
soil triangle
specific surface area
structure (soil)
subsoiling
tillage pan
tilth
total pore space

OBJECTIVES

After completing this chapter, you should be able to:

- describe the concept of soil texture and its importance
- identify the texture of a sample of soil
- describe soil permeability and related properties
- describe structure and its formation and importance
- explain other physical properties
- discuss soil compaction and tilth

Physical properties are soil characteristics a grower can see or feel. Physical properties are neither chemical nor biological, but both affect them. Physical properties greatly affect how soils are used to grow plants or for other activities. Is the soil loose so roots can grow easily through it or water seep in easily? Or is the soil tight, preventing root growth and water absorption? How well does the soil aid in supplying air, water, and nutrients? Does this soil need irrigation or artificial drainage? Is this a good soil for apple trees or corn? Will the soil present problems for constructing a landscape retaining wall? A knowledge of physical properties helps to answer these questions. This chapter describes these properties, beginning with the most basic one, soil texture.

SOIL TEXTURE

The most fundamental soil property, one that most influences other soil traits, is texture. **Soil texture** describes the proportion of three sizes of soil particles—sand (large), silt (medium), and clay (small). The size of soil particles, in turn, affects such soil traits as water-holding capacity and aeration. Let us first describe why particle size affects these properties.

Effect of Particle Size

Soil particle size affects two important soil features: **specific surface area** and the number and sizes of pores. We define specific surface area as the amount of surface area exposed by all the particles in a certain weight of soil. Specific surface area can be thought of as the "internal" surface area of the soil. Figure 4–1 uses children's alphabet blocks to demonstrate that the smaller the particles in a soil, the larger the surface area. Because soil contains many small particles, a handful of soil may hold many thousand square feet of internal surface area.

Specific Surface Area

Soil surface area is important because reactions occur on the surface of soil particles, and because water is held as a film around soil particles. Soils with greater surface area have more total water films. Imagine pouring water over a pile of marbles. Most of the water runs away quickly. Droplets clinging to the surface of the marbles are the only water retained in the pile, because water cannot soak into the marbles. Following the rule about particle size, a pile of small beads holds more water than a pile of marbles because it has more surface area for water to cling to. Because soils with the smallest particles, like silt and clay, have the largest surface area, they hold the most moisture.

Reactions that hold plant nutrients in the soil also occur on particle surfaces. Therefore, we can make the rule that the smaller the particles in a soil, the more water and nutrients the soil can retain.

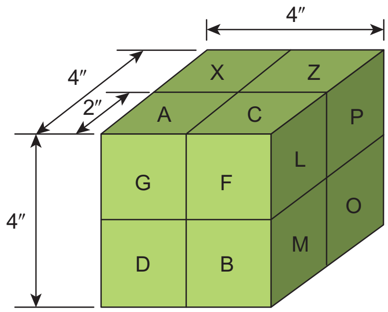
Soil Pores

Pore size and number also depend on particle size. Figure 4–2 suggests that more pores are found between small particles than between large ones. The figure also shows that pores are larger between larger particles. Thus, soils high in clay have many small pores, while soils high in sand have fewer but larger pores.

Interconnected pores may be viewed as tubes through which water and air can pass, even though they are hardly straight, but rather twisted. Because these tubes are narrow and kinked, air and water do not travel quickly. The larger pores, called **macropores**, or **aeration pores**, create the easiest pathways, and so largely determine the movement of air and water through the soil. As water drains down through the soil, it pulls air in behind it, which occupies the macropores.

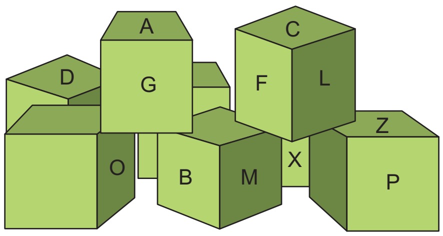
Small pores, or **micropores**, retain some water as it drains down through the soil. In such small pores, water films surrounding adjacent particles merge, holding water in place but excluding oxygen. Further, because of the small pore size, micropores make difficult pathways for water movement. Because they are generally occupied by water, micropores block the movement of air. Sometimes the larger micropores are distinguished as *mesopores*, medium-sized pores that hold readily plant-available water. Water in the smaller micropores can be difficult or impossible for plant roots to extract from the soil.

Clearly, soils desirable for plant growth need some balance of macro- and micropores: macropores for air and water movement, and micropores for water retention. It is worth noting that macropores are fragile, sensitive to disturbance. These pores tend to collapse when compressed or exposed to tillage (even, or especially, by rototillers), reducing macroporosity.



(A) Eight blocks have been put together to make a single large block. Each side measures 4 × 4 inches. The total surface area of this large block is 96 square inches:

Total area = area of each side × number of sides
96 sq. in. = 4 × 4 × 6



(B) The large block has been cut into eight equal blocks. The total surface area of all the blocks is now 192 square inches:

Total area = area of each block × number of blocks
192 sq. in. = 2 × 2 × 6 × 8

By halving the size of the blocks, the total surface area is doubled. In the soil, small particles create a large surface area for water and nutrients to hold on to.

Figure 4–1

The smaller the soil particles, the greater the specific surface area.

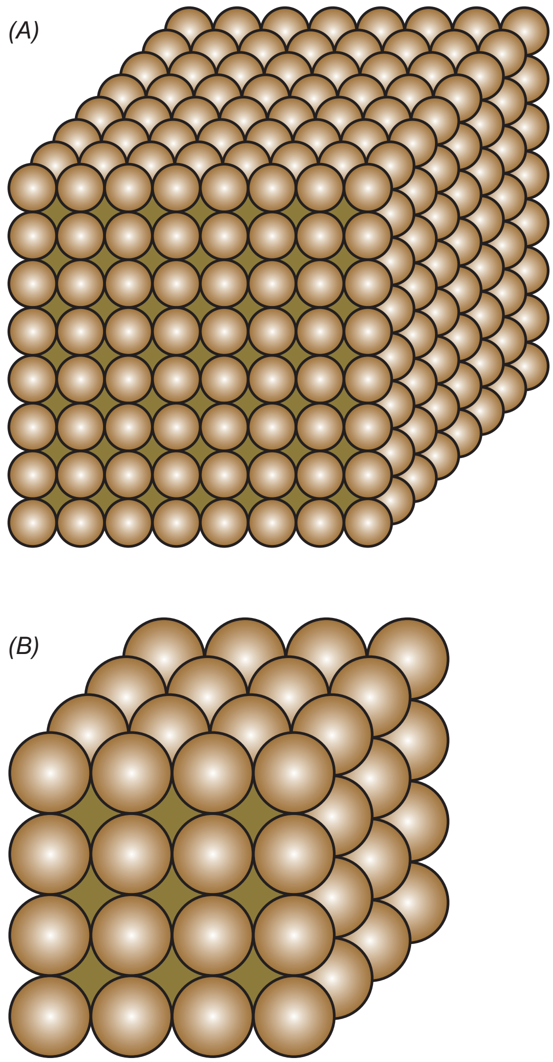


Figure 4–2

Soil particle size affects pore size. (*A*) small particles create many small pores. (*B*) Pores are larger but fewer in number between large particles. Micropores usually hold water, macropores air.

Soil Separates

Soil scientists divide mineral particles into size groups called **soil separates** and define three broad classes: sand, silt, and clay. These three together make up the **fine earth fraction** of soil used to determine texture. Larger particles, such as gravel, are considered to be coarse fragments, and are not considered in texture. Figure 4–3 names the separates and gives their sizes according to the system adopted by the United States Department of Agriculture (USDA). Other soil users, such as engineers, classify soil particles differently to suit their needs. Figure 4–4 gives some idea of the relative sizes of the separates under the USDA system.

Separate	Diameter (mm)	Comparison	Feel
Very coarse sand	2.00–1.00	36"	Grains easily seen, sharp, gritty
Coarse sand	1.00–0.50	18"	
Medium sand	0.50–0.25	9"	
Fine sand	0.25–0.10	4½"	Gritty, each grain barely visible
Very fine sand	0.10–0.05	1¾"	
Silt	0.05–0.002	7/16"	Grains invisible to eye, silky to touch
Clay	<0.002	1/32"	Sticky when wet, dry pellets hard, harsh

Based on data from the USDA

Figure 4–3

The USDA system of soil separates. The comparison shows the difference by setting a very coarse sand grain equal to 3 feet in diameter. Engineers use a different system.

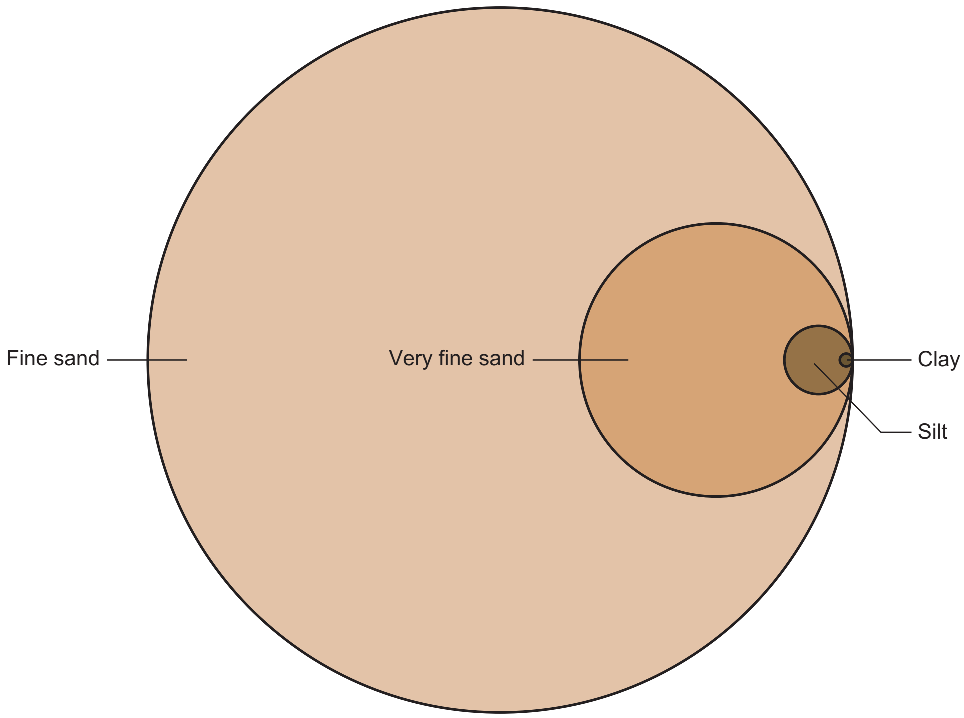


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Figure 4–4

Comparing the size of soil separates. On this scale, very coarse sand would be 3 feet across.

Sand, the largest soil separate, is composed mainly of weathered grains of quartz or other minerals. Sand particles are further divided into five subcategories, as shown in Figure 4–3. Individual sand grains, except for very fine ones, are visible to the naked eye. All are gritty to the touch. Sand grains do not stick to one another, so they act as individual grains in the soil. Enough sand in a soil creates large pores, so sand improves water infiltration (rate at which water enters the soil) and aeration. On the other hand, large amounts of sand lower the ability of the soil to retain water and nutrients.

Class	Diameter Range (mm)	Diameter Range (in.)
Gravel	2–75	1/12–3
Cobbles	75–250	3–10
Stones	250–600	10–24
Boulders	>600	>24

Based on data from the USDA

Figure 4–5
USDA size classification for stones in the soil.

Silt is the medium-sized soil separate. Silt particles are silky or powdery to the touch, like talc. Like sand, silt grains do not stick to one another. Of all the soil separates, silt has the best ability to hold large amounts of water in a form plants can use. Silt, however, erodes readily in moving water and wind because of its size and lack of stickiness, which holds clay particles in place.

Clay is the smallest soil separate, consisting mostly of tiny sheetlike crystals. Clay particles are about the size of the particles in tobacco smoke. While sand and silt result simply from rock crumbling into small particles, clay results from chemical reactions between weathered minerals to form tiny particles of new minerals. These new minerals are able to bond nutrients chemically to their surfaces, holding plant nutrients in the soil.

Particles the size of clay, unlike larger ones such as silt or sand, can move through the soil, filtering between larger particles in moving water. This is a natural process of soil formation, an example of translocation and eluviation, which often leads to subsoils enriched in clay. Also as a result, clay often appears as coatings on sand, silt, or larger soil units.

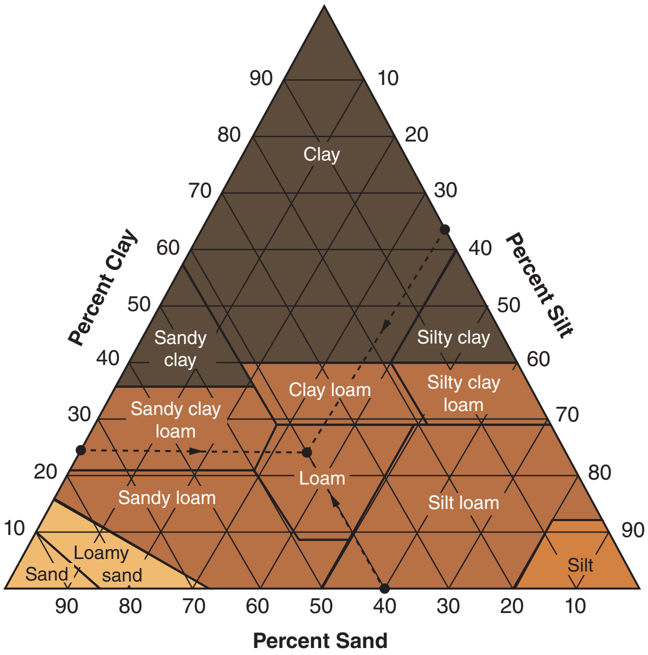
Clay particles stick to one another and so do not behave as individual grains in soil. This helps prevent them from being carried away by wind and water. Wet clay is usually sticky and can be molded. Some types of clay swell when wet and shrink as they dry.

As mentioned earlier, specific surface area influences a number of soil properties. A handful of sand may have a surface area about the size of a ping-pong table, while a handful of clay could reach the area of a football field. It is not surprising that soils high in clay better retain water and nutrients. Conversely, clay is less well aerated, and water seeps into it more slowly.

Gravel and other pieces of stone larger than 2 millimeters in diameter, called **coarse fragments**, are not considered to be part of soil texture. They often are, however, part of the soil and affect its use, as anyone who has picked rocks from a field can testify. Coarse fragments add little to specific surface area and contain no pores, so their presence reduces the water- and nutrient-holding capacity of soil, especially if they occupy more than 15 percent of soil volume. Figure 4–5 lists the USDA size classifications of rock fragments in the soil.

Textural Classification

Soils usually consist of more than one soil separate; all three are found in most soils. The exact proportion, or percentage, of the three separates is called soil texture. Obviously, any number of combinations of the three is possible, so soil scientists simplify texture by dividing soils into textural classes. Soils in the same textural class are similar.



Example: Identify a soil that is 40% sand, 22% clay, and 38% silt

1. Find 40 on the side for sand.
2. Draw a line in the direction of the arrow.
3. Do the same for clay (22%) and silt (38%).
4. The spot where the three lines come together is the soil texture. In this case, the soil is a loam.

A textural name may include a prefix naming the dominant sand size, as in "coarse sandy loam."

Figure 4–6
The soil triangle. Each side of the triangle is a soil separate. The numbers are percentage of soil particles of that type.

The 12 textural classes are shown in the **soil triangle** in Figure 4–6. Each side of the triangle represents the percentage of one soil separate. A person can measure the amount of sand, silt, and clay in a soil sample and simply read the class from the triangle. An example included in Figure 4–6 shows how to read the triangle.

Examine the soil classes carefully. Each corner of the triangle is a class dominated by one soil separate: sand, silt, or clay. The largest class is clay soil, because clay has the most powerful effect on soil properties. With as little as 40 percent clay a soil is classified as a clay soil.

Another important textural name is **loam**, a soil in which sand, silt, and clay contribute equally to the soil's properties. Sometimes loams are described as having equal *amounts* of sand, silt, and clay, which is a mischaracterization. The remaining classes have properties between those of the four major classes and their names suggest the difference. For example, loamy sand is a sandy soil containing enough clay or silt to make it more loamy.

Sand particle size greatly influences soil properties, so for the sandier soil textures, the textural class name may be amended by noting the dominant sand fraction. One

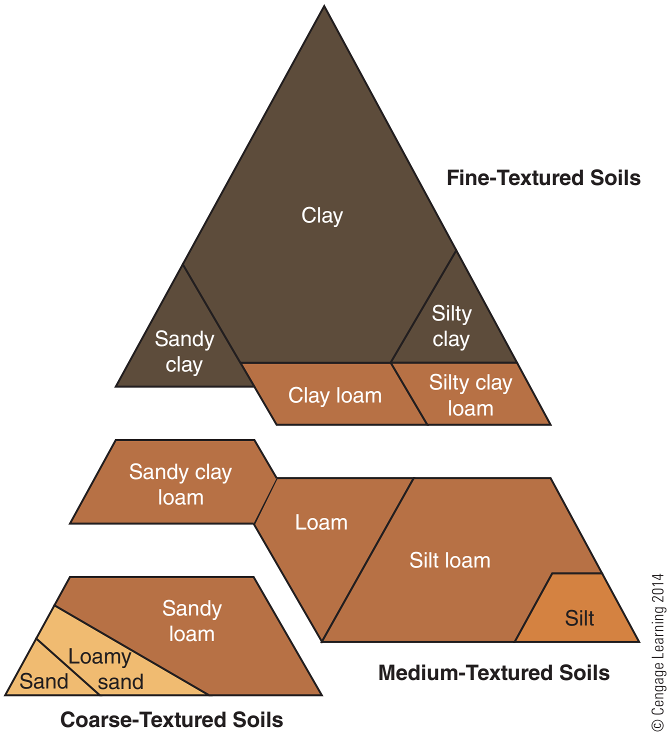


Figure 4–7
Soil triangle redrawn to show fine-, medium-, and coarse-textured soils. An exception is very fine sandy loam, considered medium textured.

might have not just a sandy loam, but a coarse sandy loam; not just a loamy sand, but a loamy fine sand. Also, in soils high in coarse fragments, the fragment name may be used as a modifier, as in gravelly loamy sand.

Growers can usually manage soils without knowing the exact soil texture, so a broader classification is often adequate. One can simply classify soils as sandy, loamy, or clayey, as described previously. Figure 4–7 shows another approach. The 12 classes are divided into three broad categories—coarse, medium, or fine—based on size of the soil separates. Very fine sandy loam is an exception to Figure 4–7. It is medium textured, reflecting the influence of sand size.

Determining Soil Texture

The amount of sand, silt, and clay in a soil can be measured by **mechanical analysis**. Mechanical analysis is based on the fact that the larger a soil particle, the faster it sinks in water. For instance, it takes only 45 seconds for very fine sand to settle through 4 inches of water, but it takes about 8 hours for large clay particles. In mechanical analysis, one stirs soil into water and notes how fast soil particles settle out. This can be observed by performing a sedimentation test, in which one measures depth of sediment at various time intervals to determine percentage of sand, silt, and clay, or by using a hydrometer to measure water density at various time intervals. The Enrichment Activities provide a source of labs for these two methods, and they are available in numerous lab manuals as well. Sand particle sizes can be determined by running them through a series of sieves of correct mesh size openings.

An even simpler test, which can be performed on-site, is the ribbon or feel test. The test is based on the feel of damp soil and how easily it can be molded. All who work with soil, including horticulturists and landscape designers, should be able to perform ribbon testing.

The procedure for the test is as follows:

Step 1 Obtain a large enough sample of soil to form a 0.5-inch ball. The sample should contain no gravel or bits of debris. If needed, run the sample through a sieve to remove such material.

Step 2 Moisten the sample to a medium moisture level, like workable putty. Work the soil between the fingers until it is uniformly moist and dry lumps are wetted. Note any grittiness, which indicates sand, or the stickiness of clay. Clay also stains the fingers.

Step 3 Mold the sample into a 0.5-inch ball and try to squeeze it lightly. If the ball breaks at the slightest pressure, the soil is a sand or coarse sandy loam. If the ball stays together but changes shape easily, it is a sandy loam, loam, or silt loam. Finer-texture soils resist molding.

Step 4 Squeeze out a ribbon between the thumb and forefinger, noting how long a ribbon can be formed without breaking. Use this guide to narrow down the choice of textures:

no ribboning: loamy sand

ribbon shorter than 1 inch: loam, silt, silt loam, sandy loam

ribbons 1–2 inches long: sandy clay loam, silty clay loam, clay loam

ribbons 2–3 inches long: sandy clay, silty clay, clay

Step 5 Put all the observations together to decide the textural class. Sand feels gritty, silt feels smooth, clay feels sticky. So, for instance, sandy clay forms a long ribbon yet feels slightly gritty. A short ribbon that feels smooth is a silt loam.

The ribbon test is useful only if one has practiced it enough to "get a feel" for it. Try it out a few times.

Characteristics of Textural Classes

Soil scientists place soils in textural classes because each class has properties important to its management. One can only generalize about textural effects because other properties also affect the soil. However, here are a few useful guidelines.

Texture governs the way water behaves in the soil. For instance, water enters (**infiltration**) and drains through (**percolation**) coarse soil most rapidly because of the large pore spaces. Thus, a coarse soil dries out most quickly after a heavy rain or in the spring, allowing a grower to get into the field more quickly. Similarly, coarse soils are more likely to need frequent irrigation. Growers with fine soils are likely to worry about the opposite problem—dealing with excess water.

Fine soils retain plant nutrients better than coarse soils. This is true partly because the rapid percolation of water through coarse soil leaches out nutrients. Also, clay particles have the best ability to retain nutrient chemicals.

Soil texture influences how easily a soil can be worked. Because clay particles stick together, it takes more horsepower and fuel to pull tools such as plows through a fine soil. Landscapers also find it harder and slower to dig holes in fine soils for planting trees—so texture can even affect what should be charged for landscaping services. In fact, soil texture strongly affects many landscape practices, such as how to design a landscape irrigation system or a retaining wall.

The stickiness of clay also affects the physical condition of the soil. For instance, fine soils often form clods when they are tilled. A crust may also form on the surface and interfere with seedling emergence. A fine soil tends to be "tight," meaning it has mostly small pores that are difficult for air and roots to penetrate. In contrast, coarse soils are "loose" and well aerated.

Clayey soils tend to retain more soil organic matter than sandy soils, which lends them a darker color. The higher organic matter content also makes them a stronger carbon sink, so efforts to sequester carbon will be most effective in finer-textured soils.

For most purposes, growers consider medium soils to be ideal. They hold water, but they do not stay wet too long. They are neither sticky nor hard to work. In general, medium soils have the good traits of both coarse and fine soils, without their bad traits.

Modifying Soil Texture

Growers and engineers use soils for many purposes. For each purpose, a different soil texture may be best. For example, corn tends to be most productive on a loam, potatoes on a sandy loam, and black walnuts on fine-textured soils. Loamy soils are easiest to use for landscapes and gardens.

Can a grower change soil texture to improve it for the crop being grown? Except in very small areas, such as golf greens or potting soils, changing texture is impractical. The amounts of clay or sand to be added are too large. Figure 4–8 shows the effect of adding sand to a clay soil to loosen it—clay particles surround the sand grains and fill in any pores that may be created. As a result, the soil continues to behave much like clay. To greatly modify clay, enough sand must be added to make the sand grains touch each other and form bridges that exclude clay from the pores between

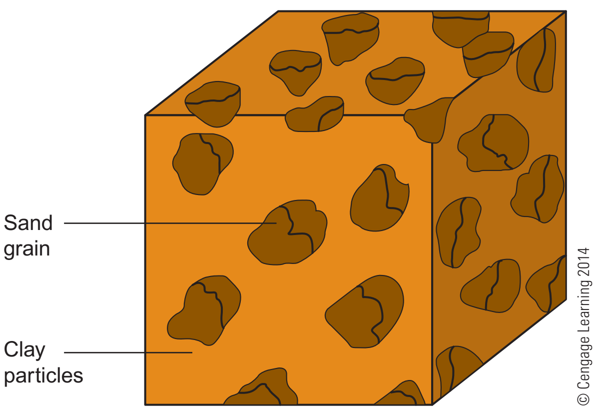


Figure 4–8
When sand is mixed into clay, clay particles surround the sand grains and large pores are not formed. Very large quantities of sand are needed to loosen clay soils—enough that sand grains touch and there isn't enough clay to fill all the gaps.

the sand grains. A better way to improve clay soils is to add organic matter, a practiced described repeatedly elsewhere in the text.

There are three ways for growers to take texture into account. First, select a crop to fit the soil or purchase land that suits the crop. For example, an apple grower may purchase land with a fine soil on which apples grow best. In many landscapes, a sugar maple (*Acer saccharum)* will not thrive on a sandy soil, while a red maple *(A. rubrum)* might do well. An axiom of landscape design is "put the right plant in the right place," and texture is an element of that. Appendix 5 lists the soil texture preferences of many common trees.

Second, manage the soil in a manner that fits the texture. For example, with proper fertilization and irrigation, coarse soils can be very productive. A sugar maple may grow on sand if well watered. When planting landscape trees in the author's home state (Minnesota), many landscapers "plant high" in heavy clay soils. That is, the top of the root ball will be a couple of inches above grade, with a bit of soil added around to make a low mound. This improves aeration and reduces excess wetness around the roots in these difficult heavy soils.

Third, organic matter can improve texture extremes by making sandy soils less droughty and more fertile and by loosening clay soils. The third choice might be considered one of the cardinal rules of soil management: *add organic matter to improve soil.*

It might be pointed out that adding organic matter does not actually change soil texture itself. Think about the definition of soil texture to determine why. It does, however, modify another powerful physical property, to be discussed shortly: soil structure.

SOIL DENSITY AND PERMEABILITY

As stated earlier, important physical properties relate to the spaces between soil particles. For a better understanding of soil pore space, this discussion will work through a series of related properties, beginning with soil density. We begin here because the density of soil—its mass per volume—is related to the amount of empty space in the soil.

Particle Density

One could ask how much soil would weigh if there were no pore space. This is **particle density (PD)**, the density of solid particles only. As an example, the PD of a soil made wholly of quartz sand would be the same as that of a solid block of quartz, or 2.65 grams per cubic centimeter (166 pounds per cubic foot).

PD varies according to the type of minerals in the parent material and the amount of organic matter in the soil. Figure 4–9 lists the density of several soil-forming minerals. Note that the densities are very similar. In fact, there is surprisingly little variation in the PDs of most mineral soils. PDs in mineral soils average about 2.65 grams per cubic centimeter, a value used as a standard in soil calculations. High amounts of organic matter reduce the value because organic matter is much lighter than mineral matter.

Mineral	Density (grams/ cm^3)	Density (lbs/ ft^3)
Water	1.0	62.5
Quartz	2.65	166
Feldspars	2.5–2.7	156–169
Micas	2.7–3.0	169–188

Figure 4–9
Densities of several soil-forming minerals.

Bulk Density

Because soil contains pore spaces, the actual density of a soil is less than the PD. This measurement is **bulk density (BD)**, or the mass of a volume of undisturbed oven-dry soil.

To measure BD, a core of soil of known volume is carefully removed from the field. The soil core is then dried in an oven at 105°C until it reaches a constant weight. This is called **oven-dry soil**. The core is then weighed, and BD is calculated. The example that follows is for a core of 500 cubic centimeters (cm^3) that weighs 650 grams (g):

$$BD = \frac{\text{Weight dry soil}}{\text{Volume dry soil}} = g/cm^3$$

$$BD = \frac{650\ g}{500\ cm^3} = 1.3\ g/cm^3$$

The BDs of mineral soils depend mostly on the amount of pore space in the soil, because particle weight is fairly constant. Since BD says something about pore space, which is important to plant growth, BD is used as an indicator of soil quality. The higher the BD, the less the pore space. BDs of the topsoils of typical undisturbed, uncultivated mineral soils range from 0.8 to 1.2, but become higher when cultivated. Compaction raises BD, and when typical soils reach a BD of 1.6 or higher, root penetration into the soil is inhibited. Severely compacted soils can reach densities of 2.2, nearly that of concrete (2.4). The BDs of organic soils are much lower, with values of 0.1 to 0.6 being common, while soils rich in sand are naturally of higher density, with values reaching up to 1.8. The unit for all these are grams per cubic centimeter. Subsoil densities are always higher; density increases with depth because of the weight of the overburden and denser structure. Subsoils of glaciated regions can be especially dense because of the extreme compression created by the ice mass sliding over them.

In general, increases in bulk density caused by soil usage is a strong indicator of reduced soil health for root growth, reduced aeration, and reduced water infiltration. This will be taken up again later in this chapter.

Soil Porosity

Total pore space is a measure of the soil volume that holds air and water. This value, usually expressed as a percentage, is known as **soil porosity**. Thus, a soil with a 50 percent porosity is half solid particles and half pore space.

Porosity can be measured by placing an oven-dry soil core in a pan of water until all of the empty pore space is filled with water. The water volume, which fills the pore space, divided by the total core volume, is porosity. The water volume, of course, would be difficult to measure directly. However, the metric system defines 1 cubic centimeter of water as weighing 1 gram. Thus, if one measures porosity metrically, water volume and weight are the same. Therefore, the difference in weight between the dry and the wet cores is the total pore space. This number is converted to a percentage to get porosity. The soil core used as an example before had a volume of 500 cubic centimeters and weighed 650 grams when dry. When wet, the same core weighed 900 grams. Porosity is thus calculated as follows:

$$\text{Porosity} = \frac{\text{wet weight (g)} - \text{dry weight (g)}}{\text{soil volume (cm}^3\text{)}} \times 100$$

$$= \frac{900 - 650}{500} \times 100 = 50\%$$

Porosity can also be calculated from BD and PD. If there were no pore space, then BD would be the same as PD. The ratio BD/PD would be equal to 1. The more the pore space, the smaller the BD and smaller the ratio BD/PD. In fact, the ratio BD/PD is simply the percentage of the soil that is solid matter. If one subtracts that percentage from 100 percent, the difference is the percentage of pore space. To make the calculation, one assumes that PD is 2.65 grams per cubic centimeter. The following equation can be used to calculate porosity:

$$\text{Porosity} = 100\% - \frac{\text{BD}}{\text{PD}} \times 100$$

If we substitute the values for the BD calculated earlier:

$$\text{Porosity} = 100\% - \frac{1.3}{2.65} \times 100 = 50\%$$

The porosity of sand (about 30 percent) is lower than that of clay (about 50 percent). Figure 4–10 shows that porosity increases at finer textures. Yet common sense tells us that water seeps into sand very rapidly, but seeps only slowly into clay even though it has higher porosity. The next section explains why.

Permeability

Permeability is the ease with which air, water, and roots penetrate through soil. In highly permeable soil, water infiltrates soil rapidly, and aeration keeps roots well supplied with oxygen. Roots grow through permeable soil with ease. We can think of permeable soil as being “loose” and impermeable soil as being “tight.”

Permeability depends partially on the number of soil pores, but it depends more on the size and continuity of the pores. The movement of air, water, and roots can be likened to walking through a maze. If paths are too narrow, progress is difficult. Progress is even more difficult when most paths come to a dead end. Like a maze with dead ends, soils lacking large, continuous pores limit the flow of air and water.

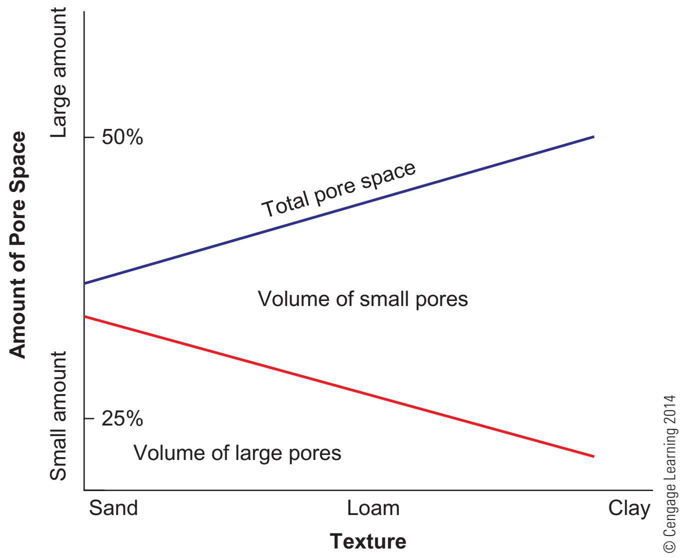


Figure 4–10
Texture affects soil pores. The top line shows total pore space in the soil. Clay has the greatest total pore space. The lower line shows space in large pores. Sand has the most large pore space. The amount of small pores lies between the two lines. Clay has the most small pore space. Loam has a balance between large and small pores.

Large, continuous pore spaces in the soil, or macropores, occur between large particles. Therefore, the number of macropores depends on texture, as shown in Figure 4–10, and permeability must also depend partially on texture. Permeability is simply a descriptive term with no numerical value; it cannot be measured directly. However, the movement of water, which reflects permeability, can be measured. **Hydraulic conductivity** is a measure of the rate of water movement through a soil. Coarse soils might have conductivities of 1 and 1.5 inches per hour or more, while fine-textured soils might measure a hundredth of that. Fortunately for those who crop such soils, another physical property, structure, influences permeability.

SOIL STRUCTURE

Heavy soils would make very poor root environments, except that **structure** can alter the effects of texture. Structure refers to the way soil particles clump together into large units (Figure 4–11). These large units are called **soil aggregates**. Aggregates that occur naturally in the soil are called **peds**, whereas clumps of soil caused by tillage are called **clods**.

Peds are relatively large, ranging from the size of a large sand grain to several inches. Spaces between clay particles may be tiny, but the spaces between peds may be large. Inside the peds are small, water-holding micropores; between the peds are large, air-filled macropores. Well-aggregated soils contain large, continuous pores that promote good air and water movement and that provide easy pathways for root growth. Good water-holding capacity is maintained within the peds.

Soil aggregation improves soil fertility and quality by its functions. By improving permeability, it promotes root growth, soil aeration, and infiltration of water into the soil. Carbon inside the soil aggregates is protected from rapid decay, so it preserves soil organic matter. Aggregates can hold plant nutrients near plant roots. Finally, aggregation stabilizes soil against water and wind erosion by improving water infiltration and generating larger particles that move less readily in wind and water. The degree of soil aggregation is an indicator of soil quality.

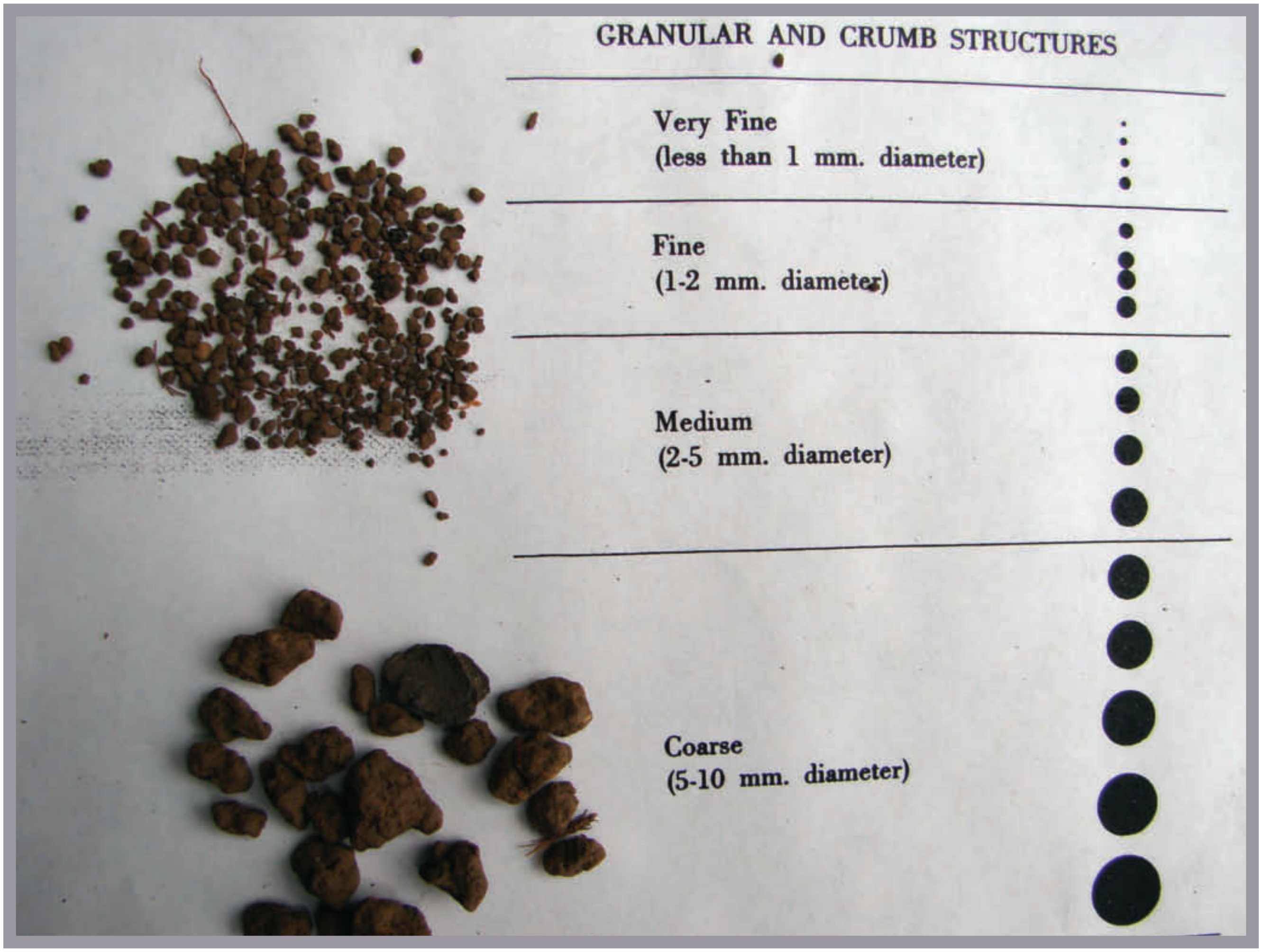


Figure 4–11
Granular structure units of two different classes. They were strong enough grade that they could be easily sieved out of a soil sample.

There are many different kinds of structure, and some are better at improving permeability than others. Soil scientists classify structure according to three groups of traits.

- *Type* refers to the shape of the soil aggregates (Figure 4–12). We term the type of structure in Figure 4–11 as *granular.* The various types are described later in this chapter.
- *Class* is the size of the peds, which can be very fine, fine, medium, coarse, or very coarse. Figure 4–11 show shows two different classes of granules: fine and coarse to very coarse. The size dimensions for each class varies depending on the type.
- *Grade* refers to how distinct and strong the peds are. One grade, structureless, applies to soils that have no peds. Weak grades are barely visible in a moist soil, whereas strong peds are quite visible and can be

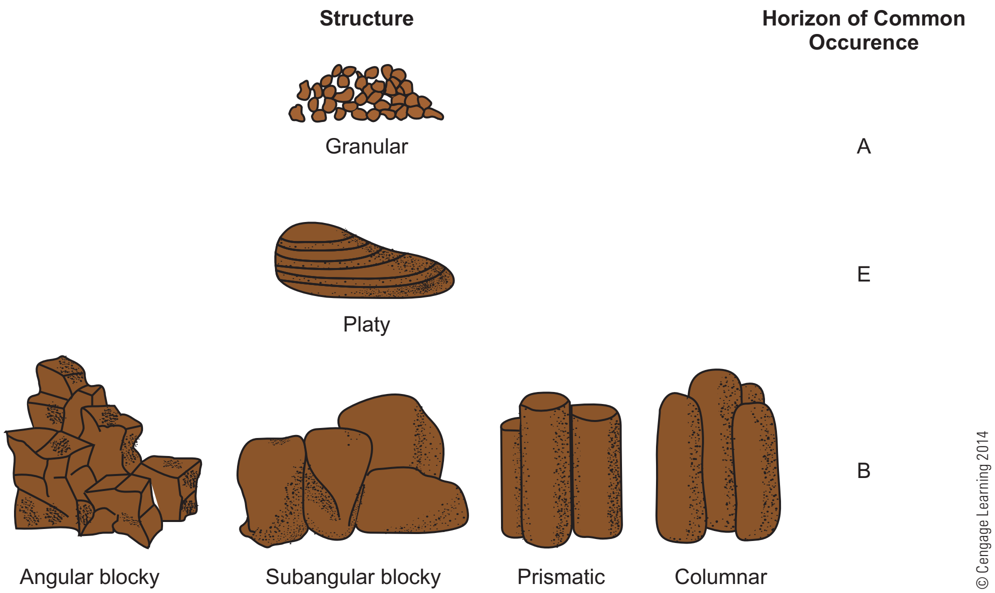


Figure 4–12 Types of soil structure.

easily handled without breaking. Moderate grade is in between. The granules shown in Figure 4–11 are strong; they were separated when sieved by the author without falling apart. The amount of disturbance needed to disrupt aggregates varies according to texture, so a sample of peds in a sandy loam soil might be rated as strong, but still be more readily broken than another sample of strong peds in a clay loam.

In soil descriptions, structure is named in the order (1) grade, (2) class, (3) type. For instance, the smaller granules in Figure 4–11 might be described as *strong fine granular structure.*

Structureless Soil

Sand behaves as individual grains, so very sandy soils seldom have much structure. These soils are called **single grain**. Sandy soils are naturally permeable, so single-grain soils have good infiltration rates and aeration.

Finer soils lacking structure are a solid mass stuck together like molding clay. These **massive soils**, as they are called, lack permeability. Massive soil is typical of some C horizons. Tillage or compaction of wet clayey soil may result in massive soil in the A horizon. This is one of the reasons for another axiom of soil management: *stay off wet soil*, especially fine-textured ones. Never till them when wet.

Types of Soil Structure

Granular structure is commonly found in A horizons. Peds are small, usually 1–10 millimeters (0.04–0.4 inch), rounded in form, and considered the most desirable of structures. Such structure increases total pore space and lowers BD compared with a soil lacking structure.

Platy structure is usually found in E horizons. Peds are large but thin, platelike, and arranged in overlapping horizontal layers. The arrangement makes discontinuous pores that reduce penetration of air, water, and roots. Soil compaction can create platy structure in the A horizon when granules of topsoil are crushed into thin layers.

Blocky structure is typical of many B horizons. Peds are large, 5 millimeters to more than 50 millimeters (0.2–2 inches) and blocklike in shape. If the ped is very angular, it is termed *angular blocky.* More rounded peds are described as *subangular blocky.* Blocky structure has medium permeability.

Prismatic structures tend to occupy lower B and C horizons. Peds are large, usually 10 millimeters to more than 100 millimeters (0.4–4 inches), forming angular columns that stand upright in the soil. If the top of the ped is pointed or flat, the structure is called *prismatic.* If the top of the ped is rounded, it is termed *columnar.* Prismatic structure is moderately permeable, whereas columnar structure is slowly permeable.

Formation of Soil Structure

Soil structure forms through a two-step process: the first creates a loose ped, and the second cements it. First, a clump of soil particles sticks loosely together to form a loose aggregate that is weak and easily crushed. This is usually by a process of localized compression. That is, a force compresses a small mass of soil together, separating it slightly from the surrounding soil mass along a plane of weakness. Compression may repeat itself several times to the same soil mass, increasing the coherence of the aggregate. Roots, especially of grasses, can surround a soil mass, and as the roots expand, create the compression. Fungal bodies can do the same. This mechanism tends to dominate in A horizons. Alternate freezing and thawing, and wetting and drying, also fractures and compresses the soil into separate soil masses. These mechanisms tend to dominate in B horizons.

Second, weak aggregates are cemented to make them distinct and strong. Clay, iron oxides, and organic matter may each act as cements. In most soils, microorganisms provide the best cement. When soil microbes break down plant residues, they produce gums that glue peds together. Biological cementation tends to glue the granules of the A horizon, while chemicals cement the blocks and prisms of the B horizon. Organic materials of an intermediate stage of decomposition function best to cement aggregates, indicating the need for repeated additions of organic matter. Maintenance of good granular structure in the topsoil depends on a continuous supply of fresh organic matter, as does aggregate stability. Hence another rule of soil management: *Maintain and improve soil organic matter content.*

The large aggregates described here normally contain within themselves smaller units. These smaller units are largely held together by calcium ions that bridge adjacent soil particles, a process called *flocculation*. These *microaggregates* shelter and protect stable soil organic matter from attack by decay organisms.

In some soils, sodium displaces calcium from the soil; these small subunits *deflocculate*, and structure is degraded. Adding calcium in the form of gypsum, calcium sulfate, is the treatment for this condition, discussed in more detail in Chapter 11. Incorporating gypsum in some tight clay soils with low organic matter *may* improve their physical condition as well.

Soil users should keep in mind that structure is not a permanent feature of the soil. It can be degraded by mismanagement, like frequent tillage with no additions of organic matter. Or it can be improved by certain cultural practices, for instance, planting a grass cover. Grasses are particularly good at creating structure. Good structure is one of the important criteria for soil quality, and to some degree is under the control of soil users.

SOIL CONSISTENCE

Soil consistence refers to the behavior of soil when pressure is applied. It relates to the degree that soil particles stick to one another or other objects and mostly results from certain types of clay (Chapter 10).

The effect of consistence can be best explained by some examples. Loose sand, for instance, shifts easily under pressure so that vehicles may get stuck in dry sand along a beach. Preparing a seedbed for planting is another example. A grower wishes to break apart large chunks of soil to get a fine surface to plant seeds in. It is the consistence of the soil that determines how easily those chunks can be broken down.

Consistence depends on how moist a soil is, so it can be measured at three different moisture levels. Each level has its own descriptive terms (Figure 4–13).

Wet Soil. Wet soil is checked for stickiness and plasticity. Plasticity is how easily soil can be molded between the fingers. To determine stickiness, some soil is pressed between thumb and forefinger, and the amount that sticks to the fingers is noted.

Moist Soil. The terms *loose*, **friable**, and *firm* apply to soils in the moist state. Loose soils do not cohere at all. Friable means that soil materials can be crushed easily under pressure. Technically, a soil is termed friable if a 1-inch block of moist soil can be easily crushed between the thumb and forefinger. Firm soils require more pressure to crush a smaller block of soil.

Dry Soil. Determined by trying to crush an air-dried mass of soil in the hand. Very hard, dry soil, for instance, can be crushed between two hands.

By rating a soil for consistence, one can infer such information as suitability for plowing, likelihood of erosion, or texture. The feel test for texture works because of the consistence of different soil textures. Often, loose soil is coarse textured, friable soil is medium textured or well aggregated, and firm soil is tight or fine textured. A firm soil may lack good structure or be compacted.

Wet			
Stickiness	Plasticity	Moist	Dry
Nonsticky	Nonplastic	Loose	Loose
Slightly sticky	Slightly plastic	Very friable	Soft
Sticky	Plastic	Friable	Slightly hard
Very sticky	Very plastic	Firm	Moderately hard
		Very firm	Hard
		Extremely firm	Very hard

Figure 4–13
Consistence terms for soil at three different moisture levels.

SOIL TILTH

Tilth is a general term for the physical condition of a tilled soil. It suggests how easy the soil is to till, how good a seedbed can be made, how easily seedlings can come up, and how easily roots can grow. Tilth is actually a combination of other physical properties, including texture, structure, permeability, and consistence. We may think of it as the physical condition of the soil.

Tillage improves soil tilth for a time, improving soil air–water relations for new seedlings. It does so by loosening the soil and stirring air into it. Fine-textured soils are most improved by tillage because coarse soils are already well aerated and loose.

Tillage tends to cause a year-by-year decline in soil structure, however. Compare the topsoil of a cultivated field with that of a nearby fencerow that has not been cultivated. Peds from the fencerow will be more numerous, stronger, and of a better type. The weakening structure of the tilled soil, in turn, lowers water infiltration, aeration, and ease of root growth—signs of degrading soil quality.

As a side note, the physical condition of about the top 3 inches of soil is of particular importance. It is this zone that most dictates the rate of water infiltration, which in turn affects how much water will be end up in the soil for plant use or how much will run off, causing erosion and transport of pollutants. This is also the zone where seed germination and initial root growth occurs. So here is another rule of sustainable soil use for the reader: *Pay particular attention to physical condition of the top 3 inches.*

The next sections detail injuries to soil tilth (Figure 4–14). Note that several affect the top 3 inches.

Image courtesy of Ed Plaster

Figure 4–14
Tilth ruined by heavy construction equipment operating on wet soil. All damages described here—crusting, puddling, compaction, destruction of structure—are shown. Building construction sites can experience massive soil damage. For best results, this soil should be leveled, tilled deeply to break up compaction, and generous amounts of an organic amendment applied to begin rebuilding the soil.

Compaction

Compaction results when pressure is applied to the soil surface. Light compaction in aggregated soils squeezes soil aggregates together, reducing the size of interped pores. Further compaction begins to crush the aggregates. In single-grain or massive soil, pressure forces individual particles closer together. Compaction primarily alters soil traits related to pores and soil strength.

Compaction can profoundly alter soil traits such as porosity and permeability. Not only can peds collapse and particles be squeezed together, but small soil particles can be forced into spaces between larger soil particles. Furthermore, generally "flat"-shaped soil units, such as clay particles, which may be randomly oriented in undisturbed soil, get reoriented into a horizontal position and become tightly stacked. Granules can be flattened into platy structural units. Total pore space declines, while the number of micropores increases and macropores are lost. Some micropores shrink enough to become so tiny as to make the water in them unavailable to plants. Pores become disconnected, and the pathways for gas and water movement more tortuous.

Compaction increases **soil strength**, the degree to which a soil can resist movement owing to pressure. Recall from Chapter 1 that roots must push aside soil to grow. Put another way, roots grow well only if root pressure exceeds soil strength. Compaction, therefore, increases the resistance that roots must counter as they grow through the soil. The effect is most pronounced in dry soil, because drying itself increases soil strength. In most cases, increased soil strength poses the major problem of compacted soil.

As a result, severe compaction has the following unfortunate results:

- Reduced porosity and permeability.
- Reduced air exchange, and a longer residence time for air in the soil. Oxygen content may fall and carbon dioxide content increase.
- Decreased infiltration rate of water.
- Increased erosion and pollutant transport associated with greater runoff.
- Increased runoff from lawns and large grounds, which wastes water and increases transport of pollutants into surface water.
- Reduced water percolation, which can leave soils excessively wet.
- Reduced availability of water that is in the soil.
- Restricted root growth.
- Increased evolution of nitrous oxide, a greenhouse gas, from the soil (see Chapter 5), with a loss of nitrogen available to plants, owing to lower oxygen conditions.
- Reduced uptake of potassium owing to lower oxygen conditions.

Interestingly, roots try to compensate by changing their growth habit. Roots increase branching and secondary root formation in lightly compacted soils, which can improve phosphorus uptake. But in severely compacted soils, roots tend to be less branched, shorter, and thicker. This shape better protects them from higher soil pressure and increases root pressure that can be exerted to deform the soil enough to allow root growth. While these modifications aid growth in compacted soil, they also reduce root effectiveness in gathering water and nutrients. Roots also find and follow channels in the soil, like fractures and channels left by earthworms and decaying roots.

Compaction is primarily caused by wheel traffic, whether it be wheels on farm tractors and grain carts, large lawn mowers, construction equipment, or off-road vehicles. Cattle and even human footsteps on paths compress the soil. We can divide compaction into three types: surface compaction, subsoil compaction, and tillage pans.

Surface compaction compacts the top few inches of soil, to the depth of tillage, and particularly affects that important surface zone. It occurs when lighter loads compress the soil, but do not transmit compression deeper into the soil. Common farm tractors, lighter equipment, or cars parked on lawns create surface compaction. In cultivated situations, tillage tends to alleviate surface compaction, but in places where tillage is not possible, such as lawns or soccer fields, reducing surface compaction presents a considerable challenge. Many tree species are especially sensitive to compaction, so construction and forestry activities can severely harm tree vigor and health.

While tillage breaks up surface compaction, more severely compacted layers appear just below the depth of tillage, creating **tillage pans**. These form over time with repeated tillage operations. The dense layer inhibits deep rooting.

Heavier loads applied to wet soil create subsoil compaction to depths up to 3 feet. Loads from equipment heavier than 10 tons per axle, typical not of most tractors but common in grain carts, large combines, dump trunks full of gravel, and other heavily loaded equipment, compress the soil severely. Wet soil permits soil particles to slide past each other more easily, transmitting compression deeper into the soil. In dry soil, soil particles are more fixed in place, and even heavy loads produce surface compaction only. Subsoil compaction greatly restricts deep rooting and water percolation. In dry years, plants may suffer stress from lack of access to deeper soil water; in wet years, water may hang above the compaction, keeping it waterlogged.

The Tree Protection Zone

Your author has seen numerous trees killed around construction sites by soil compaction, piling soil on top of roots, trench digging, and others. Many experts recommend a Tree Protection Zone, an area that must be protected from disturbance during construction and later. We can take this zone also as a critical zone for avoiding soil compaction. There is no commonly agreed upon zone size based on research, but a number of rules are followed. One could suggest a circle around the trunk whose radius is at least 1.25 feet for every inch of trunk diameter at 4 1/2 feet. This is the *minimum* distance; twice that would be better. For instance, during construction fence off this area. Don't park cars in that area. Be very cautious about gardening there. Landscapers, homeowners, and contractors should heed the advice for the health of a tree, a highly valued item in a landscape.

The degree of compaction relates to the natural compressibility of a soil, its moisture content, axle weight, inflation pressure of tires, and how often equipment is driven on the soil. Fine-textured soils and wet soils are the most compressible. Large rounded grains of sand contact each other at several points, so they do not compress easily. Silt is more compactable. Under wet conditions, flat clay particles realign horizontally, rather than being randomly positioned, packing tightly. Furthermore, a high water content weakens the binding of soil particles within a ped.

Compaction has varying effects on plant growth and yield. Research indicates these effects:

- Any degree of compaction inhibits growth and decreases yields when conditions are wet.
- Slight compaction may improve growth and yields under normal conditions, especially on sandy soils that could use a few more micropores.
- Moderate compaction can improve yields in dry soils during dry years by increasing micropore space in order to hold water. Moderate compaction can also improve seed germination by ensuring good soil–seed contact (hence gardeners who press down on newly planted seed rows).
- Severe compaction always inhibits production.
- The finer the soil texture, the more damaging is compaction.

In agricultural fields, subsoil compaction and tillage pans can be temporarily broken up by deep tillage (Chapter 16), but compaction is a problem for all soil users. Virtually all landscape sites are compacted by construction equipment. LEED standards (see Chapter 1) call for compacted construction site soils to be tilled to at least 6 inches and incorporation of amendments and mulches to relieve compaction and improve water infiltration. Parks and recreational areas suffer from the pressure of countless footsteps, mowers, and off-road vehicles. Logging operations compact forest soils. Compaction can be most severe in these nonfarming areas, such as football fields, because the land cannot be plowed.

Other forces as well as surface-applied pressure create compaction. Vibration increases soil settling and sifts small particles into larger pores; this can be a problem near large construction sites or roads. Repeated heavy rainfall and flooding does the same, and may be one of the most damaging, long-term results of a flood.

The natural processes that create structure can slowly repair a compacted soil. Repeated freezing–thawing cycles, for instance, may fracture compaction—but not where the soil never freezes, nor where it freezes solid for the whole winter. Rather than wait for natural action, it is best to avoid compaction or to break it up with machinery.

Compaction can be measured in two ways. The most accurate is to compare the BD of the compressed soil to that of nearly unaffected soil. An average uncompacted tilled loam might have a BD of about 1.3 grams per cubic centimeter. Compaction by farm equipment can raise BD to 1.8. This amounts to a reduction of pore space from 50 percent to almost 30 percent.

Simpler, but less precise, is the use of a **cone penetrometer** (Figure 4–15). A rod with a cone-shaped tip is pushed into the soil, and a dial reads the pressure needed

Figure 4–15
A digital cone penetrometer measures soil compaction in a habitat reconstruction project in Minnesota.

to penetrate the soil. The more compacted the soil, the greater the resistance to penetration. The result is an index that can be compared to a nearby unaffected soil. Unfortunately, soil type, moisture level, and stoniness also affect the result. Dry soils display much greater soil strength than moist soils, because soil particles will not slide readily past each other and so are harder to penetrate. Use cone penetrometer indices best by comparing nearby plots of the same soil type and moisture level, or the same soil at the same moisture content over time. They are also handy for detecting subsoil compaction, because the reading will jump when a compacted layer is hit. With practice, a probe like a long screwdriver or survey stake can substitute for a penetrometer to form some notion of compaction on a site.

Direct Aggregate Destruction

Plowing tends to create large aggregates as it flips the soil over. However, other tillage operations, such as cultivating, tend to crush soil aggregates. High-speed rototillers are especially destructive because they batter aggregates apart. Many gardeners favor the fluffy, loose bed created by rototillage, but over the long term, structure is hurt. Excessive rototillage can reverse all the gardener's efforts of adding organic matter.

There are two reasons why tillage destroys aggregates. First, by stirring oxygen into the soil, tillage speeds up organic matter oxidation. This loss, in turn, reduces the amount of "organic glue" that holds peds together. Second, tillage tools smash the now-weakened peds. This leads to another axiom of sustainable soil management: *till as little as possible* (see Chapter 16).

Puddling and Clods

Working wet soil greatly harms tilth, especially in soils high in clay. When pressure is applied to very wet soil aggregates, they fall apart. This results in a condition known as **puddling**—the conversion of aggregated soil into massive soil. Puddled soil is very dense and tight. In fact, it is done on purpose in some rice paddies, canals, and reservoirs to keep water from leaking away.

Working soil that is either too wet or too dry can also break up soil into large, seemingly indestructible clods. Soils with a hard consistence are most likely to form such clods.

Surface Crusts

Most forms of tillage bare the soil until the crop grows large enough to cover the soil. When raindrops hit this bare surface, their impact breaks apart peds on the surface. Free soil particles then splash around, washing into spaces between large particles and sealing the surface. As soil dries, this sealed surface hardens into a crust. The higher the clay content in the soil, the more severe the condition.

Water filters into the soil through pores open to the surface. By clogging the larger pores that are conduits for water movement, infiltration slows dramatically. Aeration suffers as well. Plants may experience water stress because less water is stored in the soil, and the water that did not enter the soil runs off the surface, carrying soil particles and eroding the surface. Because infiltration is slowed, irrigation must be applied more slowly for longer periods.

A hard crust creates a barrier to seedling emergence, causing an erratic stand in the field and production losses. Interestingly, just as root architecture responds to soil compaction, so does the emerging shoot respond to the barrier by becoming thicker and shorter.

Crusts may be broken by light cultivation, but can re-form with further irrigation or rain. Keeping the soil covered with vegetation or mulch and maintaining aggregate strength are more effective solutions. Or, put as another soil management rule: *avoid bare soil.*

Improving Tilth

As noted earlier, tilth relates to the properties of texture, structure, permeability, and consistence. However, texture and consistence cannot, in most cases, be changed. Therefore, improving tilth is largely a matter of improving structure and avoiding compaction or crusting. The following practices can help protect or improve tilth:

- Never work wet or quite dry soils. Unfortunately, the demands of growing a crop or scheduling activities, such as landscaping, can interfere with this rule.

- Avoid unnecessary traffic over the soil. If possible, set aside paths through fields and nurseries to limit driving on the soil. If possible, drive only on dry or frozen soils, especially with heavy loads.
- Use controlled traffic in the field by setting the wheel base on all equipment to the same width. Then always drive in the same rows. While the wheel tracks will compress more severely, the remaining rows will be compaction free.
- Use equipment with the lowest practical axle weight.
- Large or dual tires do not seem to reduce compaction greatly, but they spread it over a wider area. Flotation tires with low inflation reduce the pressure applied to the soil surface.
- Reduce the number of tillage operations. One can reduce trips across the field by combining operations or by simply not repeating them so many times.
- Some modern tillage practices, called minimum or reduced tillage, use less tillage. This is covered in Chapter 16.
- Deep plowing, or **subsoiling**, can break up tillage or natural hardpans, resulting in deeper penetration of water and plant roots and improved yields. The benefits may be short-lived, however, because further tillage reforms the compacted layer.
- Wherever possible, keep the soil covered by vegetation or mulch. Crops that fill in between rows quickly and crops that form complete cover, such as alfalfa, protect soil from raindrop impact. Tillage that leaves a lot of residue on the soil surface also helps by creating a mulch (Figure 4–16).

Photo by Lynn Betts, USDA Natural Resources Conservation Service

Figure 4–16
Corn residues in this no-till corn in Iowa act as a mulch that protects soil from raindrop impact and reduces average soil temperature.

- Incorporating grasses into a crop rotation improves structure, and as little as three years of continuous grass cover can improve structure on a degraded soil.
- Avoid bare-fallow treatments, which destroy soil structure.
- Frequently add organic matter to the soil. Growers can leave residues in the field and spread manure. Gardeners and some organic farmers use compost. Lawn clippings, leaves, and any other source of organic matter can be useful. Lots of organic matter should be incorporated into soil being prepared for turf and landscaping. A note to professional and amateur gardeners: Manure-based composts can be rather salty, and so cannot be used as freely as some other sources like leaf compost.
- Grow “green manure” and cover crops (Chapter 6) as part of cropping practices. Plant roots help create loose aggregates, while decaying organic matter glues them together. Tap-rooted plants such as alfalfa also help break up hardpans. Even gardeners can protect and improve soil this way.
- For people working on turf areas, be attentive to avoiding practices that compact soil, like driving a truck loaded with rock mulch on the lawn or driving back and forth over an unprotected lawn with a skid loader.
- Treat high-sodium soils with gypsum to remove excess sodium (see Chapter 11) and manage high-sodium irrigation water correctly (Chapter 9).
- Gypsum (see earlier in chapter) may also help some tight, low-organic-matter clay soils. Adding organic matter would probably help more.

Soil Channels

To micropores and macropores, we could add a third type of soil pore: large, continuous channels that begin at or near the surface and lead deeper into the soil. These may be created by cracks in the soil, but more often are biological in origin. Earthworms create most of the channels as they drag food from the surface into their burrows, and decayed roots leave soil channels behind. These channels caused by soil life are termed **biopores**, and are very important in undisturbed soil.

Biopores greatly enhance soil aeration and water infiltration. Water on the soil surface, as well as air, can quickly move deeper into the soil down these channels. Roots also tend to follow these channels, particularly in hard soil. We consider these channels to be generally beneficial to soil function, but such paths can also speed downward flow of pollutants such as pesticides and nutrients, possibly endangering groundwater.

Water enters only those channels that are open to the soil surface, unless the soil is completely saturated. Tillage erases the tops of these channels, preventing water from entering them readily and reducing their effectiveness, while no-till soil management (Chapter 16) preserves them. They are also promoted by leaving organic matter on the soil surface for earthworms, and by other means of enhancing earthworm populations (Chapter 5).

SOIL PANS

An earlier section of this chapter mentioned plowpans. Any layer of hardened soil is called a **pan**. Pans restrict deep rooting of crops and deep percolation of water, and can be a serious hindrance to cropping. Water may also perch atop such layers, hindering drainage and causing saturation in the root zone. Pans can also promote soil runoff and erosion. The increased runoff may carry agricultural chemicals off the field, contributing to water-quality problems elsewhere.

Growers create plowpans, but other types are natural. Here are some examples:

- **Claypans** occur where extreme illuviation has caused a very high clay content in a subsoil layer. The layer is quite dense.
- **Fragipans**, like claypans, result from clay accumulation. Here the clay binds soil particles into a hard, brittle layer.
- **Plinthite** layers are cemented by a special type of clay common to the tropics. When plinthite dries, it hardens into a bricklike substance; the process cannot be reversed by later wetting. Plinthite commonly renders tropical soils poor for agriculture.
- **Caliche** and **duripans** are layers of soil in which chemicals cement soil particles together. Lime cements caliche, typically a white, hardened layer found in arid regions. Many soils of the American Southwest contain caliche, an obstacle that may need to be broken up when planting landscapes.

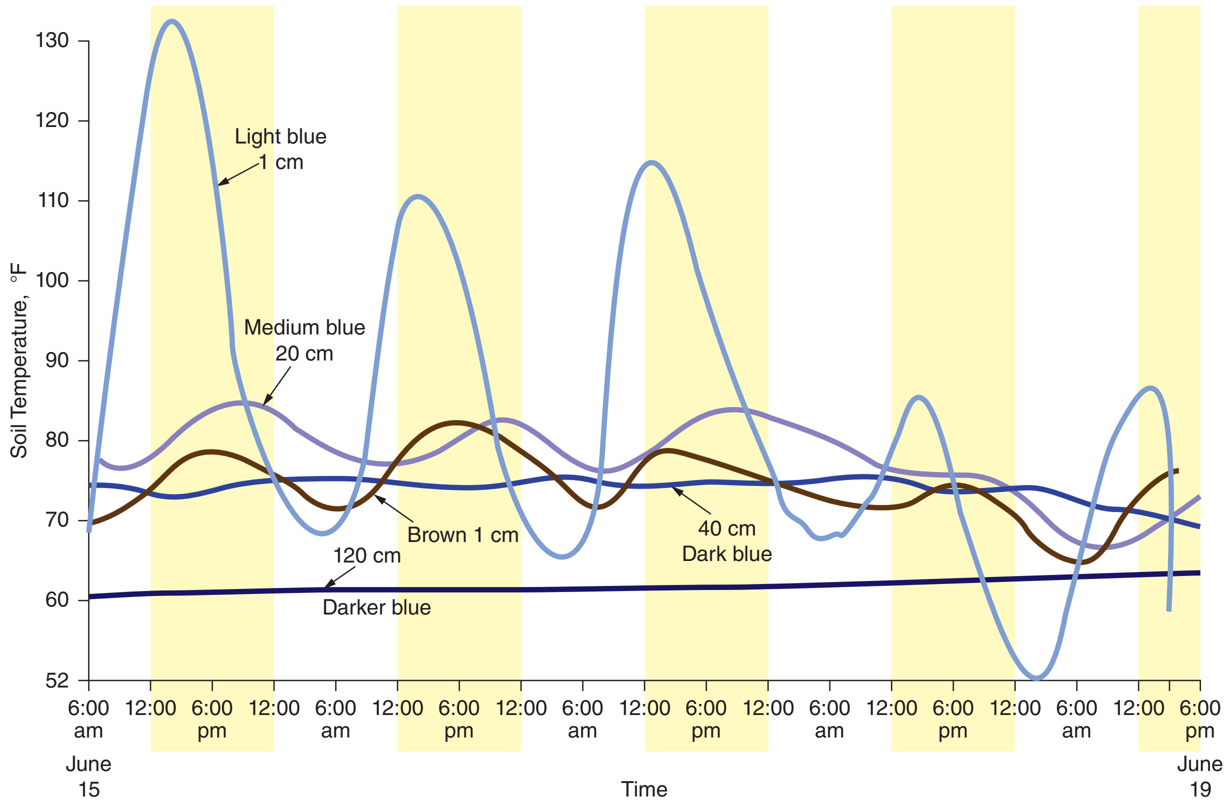
SOIL TEMPERATURE

As indicated in Chapter 1, soils in the growing regions of the world maintain a temperature balance over the growing season that is satisfactory for plant growth. Soil temperature depends on several interacting factors of energy inputs of sunlight and air temperature, soil's absorption and conductance of heat, and loss of heat at the surface. Because soil is warmed by sunlight striking its surface, soil temperature responds to the amount of solar energy received. Cold air absorbs heat from the soil, and thereby lowers soil temperature, while warm air can lend heat to the soil.

Soil temperature varies according to the amount of solar energy absorbed. Dark-colored soils absorb sunlight energy readily, while light-colored soils reflect a greater proportion of sunlight and remain cooler. Any material covering the surface also affects light absorption, including turf, mulches or crop residues, or shading from above by crop or tree canopies.

For soil to warm below the surface, heat must be conducted deeper into the earth. Soil does not conduct heat well; in a sense, soil at any depth is insulated by the material above. As a result, during the summer, deeper soil is cooler than surface soil, while in the winter, it is warmer. Certain mulches also insulate the soil surface, reducing heat conductance into and out of the soil.

Energy received at the soil surface must warm not only soil particles, but also water contained in soil pores. It takes five times the energy to heat water than to heat



Soil Temperature: Five Days in June, Minnesota

The chart above shows several temperature readings from June 15 through 19 under bare soil and sod at a location in Minnesota. The blue lines are taken under bare soil. At 1-centimeter depth (about 0.4 inch), hourly soil temperatures vary wildly, peaking as high as 130 degrees on June 15 at 3:00 p.m. and falling to 52 degrees late at night a few days later. At 40 centimeters (about 16 inches), there is little daily variation. Also note the delay effects—the deeper the reading, the more delayed the temperature peaks and valleys. At 120 centimeters (about 4 feet), there is no measurable daily variation, but simply a slow rise because deeper soils slowly warm from winter cold as heat is conducted downward from above. The brown line displays readings taken at 1 centimeter under sod. The insulating effect of sod is evident, with the average temperature at that depth being lower, and temperatures not rising nearly as high during the day and falling less during the night. Organic mulches have similar affects. Cooler soil temperatures later in the period reflect a short-term cooling trend in the weather.

Adapted from Hourly Soil Temperatures, 6/20/07. St. Paul Campus Climatological Observatory, Department of Soil, Water and Climate, University of Minnesota.

soil particles; that is, it takes five times as much energy to heat water by one degree than to heat, say, dry sand by one degree. Therefore, it takes much more energy to warm wet than dry soil. As a consequence, dry soil warms up much more quickly, and reaches higher soil temperatures than does wet soil. Evaporation of water from the surface of damp soils also cools the soil. One practical effect is that sandy soils, which hold less water, warm more quickly in the spring than finer-textured soils, and so can be planted earlier in the year. This is important for growers of produce that receive better prices when they get to market sooner.

Soil moisture, for the same reasons, affects the conductance of heat into and out of the soil. The movement of heat energy deeper into the soil in the summer is slowed by having to heat the water it encounters. Similarly, in the winter both soil particles and water must give up heat for soil to cool. As a consequence, in cold climates frost intrudes deeper and more quickly into the soil if ground enters the winter dry.

Soil temperature varies on all time scales: daily, seasonally, and even over much longer periods. The degree of variation depends on depth. The surface of a bare, dark soil rises dramatically during the day, and cools at night. Surface temperatures of unshaded soil can even reach temperatures that damage seedlings of some plants. *Heat canker* is the thermal death of plant cells at the soil line, and is an issue for seedlings because they are tender and do not shade the soil. Carrots, sunflowers, small grains, and evergreen seedlings in nurseries can be prone to heat canker.

As one measures deeper in the soil, daily variation diminishes rapidly, as shown in the accompanying sidebar, titled "Soil Temperature: Five Days in June, Minnesota. Daily variation quickly declines even at shallow depths, and deep in the soil profile, there is little or no daily variation.

Similarly, soil temperature varies seasonally in response to changing levels of light energy and air temperature. The soil surface experiences the quickest and most severe temperature cycle, while temperature deep enough varies little over the seasons. Deep soil also lags surface conditions, so deep soil reaches its lowest temperatures after the coldest winter conditions are past, and its warmest temperatures after the hottest days of the summer.

On an even longer time scale, deep soil temperature responds to long-term climate change. Temperature records measured 40-feet deep in the earth beginning in 1962 at the University of Minnesota reveal a significant temperature rise (3.5°F) at that depth. Seasonal temperature responses are negligible at this depth, so the rising temperatures indicate long-term warming in Minnesota.

Temperature Effects

Soil temperature is critical to growers because it affects seed germination and root growth, as well as water and nutrient availability and biological activity.

Each plant species has a range of proper temperatures for germination, with a minimum below which seed does not germinate, an optimum for best and most rapid germination, and an upper range. Above that, seeds may fail to germinate, die, or enter a dormant state. In field growing, soil temperature determines planting date. Cool-season plants such as peas that can germinate in cool soil can be planted early in the spring, while warmer season crops must be planted later. Gardeners plant seeds partly based on frost-free dates, but also, perhaps unknowingly, based on soil temperature.

Weed emergence also responds to soil temperatures; for instance, in turf of the author's home state the timing of preemergent herbicide application depends on soil temperature. In greenhouses, germination temperatures are controlled by heat mats or special germination chambers for optimum results.

Root growth also depends on soil temperature, with species-specific responses. Warm-season crops such as corn or tomatoes grow best at warm soil temperatures, while peas and other cool-season vegetables prefer cooler temperatures. Therefore, soil temperature also partially determines when things like tomato transplants are planted; if installed too early, roots fail to develop in the cold soil. Cool-season turf grasses common to northern states stop growing at soil temperatures above 75°F, causing stress during hot spells and preventing their culture in warm climates. The growth of new roots of transplanted trees of many species strongly responds to soil temperature, which affects the best time of year for transplanting. Root injury due to very high soil temperatures often occurs in plants grown in containers, especially dark-colored ones, when sunlight strikes the containers.

In addition, soil temperature influences the availability of nutrients and the ease of water uptake for plants. In cold soils, both nutrient availability and uptake decline, so nutrient problems occur in cold soils. Phosphorus uptake is particularly slow, which affects how growers fertilize in cold climates. Cold water in the winter increases the challenge of growing greenhouse crops in northern states: Do the purple leaves in Figure 12–7 in Chapter 12 come from underfertilization with phosphorus or from cold soil that inhibited uptake? Either is possible.

Cold soil also slows water uptake by plants; folks prone to letting their houseplants wilt might try watering with slightly warm water for a quicker response by that limp peace lily.

When soil temperature is higher than air temperature, soil warms the air above it. During the night, soil temperature is often higher than air temperature, and during the fall and spring, warm soil may protect low-growing plants from nighttime frosts. Because moist soil holds more heat than dry soil, this frost protection is most effective if the soil is kept bare (not insulated by mulch) and damp.

Winter soil temperatures influence survival of vegetation. Plant roots are much less tolerant of cold temperatures than above-ground plant parts, so abnormally cold winters lacking an insulating snow cover can induce winter injury. In cold climates, outdoor plants growing in pots must be protected during the winter, and root damage in nursery trees and orchards with bare soil is not uncommon.

Soil temperature also has an effect on the biological activity of soil microorganisms; below about 40°F, most are essentially dormant. Therefore, many of the biological processes described in the next chapter are strongly influenced by soil temperature. For instance, the biological activity that converts ammonium nitrogen to nitrate nitrogen slows dramatically below 50°F, so in colder climates application of anhydrous ammonia during fall should wait until soil has chilled.

Managing Soil Temperature

Soil temperature responds to natural conditions that growers have little control over such as light intensity and air temperature. Watering soil can help keep it cool; indeed, watering cool-season turf during periods of heat stress is the only protection a turf manager can offer. Some soil manipulations can raise spring soil temperatures, such as plowing in the fall, improving drainage, and planting on ridges (Chapter 16). However, the most effective means of managing soil temperature is mulching.

Growers use mulches to hold moisture in the soil and suppress weeds, but mulches also affect soil temperature. Three broad classes of mulches are in common use: organic materials, inorganic materials, and plastic sheeting. Each has different effects on soil temperature.

Organic mulches consist of materials like plant residues left on the soil surface (Figure 4–16), straw, leaves, or wood chips. Such materials conduct heat about 10 times more slowly than soil, and so have strong insulating properties. They also intercept sunlight so that it does not directly raise the surface temperature of the soil. Organic mulches moderate soil temperatures, keeping it cooler during the day and warmer at night, but reducing average soil temperature during the summer. Conversely, organic mulches slow heat loss in the winter, keeping soil temperatures higher. Therefore, organic mulches are often used to protect roots of landscape and garden plants that may be damaged by severe freezing. In the most northern states, the special roots used on dwarf apple trees are marginally hardy; orchardists often mulch the roots with an organic material. Sod insulates soil as well, and helps protect plant roots during winter.

Sometimes we want to keep the soil frozen. *Frost heaving*, the raising of soil layers by a complex process involving water freezing in the soil, occurs most often in medium- to finer-textured soil exposed to repeated freeze–thaw cycles. It can lift landscape and garden plants right out of the soil or break their roots. A good organic mulch applied *after* the soil freezes reduces those cycles and protects the plants.

Inorganic materials mostly include gravel of various kinds, which conduct heat easily and have little insulating value. Therefore, they do not moderate soil temperatures to the degree of organic materials. Landscapers in cold climates should avoid rock mulches on plants with marginally hardy roots. Recently, recycled rubber granules have also been introduced as mulches. Your author has to admit, he has no idea about their insulating properties.

Plastic sheeting tends to raise soil temperatures. The temperature of black plastic rises dramatically under sunlight, and some of that heat is conducted into the soil below. Growers of heat-loving, high-value vegetables often plant through black plastic laid out on the ground (Figure 4–17) to increase soil temperature, promote growth and productivity, suppress weeds, and shorten time to harvest. Clear plastic warms the soil even more by letting sunlight pass through the plastic to warm the soil directly, but preventing heat from escaping. In hot, sunny climates, soil under clear plastic gets hot enough to kill weeds and pathogens, and so can be used as a soil sterilization treatment.

Fire and Soil Temperature

Soil temperature, of course, affects soil and plants in natural ecosystems as well. Some plants from cool, moist climates do not tolerate warm soils well, which has implications for landscape plants. In the author's home city, Colorado spruce (*Picea pungens*) is popular and widely planted, but is always under stress and short lived in this urban soil, which is warmer than its native high-elevation habitat in the Rockies.

An interesting case that exemplifies several temperature principles is fire. Fire is present or even necessary in many natural ecosystems like prairies, the brushlands

Photo by Bob Nichols, USDA Natural Resources Conservation Service

Figure 4–17
Growing zucchini on black plastic in South Carolina. Black plastic raises average soil temperature, which promotes early production of this crop.

of the West, and some forests. Fire heats the soil directly, but aftereffects are usually more important. With the dense vegetation and organic residues above the soil surface now thinned or removed, more light reaches the soil surface. The soil is now covered with a layer of dark ash, which absorbs sunlight. Both conditions raise soil temperature, which promotes germination of a new generation of plants, often of species that had been earlier crowded out by more aggressive species. Mineral nutrients are also recycled in the process. Figure 4–18 shows the differences.

SOIL COLOR

While soil color is easily noted, it does not itself greatly affect the soil except for its contribution to temperature. However, color indicates much about soil conditions, and is an important part of soil description.

Soil particles themselves display little color; most are particles of minerals that are nearly white or colorless. Color appears when particles become painted with some coloring agent. These coatings consist primarily of decayed organic material, which is black and darkens the soil, and iron minerals. Iron occurs in several mineral forms, each of a different color, and it is the amount of soil oxygen that determines the iron compounds present.

With ample soil oxygen, iron is mostly present as the ferric species, or Fe^{+3}, the oxidized form of iron. In the absence of oxygen in waterlogged soil, iron is biologically reduced to the ferrous species, or Fe^{+2}. While ferric, or oxidized, iron compounds come in shades that are reddish or yellow, ferrous-iron compounds appear gray or even bluish. Soil bacteria perform the chemical reduction as they consume carbon in an environment that lacks oxygen.

Figure 4–18
A prescribed burn in an Iowa prairie. Fire is an essential part of many healthy prairies. Note that shading vegetation is removed, so more sunlight hits the soil. The layer of black ash absorbs more of that energy. The soil is warmed, promoting germination of many plants, among other effects.

Soil may also display whitish deposits that indicate accumulations of salts and lime. Soil color, then, can be a useful guide to organic matter content, drainage and aeration, and the presence of salts.

Color as a Guide to Soil Use

Soil color can be a useful guide to the suitability of the soil for various uses. Here are some ideas.

Dark Brown to Black

Dark topsoil colors result from organic matter or dark parent materials, usually the former. The organic matter accumulation that creates dark colors arises from two situations, which can often be distinguished by smell:

- Organic matter can reach very high levels in soils that are usually waterlogged. Such soils often have a sour, oily smell.
- Organic matter can also reach high levels in adequately aerated soils, especially prairie soils. These soils have the earthy smell of good soil, and usually have good fertility.

White to Light Gray

This color may indicate that the chemicals that color soil have leached out. It may be seen in heavily leached sandy soils and E horizons. White color may also be due to accumulations of lime, gypsum, or other salts. Fertility of these soils may be compromised by leaching or accumulation of salts.

Light Brown, Yellow to Red

These are the colors of oxidized iron minerals, chemically similar to rust. Such color indicates adequate drainage because there is enough oxygen in the soil to form the oxides.

Bluish-Gray

These colors, called **gley**, are the color of reduced iron compounds; their presence indicates a lack of oxygen in the soil layer in which they are found. Gleying typically occurs in the B horizon. The depth of gleying indicates how deep the soil saturates (Figure 4–19).

Mottled Colors

Subsoil shows patches of different colors, often spots of rust, yellow, and gray (Figure 4–20). **Mottling** in the subsoil suggests that the soil is waterlogged for part but not all of the year. Some wetland plants transport oxygen to their roots, leaving rust-colored zones in an otherwise gleyed soil around their roots. Because mottles result from oxidation–reduction reactions involving iron, the preferred technical term for mottling is now **redoxymorphic feature**.

Clearly, soil color indicates drainage. Broadly speaking, a very black topsoil that feels soft and squishy with an off-smell indicates a decayed organic surface horizon typical of very wet soils. Gley near the surface also indicates very poor drainage, while gley or mottling a bit deeper in the soil indicates less severe drainage problems. Figure 4–19 shows a classification system for soil drainage based on soil color. Those who must—or at least, should—analyze soils with which they will be working, such as landscape designers, ought to examine at least the upper parts of the soil for color.

Drainage Class	Description
Very poorly drained	In level or low spots, black topsoil with gray color under the A or AB horizon, water table very near surface much of the year
Poorly drained	High water table part of the year or impermeable subsurface layer, gray or black surface, gray B horizon with brownish mottles at 6–20 inches
Somewhat poorly drained	Gray or brown A horizon with brownish upper B horizon, gray and rust mottles between 6- and 20-inch depth
Moderately well drained	Fairly bright colors in upper B horizon, few mottles between 20- and 40-inch depth
Well drained	Free of mottles above 40-inch depth, may be a few mottles below 40 inches
Excessively well drained	Sandy soils with rapid permeability, shallow soils on steep slopes, soil free of mottles

Courtesy of USDA

Figure 4–19
Guide for determining soil drainage class using soil color.

Image courtesy of Ed Plaster

Figure 4–20

Excavation for a basement in Minnesota reveals soil mottling, visible in this clump of soil.

Photo by Bob Nichols, USDA Natural Resources Conservation Service

Figure 4–21

Munsell color chart being used to determine soil color in Nebraska.

Describing Soil Color

A simple description of a soil as "dark" would not be adequate for a soil survey. Soil surveys rely on a system that provides a precise description of soil color, the **Munsell color system** of color notation.

Using the Munsell method, the surveyor matches the soil to standard color chips (Figure 4–21). The Munsell system identifies each chip with three variables:

- *Hue* is the color, such as red or yellow.
- *Value* is the lightness or darkness of the hue. Value is denoted by numbers 0 to 10, where 0 is black, each subsequent number represents a lighter color, and 10 is white.
- *Chroma* is the purity of the dominant color, and is also denoted by a number. Low chroma suggests muddy colors.

Using the Munsell system, a soil might be labeled 10YR 3/6. This soil has the hue 10YR, a yellow-red; the value 3 (dark); and the chroma 6. Each Munsell color designation has an associated color description; in this case, the soil is described as dark yellowish-brown.

SUMMARY

The most basic physical property of soil is texture—the proportion of sand, silt, and clay. All the possible combinations of the three are divided into 12 textural classes. These classes range from the coarsest, which is sand, to the finest, which is clay. Medium-textured soils are called loams.

Texture strongly affects how growers use soil. Coarse soils are easy to work and dry out quickly. They warm up early in the spring, but do not hold nutrients well. Therefore, coarse soils perform best with irrigation and proper fertilization. Fine soils hold water and nutrients well, but they are more poorly aerated unless of good structure. Fine soils tend to stay wet later in the spring and are more difficult to work.

The ease with which air, water, and roots move through soil is called permeability. Permeability largely relates to the number of large, continuous pores. Pore spaces lie between the textural units of sand, silt, and clay, or between the structural units of grains and blocks, and in soil channels like biopores. Coarse soils, because of their large sand content, are naturally permeable. Finer soils depend on structure, the aggregation of soil particles into peds, to create large pore spaces. Structure forms when root masses, freezing–thawing cycles, or other forces create loose aggregates, which are then cemented by chemicals or gums exuded by soil organisms, so improving soil organic matter content helps “loosen” clay soils by improving structure. Biopores are larger channels like earthworm burrows and decayed root channels.

Consistence measures traits such as stickiness, plasticity, and friability. Soil tilth, the physical condition of the soil for growing plants, results from the interaction of consistence, texture, structure, and permeability. Tillage, done correctly, improves the tilth of a seedbed in the short term. In the long term, tillage can cause compaction, crusting, puddling, or deterioration of structure. Minimizing tillage, adding organic matter, and working soil at the proper moisture level preserve tilth. Some soils contain hardened soil pans such as plowpans or caliche.

Seed germination and plant growth are strongly affected by soil temperature. Some crops, like corn, germinate best in warm soil, while others, like peas, accept cooler soils. Growers can change soil temperatures by using mulches. Organic mulches lower the average soil temperature, while plastic mulches raise it.

Soil color is an indicator of soil conditions. For instance, dark color in the topsoil suggests a high amount of organic matter. Gray or mottled colors suggest slow drainage. Soil scientists use the Munsell system to identify soil color.

REVIEW

1. Which are likelier to have a higher oxygen content—pores within soil peds or pores between soil peds? Explain your reasoning.
2. What should professional gardeners do to maintain or improve structure in the gardens they care for?
3. Equipment operating on a construction site during wet weather strongly puddles the soil, as in Figure 4–14. Has this changed particle density? Bulk density? Texture? Structure? Permeability? Explain your answers.
4. What effect would you expect the addition of large amounts of organic matter to have on BD? Explain.
5. One study compared soil under a filter strip (see glossary) around a grazing area with nearby grazed land. Surface bulk density of the grazed soil was 1.45 grams per cubic centimeter, while in the filter strip it was 1.05 grams per cubic centimeter. Calculate and compare the porosities. In what other ways might these two soils differ?
6. Looking at Figure 4–10, what soil textures give the best balance between micropores and macropores? What would be the effects?
7. In choosing a site to build a home with a basement, would you prefer one with a gray subsoil or a light-brown subsoil? Explain your answer.
8. A Bonneau soil near Gainesville, Florida, is 89.3 percent sand (mostly fine sand) and 10.6 percent silt. How much clay is in this soil? What would be its full textural classification? What would be some characteristics of this soil?
9. What soil textures would be best for the following uses, according to Appendix 5?
   a. Permanent grass pasture
   b. Bare root nursery
   c. Ball and burlap nursery
   d. Woodland wildlife habitat
   e. Home septic systems

10. You are a landscape installer with many jobs lined up and a tight schedule. It has just rained heavily. Which job sites will you go to first: those with sandier soils or those with fine-textured soils? Why?
11. If you mix a cubic yard of a large particle like composted pine bark chips with a cubic yard of a finer particle like sand (one might do this to create a potting soil for nursery containers), you will get less than 2 total cubic yards. Why?
12. We take a 100-gram sample of soil, and sieve out all the particles larger than 2.0 millimeters, removing 15 grams. The remaining portion contains 32 grams of sand and 28 grams of silt. What texture is the soil? What percentage of the original sample was clay? From a textural view, what percentage is clay? What percentage was coarse fragments?
13. We carefully dig an evergreen out of a nursery, with the root ball intact, and insert it into a pot. If the BD of the soil is 1.2 grams per cubic centimeter, and the volume of the pot is 8 liters (8,000 cubic centimeters, about 2 gallons), what would be the weight of the soil? What moisture content of the soil does this apply to? (Hint: Consider the definition of BD.)
14. A soil sample weighs 150 grams when dry and has a volume of 107 centimeters. What is the BD and porosity of this soil? Assume a PD of 2.65 grams per cubic centimeter.
15. In the author's home state, many "hardy" shrub roses are really only partially hardy and often die back to the roots during the winter. If the roots survive, the rose will regrow and bloom that summer. Which mulch would you recommend for mulching these shrub roses: gravel, black plastic, or wood chips? Why?
16. A thinking question: Rain gardens (Figure 1–15 in Chapter 1) are becoming popular ways to intercept runoff in some cities. Designed to allow water to infiltrate quickly, they usually have a substrate of a sand–peat mix. Failure to function after a few rains has been commonly reported in areas with clay soils. Can you explain this from information in this chapter?

ENRICHMENT ACTIVITIES

1. Obtain soil samples of different known textures and practice the ribbon test. Then try to identify some unknown samples. Practice the Munsell color system on the same samples.
2. For directions for a sedimentation test, try http://www.neighborhoodlink.com/org/essi/clubextra/68869535.html. Click on Sedimentation Bottle
3. For a procedure using a hydrometer, visit the website for the International Crops Research Institute for Semi-Arid Tropics and search for "hydrometer" or try http://www.icrisat.org/what-we-do/learning-opportunities/lsu-pdfs/Soil%20Texture.pdf.
4. Try this method of measuring BD. Dig a small hole in the ground, saving the soil for later measurement. Line the hole with a plastic bag, and measure the volume of water it takes to fill the hole. Now oven-dry the soil, weigh it, and calculate BD.
5. If you don't have access to a Munsell soil page, there is a sample page for the hue 10YR at Color Chart's website: http://www.color-chart.org/munsell-color-chart.php.
6. The Soil Science Education Homepage (SSEH), designed for high school students, has good drawings and photographs of soil structure at http://soil.gsfc.nasa.gov/index.php.
7. As part of The Soil Management Series, the University of Minnesota Extension has a good publication on compaction on agricultural fields at http://www.extension.umn.edu/distribution/cropsystems/DC7400.html.
8. For urban-landscape compaction, visit the University of Florida IFAS Extension's website to read an article titled "Soil Compaction in the Urban Landscape" by Amy L. Shober and Geoffrey C. Denny: http://edis.ifas.ufl.edu/ss529.
9. Design and carry out a test to observe the effect of stoniness on water-holding capacity. Use two identical pots, some dry coarse-textured soil, gravel, and water. Record your method and results.

CHAPTER 5

Life in the Soil

TERMS TO KNOW

actinomycete
aerobic
algae
anaerobic
antagonism
arthropod
autotroph
bioremediation
carbon cycle
decomposer
denitrification
detritus
fixation
fungi
herbivore
heterotroph
humus
hyphae
immobilization
inoculation
macrofauna
mesofauna
methane
methanogenesis
microfauna
microflora
microorganism
mineralization
mycelium
mycorrhizae
nematode
nitrogen fixation
nonsymbiotic nitrogen fixation
organic matter
parasite
predator
primary consumer
primary producer
producers protozoa
rhizosphere
saprophyte
secondary consumer
solarization
symbiont
symbiosis
symbiotic nitrogen fixation

OBJECTIVES

After completing this chapter, you should be able to:

- define the carbon cycle and explain its importance
- describe the soil food web and explain its importance
- briefly describe soil organisms
- list ways that soil organisms are important
- describe how to promote populations of beneficial soil organisms

We live in a world teeming with life, yet few people know the creatures inhabiting the soil beneath our feet. Every acre of soil is home to 2 or more tons of living things (Figure 5–1). Soil results from physical, chemical, and biological forces acting on the earth's surface; the activities of biological organisms make soil be a soil, rather than, say, sand in a sandbox.

What are these organisms, and why are they so important to agriculture, horticulture, and natural ecosystems? It has been suggested that a teaspoon of fertile soil hosts thousands of separate species of such organisms. That teaspoon could contain:

- 100 nematodes
- 250,000 algae
- 300,000 amoeba
- 450,000 fungi
- 11,700,000 actinomycetes
- 100,000,000 bacteria

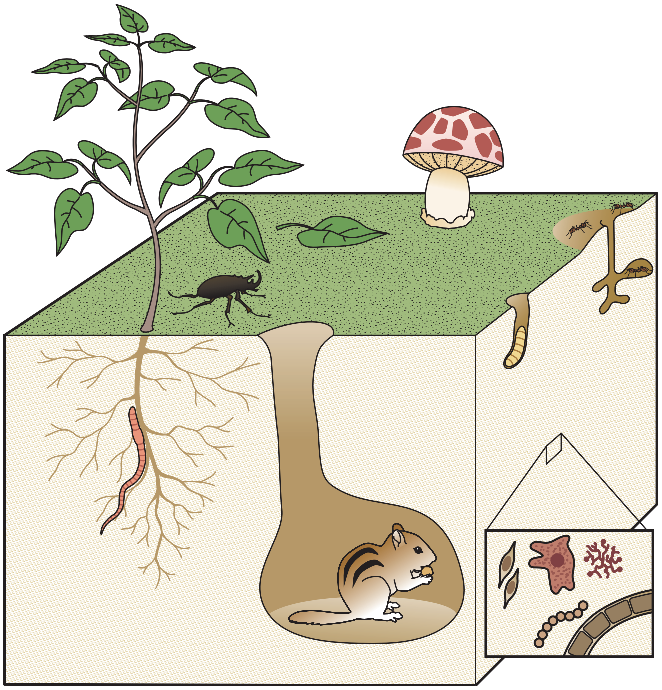


Figure 5–1
Soil teems with life. Life helps make soil the way it is. Each of the life forms drawn here will be discussed in this chapter.

We have a lot more to learn about the ecosystem that functions in the soil; numerous organisms remain to be identified. Soils host a remarkable diversity of organisms; indeed, high diversity is an indicator of soil quality. This chapter will introduce many of the organisms we know, their important functions, and how they can be managed. We begin with the soil food chain and the carbon cycle.

THE SOIL FOOD CHAIN AND CARBON CYCLE

A food chain, or food web, is a model of how food—which is to say, carbon and energy—moves from one organism to the next. All organisms are part of some food chain. Food chains operate above the ground and in the soil, and they interconnect. The base of most food chains, both above and in the soil, is photosynthesis by plants. During photosynthesis, two events occur that make life possible. First, carbon dioxide in the air is changed to organic carbon, the building block of living tissue. Second, photosynthesis converts solar energy to chemical energy stored in sugars and other energy-rich compounds. In short, photosynthesis generates the mass and energy needed by most life on the planet.

Life forms, mainly plants, that manufacture their own food and form the base of the food chain are said to be **primary producers**. Some other creatures eat the plants, and so are **primary consumers**, also known as herbivores. Above-ground examples include creatures like deer and leaf-eating insects. Predators that consume primary consumers are **secondary consumers** (such as fox and ladybeetles), and so on up the chain. Carbon and energy move up the food chain from plants to the highest level (Figure 5–2).

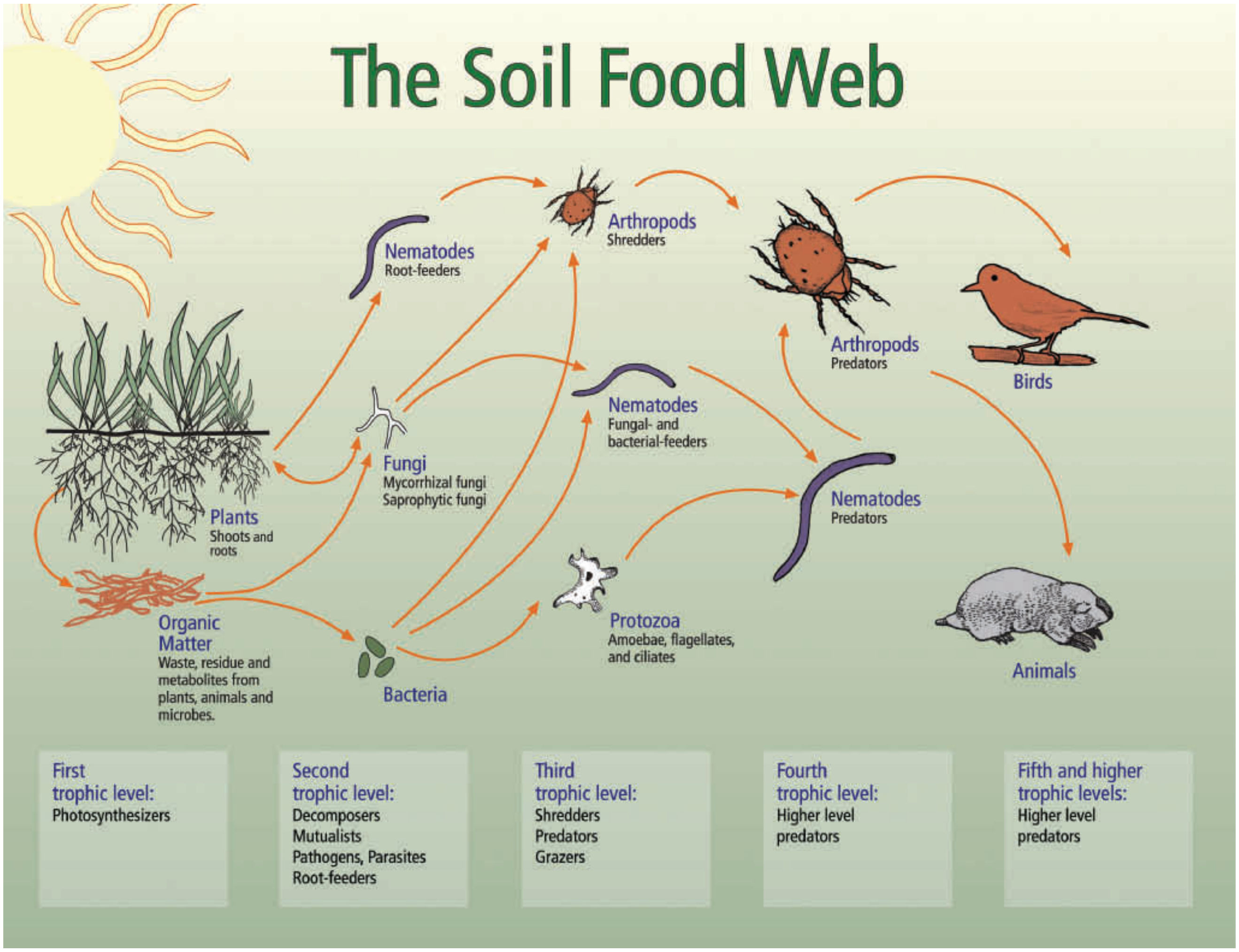


Image courtesy of USDA Natural Resources Conservation Service. Soil and Water Conservation Society (SWCS). 2000. Soil Biology Primer. Rev. Ed. Ankeny, Iowa: Soil and Water Conservation Society. Soil Biology Primer [online]. Available: soils.usda.gov/sqi/concepts/soil_biology/biology.html.

Figure 5–2

A food chain is a simplification of the food web, the total of the interactions between all the organisms in a place. It illustrates the movement of carbon and energy from the lowest level, primary producers, to the highest secondary consumers in a place. This figure shows some vocabulary for food chains and illustrates examples in the soil food web.

If the food chain contained only producers and consumers, the chain would collapse and all the world's carbon would be fixed in the bodies of dead life. This does not happen because another type of food chain breaks down and recycles dead organisms, called the detrital food chain. **Detritus** is simply dead organisms or their products, such as crop residues, fallen leaves, or animal wastes, and when it enters the soil, we call it soil organic matter. While the regular food chain is based on plants, the detrital food chain is based on detritus. The soil is the main location of the detrital food chain.

Decay organisms, or **decomposers**, consume **organic matter** as a food source, returning most of the carbon to the atmosphere as carbon dioxide by their own respiration, leaving behind a residue called **humus**. In the process, plant nutrients that were tied up in the bodies of plants and animals are released. This is the grandest function of soil life: the recycling of carbon and nutrients. If we combine both food chains, we have a grand cycle of carbon on earth, called the **carbon cycle**, shown in simplified form in Figure 5–3.

Figure 5–2 incorporates both food chains into a single picture of the soil food web, employing the technical term *trophic level.* A trophic level is a place in a food chain derived from a Greek word referring to food or feeding. So a trophic level is a "feeding" level; primary producers, for instance, occupy the first trophic level. As this chapter discusses soil organisms, refer back to this figure to see their place in the food web. High soil quality needs a robust, active food web for reasons that this chapter discusses.

In the complex ecology of the soil, there are six roles of interest to those who study soil:

- **Producers** (first trophic level) include mostly plants and a few microorganisms. They produce their own food from inorganic carbon (like carbon dioxide) by photosynthesis or by certain reactions with soil chemicals. The technical term for producers is **autotrophs**, from a Greek term meaning to supply one's own food. All other organisms are **heterotrophs**, meaning they get their food from others.

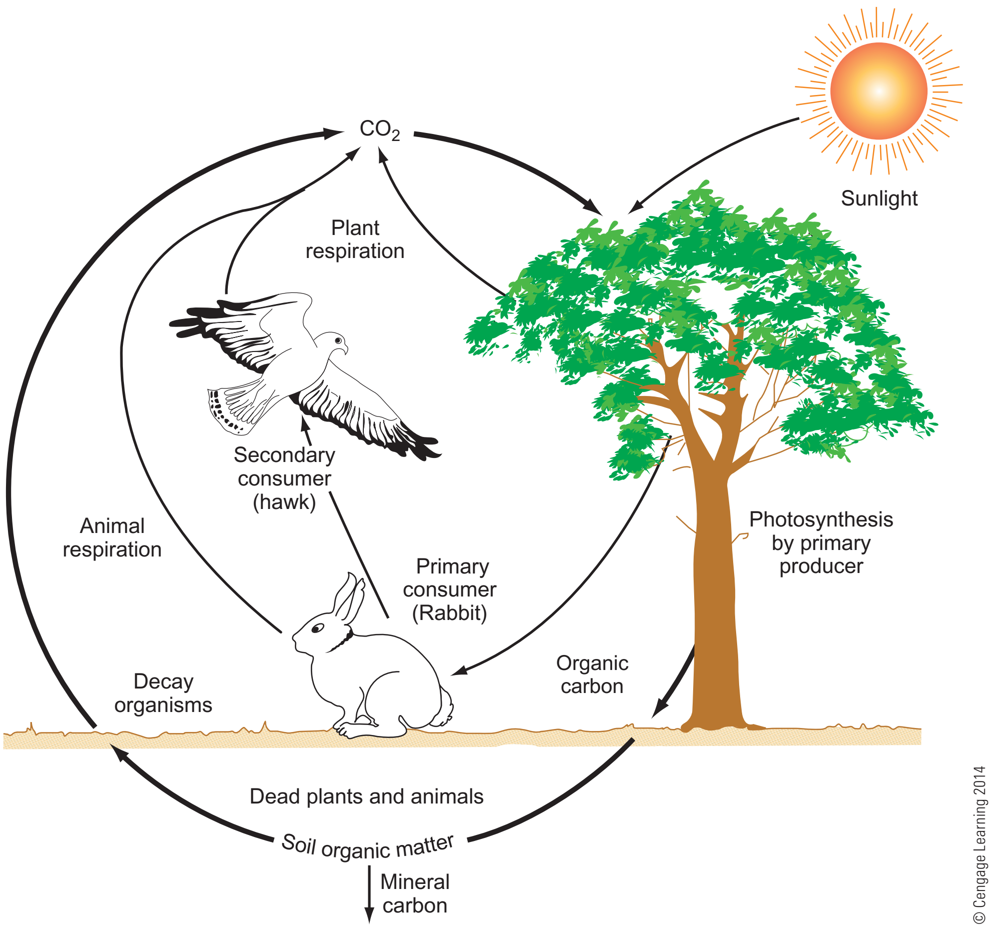


Figure 5–3
The carbon cycle begins when plants change inorganic carbon (carbon dioxide) into organic carbon in plant tissue. The cycle closes when microorganisms decompose organic matter to carbon dioxide.

- **Herbivores** (second trophic level) are animals that feed on plants. Examples in the soil could be the root-feeding nematodes pictured in Figure 5–2, or animals like pocket gophers.
- **Predators** (third and higher trophic levels) prey on other soil life. They help keep parasite populations in check and perform other functions. Predators are secondary or higher order consumers. Examples in Figure 5–2 include predatory nematodes that feed on other nematodes.
- **Parasites** are organisms that live intimately with another organism while feeding off of it. The parasite benefits; the host suffers. Examples in the soil include certain root-attacking fungi and bacteria as well as very tiny worms called nematodes. Here, parasitism is another way to operate on the second trophic level. These organisms are all responsible for plant diseases.
- **Saprophytes**, or decomposers, feed on dead organic matter. Those feeding off relatively fresh organic material can also be called *detritovores*, organisms that feed on organic detritus. Figure 5–2 pictures them as operating on the second trophic level.
- **Symbionts** are organisms that live with another organism in a partnership helpful to both (unlike parasites that injure the host). Ecologists would call this relationship "mutualism," but people who work with soils tend to use the broader term **symbiosis**.

The above list classifies organisms as to ecological function. Soil organisms can also be classified in other ways. They can be classified taxonomically, that is, as animals, plants, fungi, bacteria, and so on. They can also be classified as to their preferred environment. For instance, we call soil organisms that need oxygen **aerobic**. Aerobic organisms use oxygen in the process of consuming, or oxidizing, organic compounds; that is, oxygen is the electron acceptor in redox reactions (see Appendix 1 for discussion of redox reactions). Some bacteria need no oxygen, using other chemicals in the soil as electron acceptors. **Anaerobic** bacteria exist in low-oxygen sites, such as water-filled micropores inside soil aggregates, in all soils, but are most plentiful in poorly drained soils. Examples include the anaerobic bacteria that use ferric iron in the oxidation of organic matter, reducing it to the ferrous form that lends wet subsoils their gleyed color.

We often broadly classify soil life by a system that involves both size and taxonomy. This classification is based on the older idea that all life is either flora (plant) or fauna (animal). **Microflora** are mostly microscopic organisms that were once classified as primitive plants, including bacteria, fungi, and algae. While they have been reclassified into their own kingdoms, the category is still useful when discussing soil life. **Microfauna**, like protozoa, are microscopic organisms once considered single-celled animals, also now placed in their own kingdom. The larger, but still small **mesofauna** are multicelled animals, such as the smaller insects. **Macrofauna** are animals large enough for us to see, such as earthworms and woodchucks. Each of these categories plays a different role in the soil food chains.

Now let us examine organisms that live in the soil, beginning with microorganisms.

MICROORGANISMS

Microflora and microfauna are **microorganisms**, organisms too small to be seen with the naked eye. They are observed by soil scientists under an optical or an electron microscope. While there are other microorganisms, here we will consider bacteria, fungi, actinomycetes, algae, and microfauna.

Bacteria

Bacteria are simple, single-celled organisms that lack a nucleus; they are the most abundant inhabitants of the soil and the most numerous of the microflora. A more recently identified, similar kingdom called the Archaeae will be included here as bacteria. Common soil bacteria are rod-shaped, though many assume other shapes (Figure 5–4). They are about 1/25,000 inch wide and slightly longer. While they are single-celled, many cling together to form chains. Bacteria usually grow as small colonies on the surface of soil particles and in smaller pores. They are most dominant in nonacid, grassland, and plowed soils.

Bacteria are the most variable of soil organisms. While most are aerobic, many thrive in anaerobic soil. Most are heterotrophic, yet many obtain energy autotrophically from chemical reactions with certain soil substances.

Most soil bacteria are saprophytic. They comprise one of the groups most responsible for breaking down organic matter in the soil, especially easily decayed materials. Bacteria exude enzymes into their surroundings that break down simple compounds such as sugar and cellulose, then the bacteria absorb the products. A few species are parasites, causing plant diseases such as crown gall (*Agrobacterium tumefasciens*), which causes a tumor-like growth on roots of many plants.

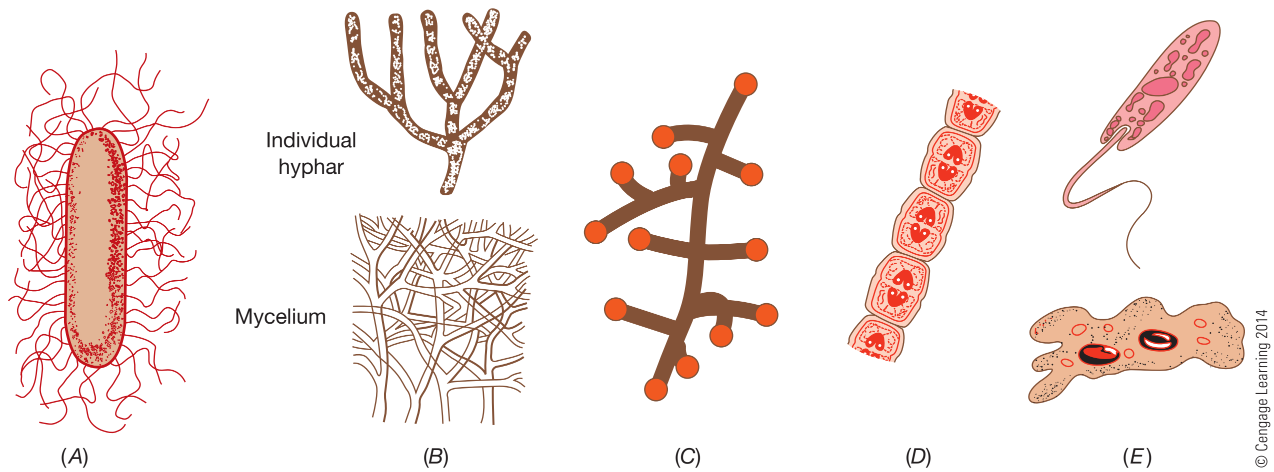


Figure 5–4

Soil microorganisms show a great diversity. (*A*) Rod-shaped bacteria with "hairs" that move the bacteria. Not all bacteria have such hairs. (*B*) Fungal mycelium, composed of individual hyphae. (*C*) An actinomycete, a bit fungal in appearance but actually a bacterium. (*D*) One form of algae. (*E*) Protozoa, including *Euglena* (top) and *Amoeba* (bottom).

Fungi

Most **fungi**, more complex multicellular organisms, resemble a mass of tangled threads, or **hyphae**, called a **mycelium**. The mycelium is the vegetative body of the fungus (Figure 5–4). Fruiting bodies grow from the mycelium. These bodies release spores that may be considered the "seeds" of fungi. Some fungi grow to become quite large—the common mushroom is a fungus. The mushroom is the fruiting body of a fungus whose hyphae feed on decaying material in soil. However, much of the fungi in the soil must be examined under a microscope, and are considered microflora.

While fungi are less numerous than bacteria, because of their larger size, they generally make up the largest microbial mass in the soil. Fungi are entirely heterotrophic and aerobic, and occupy larger pore spaces. Fungi tend to dominate in acid and forest soils. In agriculture, plowing and tillage disrupts mycelial networks and suppresses fungal population, so minimal tillage systems favor fungi.

Along with bacteria, fungi act as the main soil decomposers. Fungi can attack matter that resists breakdown, partly because hyphae can grow into the material, unlike bacteria, which can only work on the material's surface. Fungi also better attack litter on the soil surface, again partially because hyphae can grow into the litter from the soil. Fungi help create soil structure as hyphae grow through the soil.

Many fungi are plant parasites, such as the wilt fungus (*Verticillium* spp.) that attacks potatoes, several important landscape plants, and many other plant species. A group of soil fungi called "damping-off" and "root rot" fungi, such as *Rhizoctonia*, attack seeds and seedlings and cause root rot, particular problems for greenhouse and container nursery growers.

A few odd fungi are predators. For instance, certain fungi capture and consume nematodes (a microscopic worm). These fungi trap nematodes either by growing rings that can tighten around the body of a nematode (Figure 5–5) or by growing knobs covered with a sticky substance. After the nematode is trapped, hyphae grow into its body until it is consumed.

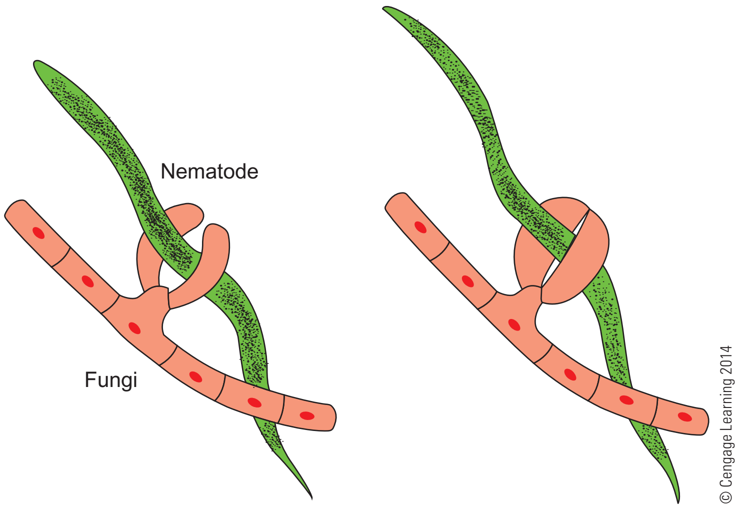


Figure 5–5
A fungal hypha is shown trapping a nematode. Once the nematode enters the ring, the ring constricts, trapping the animal. The nematode is then digested by the fungus.

Actinomycetes

Actinomycetes, also called mold bacteria, while resembling fungi in appearance, are classified as bacteria. They look like fungi because they grow a threaded network. Like fungi, actinomycetes can work on resistant organic matter. Actinomycetes are particularly tolerant of dry soil and may dominate soils after prolonged moisture stress. They also thrive in more alkaline soils or in high-temperature conditions.

Many actinomycete species produce chemicals that stop growth of other microorganisms, a phenomenon called **antagonism**. Many useful antibiotics of modern medicine derive from soil actinomycetes. In fact, the characteristic odor of damp, well-aerated soil comes from the most important genus of antibiotic-forming actinomycetes, the *Streptomyces*. In the soil, these natural antibiotics sometimes protect plant roots from attack by disease-causing organisms.

All but a few species of actinomycetes are saprophytes, though a few produce such plant diseases as potato scab (*Streptomyces scabies*).

Algae

While algae growing in water may be quite large, most soil **algae** are single-celled. Some algae are simple chlorophyll-containing plants that live in high-water environments. Others, the "blue-green algae," are actually autotrophic bacteria called *cyanobacteria*. In the soil, most live in water films. Like higher plants, algae can photosynthesize and are considered primary producers.

As producers, algae add slightly to the organic matter of soil. Certain algae combine with fungi to form lichens. Lichens growing on rocks release mild acids that dissolve minerals, adding to soil formation (Chapter 2). Blue-green algae also add nitrogen soil by a process described later.

Microfauna

The microfauna of the soil are **protozoa**, the kingdom Protista, and though they are not truly animals, we tend to think of them as simple, single-celled animals. *Amoebae* and the interesting *Euglena*, a chlorophyll-containing protozoan capable of photosynthesis, are examples (Figure 5–4). These microorganisms live in water films in the soil and are able to move about capturing prey.

Protozoa are mostly predators, and they capture their prey by engulfing them and absorbing them into their bodies. While protozoa require water to be active, they form protective bodies or cysts when conditions are unfavorable, and can survive for long periods in this inactive state.

Most protozoa graze on soil bacteria, thus playing an important role in regulating bacterial populations. They also perform a function in the release of nitrogen into the soil during organic matter decay. The bodies of bacteria are very high in nitrogen, while bacteria-grazers need less nitrogen. Protozoans and other bacteria-feeders excrete excess nitrogen as ammonium ions, a form of nitrogen immediately useful to plants.

Protozoa populations increase dramatically near plant roots in the rhizosphere, to be discussed next. Here, by feeding on bacteria interacting with plant roots, they have numerous indirect effects on plant roots.

DISTRIBUTION AND FUNCTIONS OF MICROORGANISMS

Organic matter decay is an important task of soil organisms. However, many organisms perform other tasks that also are important to agriculture; indeed, biological activity is an important indicator of soil quality. Before examining these tasks in detail, let us look at where organisms live in the soil, because their location affects their function.

Distribution in the Soil

Most microorganisms need air, water, and food to thrive. These materials are best supplied in the top 2 feet of soil, especially the A horizon. Here, organisms find the most oxygen, the most organic matter for food, good soil structure, and water storage. Thus, most soil organisms live near the soil surface (Figure 5–6), as do most plant roots.

Plant roots exude, or "leak," a variety of organic chemicals into the surrounding soil, including sugars and other organic compounds. In addition, roots slough root caps, bits of bark, and old root hairs. All this material acts as food for microorganisms, which, in response, multiply in great numbers. This area of high biological activity surrounding plant roots, called the **rhizosphere**, extends up to about 1–2 millimeters, less than an eighth of an inch, from plant roots.

The effect of the rhizosphere and the preference of microbes for the top layer of soil mean that microbe populations concentrate near plant roots. As a result, the desirable (or undesirable) activities of microbes reach their peak near plant roots—mostly to the benefit of plants. In fact, most root–soil–microbe interactions described in this text take place in the rhizosphere, which is essentially an interface zone between root and soil. In many ways, the properties of the rhizosphere can be very different than those of the surrounding bulk soil.

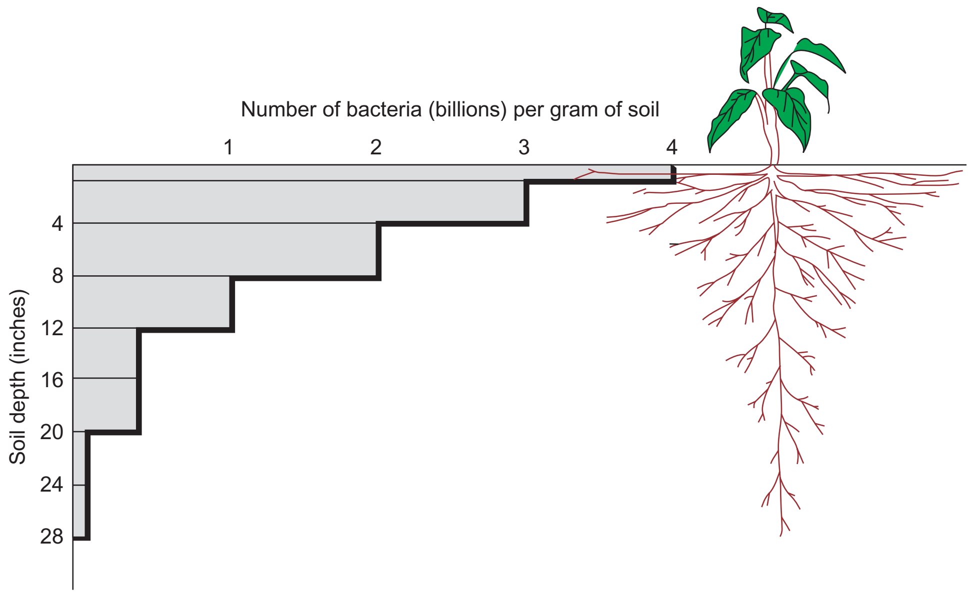


Figure 5–6
The population of bacteria decreases from a maximum near the soil surface to a minimum near the greatest soil depth for a fertile loam.

The interactions between plant roots and rhizosphere organisms can be quite dynamic and profound, even to the extent of chemical signaling between them. For instance, plant hormones exuded by a root might induce certain nearby bacteria to produce hormone mimics that in turn alter growth of the plant. Since plants expend a surprisingly large percentage of the energy they produce by photosynthesis on supporting this rhizosphere population, one assumes that on net, it must be a good investment—that is, beneficial to the plant.

From an ecological point of view, the rhizosphere can even affect the species composition of plant communities, since interactions between plant roots and the soil organisms can favor some plant species over others. Since the plant species in turn determine the animal species that live there, the rhizosphere can have far-reaching consequences in natural ecosystems.

As an aside, invasion of native ecosystems by exotic plants like the invasive shrub buckthorn (*Rhamnus cathartica*) in deciduous forests alters the soil organism population, particularly in their rhizospheres, in ways that are usually harmful to the ecosystem. Buckthorn alters the soil in numerous ways; even if the shrub is removed, its effects linger in the soil. As a further aside, rising carbon dioxide levels in the atmosphere appear to enhance movement of plant carbon into the rhizosphere, which likely will also alter rhizosphere processes in natural ecosystems over time.

Nutrient Cycling

Nutrients taken from soil by plants cannot be used by other plants, nor can chemicals in the bodies of living microorganisms, animals, or fresh organic matter. The nutrients in living bodies or fresh organic matter are said to be **immobilized**. These nutrients are bound in complex organic forms. The removal of free nutrients from the soil by soil life is said to be immobilization.

Unlike animals, plants need nutrients in simple, inorganic, ionic forms. Thus, plants cannot use immobilized nutrients until they have been changed to simple, inorganic forms by microbial decomposers. This process is called **mineralization**, and the microbes that do this are abundant in the rhizosphere. Immobilization and mineralization are opposite processes (Figure 5–7). The sulfur cycle is an example of these processes (Figure 5–8).

Most soil sulfur comes from the weathering of sulfur-containing minerals. Some of it comes from industrial pollution as sulfur dioxide in acid rain. Sulfur in minerals is changed by microorganisms in the soil to sulfate ions. Plants absorb sulfate to make protein and other compounds, thus immobilizing the sulfur. When leaves fall, they decay and soil flora mineralize the sulfur in the leaves to sulfate ions. Some sulfate is taken up again by plants, some is again immobilized in the bodies of microorganisms, and some leaches away.

The sulfur cycle shows how immobilization and mineralization lead to elements being recycled by plants and microbes. An essential element of this recycling process is the storage of nutrients for plant use. Many mineralized nutrients easily leach from soil. This loss is reduced by soil flora, which capture nutrients for their own use. When they die in the rhizosphere, the nutrients are available again to plants. Therefore, soil organic matter and life can be seen as a means of nutrient storage.

We could say that the soil food web preserves nutrients, and that unhealthy soils with an impoverished microbial population leak nutrients. This includes farm fields and gardens. In natural ecosystems, it is the recycling of nutrients through decay of organic matter that primarily defines nutrient availability and productivity of the

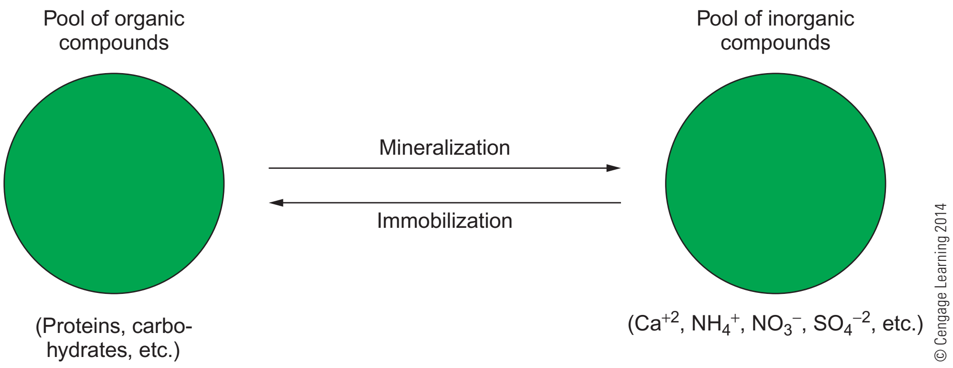


Figure 5–7

Nutrients can be viewed as occupying two pools of compounds and can pass back and forth between them. When organisms die, their parts create a pool of organic compounds. Decay mineralizes these compounds to inorganic forms. These, in turn, are taken up by plants or other organisms, and so are immobilized back into the organic pool.

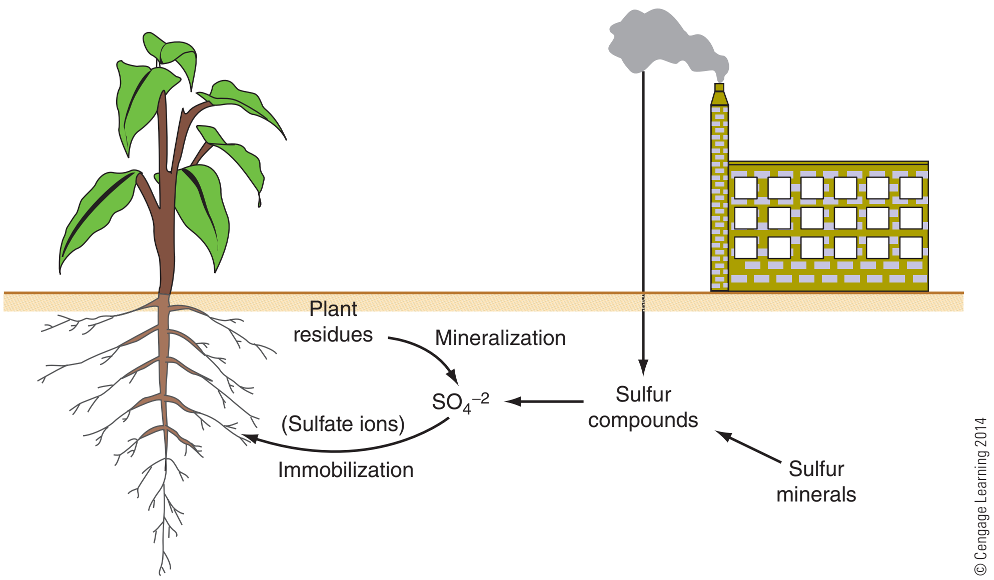


Figure 5–8

The sulfur cycle is an example of the way microorganisms recycle plant nutrients.

system. Conifer needles, for instance, decay more slowly then regular leaves, so conifer forests are less productive than hardwood forests.

Microorganisms are involved in another important cycle, the nitrogen cycle. The nitrogen cycle is covered in detail in Chapter 12, but we can look here at the role microbes play in the cycle.

Nitrogen Fixation

Nitrogen comes from nitrogen gas (N_2) in the atmosphere—approximately 34,500 tons of it over every acre of the earth's surface. Higher plants cannot use even one molecule of this nitrogen gas. However, certain bacteria, blue-green algae, and actinomycetes can use it. They absorb the gas and convert it to ammonium that plants can use. This process is called **nitrogen fixation**.

Legume plants (family *Fabaceae*), such as alfalfa and soybeans, host an important group of nitrogen-fixing bacteria in the genera *Rhizobia*, *Bradyrhizobia,* and others. The bacteria occupy the soil as free-living organisms feeding off rhizosphere carbon, but if they contact legume roots, an infection occurs. In fact, legumes in need of nitrogen exude chemicals into their rhizospheres that attract the bacteria, another example of chemical signaling between roots and microorganisms. These bacteria invade the root hairs, which respond by surrounding the bacteria with plant cells to form a lump, or nodule, on the roots (Figure 5–9). The bacteria get minerals and food from plant roots while the nitrogen it has fixed can be used by the plant, so this association is useful for both bacteria and plant. The way the bacteria gather nitrogen is thus called **symbiotic nitrogen fixation**. Up to 300 pounds of nitrogen per acre can be added to the soil yearly by the legume–*Rhizobium* association.

A number of noncrop plants also host nitrogen-fixing bacteria. A number of garden plants like lupine are legumes, and legumes are prominent members of prairie ecosystems and landscape prairies (Figure 5–9). Some trees, such as locusts (*Robinia* sp.), are also legumes. Many non-legume plants, such as alders (*Alnus* sp.), host nitrogen-fixing actinomycetes of the genus *Frankia* and cycads, often used as indoor foliage plants, host nitrogen-fixing cyanobacteria. Alders can add between 70 and 150 pounds of nitrogen per acre each year. Such trees add to the nitrogen status of woodlands and can be used to good effect in efforts to replant forests. Some have been useful in reclamation of surface mines, dumps, and other heavily disturbed areas.

A few genera of free-living bacteria (*Clostridium*, *Azotobacter*, and others) also fix nitrogen. These nonsymbiotic bacteria do not live on plant roots. **Nonsymbiotic nitrogen fixation**, for the most part, is not considered important to agriculture. Under

Image courtesy of Ed Plaster

Figure 5–9
Nitrogen-fixing nodule on the root of a blue indigo (*Baptisia australis*), a prairie legume and common garden perennial. Legumes are an important part of prairie ecosystems.

the best conditions, it adds about 40 pounds of nitrogen yearly to an acre. In some ecosystems, however, free-living bacteria may be particularly concentrated in the rhizosphere, enhancing their benefits to host plants and having a greater contribution to the plant community than one might expect.

Another interesting group of free-living nitrogen fixers is blue-green algae, an order of bacteria called *cyanobacteria*. Blue-green algae grow in aquatic environments; thus, they thrive in water films in the soil. Their small numbers in well-drained soil limit the amount of nitrogen they can add. Blue-green algae can achieve high populations in rice paddies and have been an important source of nitrogen for rice production.

Biological nitrogen fixation supplies most of the nitrogen to natural ecosystems, so it plays a particularly important role there. Prairies, for example, are largely inhabited by members of the grass (*Poaceae*), sunflower (*Asteraceae*), and legume (*Fabaceae*) families, and legumes provide most of the nitrogen (Figure 5–9).

Mineralization

The nitrogen fixed by soil microbes is, of course, immobilized in the bodies of microbes or host plants. When these die, they decay to form a pool of organic nitrogen. The nitrogen is mineralized to ammonium ions (NH_4^+), which may be absorbed by plants for growth. Protozoans and other bacteria-feeders also excrete ammonium ions as they graze on bacteria. Mineralization is a facet of decay, so conditions that promote decay promote mineralization: warmth, moisture, and high oxygen content. In fact, a traditional way to "fertilize" plants is to cultivate, which stirs oxygen into the soil, accelerates decay of soil organic matter, and stimulates a burst of mineralization to release nitrogen.

Nitrification

While plants use ammonium, most is oxidized by a group of bacteria (*Nitrosomonas*) to another form of nitrogen—nitrite ions (NO_2^-). Nitrite ions are then quickly oxidized by other bacteria (*Nitrobacter*) to nitrate ions (NO_3^-), the favored form of nitrogen for many plants. Nitrites are toxic to plants, but reside in the soil for a very short time. The net reaction of these processes looks like this:

$$NH_4^+ + 2O_2 \rightarrow NO_3^- + H_2O + 2H^+$$

Nitrification is an oxidation process that strips hydrogen off the nitrogen atom, producing lots of hydrogen ions. Because hydrogen ions make soil acid, nitrification is an acidifying process (a fact of considerable importance discussed in later chapters).

Conditions that promote the activity of the nitrifying bacteria naturally increase the rate of nitrification. These include a warm, moist, nonacid and well-aerated soil. Nitrification will be inhibited by the opposite conditions, such as cold soil below 50°F, and can also be artificially slowed by the application of chemicals called nitrification inhibitors. One might want to inhibit nitrification to slow the loss of nitrate nitrogen from the soil, a problem also discussed in later chapters.

Nitrate ions are taken up by plants or other microbes. This action completes a cycle in the soil: from living matter to organic matter to ammonium to nitrites to nitrates and back to living matter. Some nitrates, however, are changed by other bacteria to nitrogen gas again. It then escapes back to the atmosphere. This process is called **denitrification**.

Denitrification

Denitrification completes the nitrogen cycle by converting nitrate ions to nitrogen gas, which filters out of the soil. Certain anaerobic, heterotrophic bacteria use nitrate instead of oxygen to oxidize (i.e., use nitrate as an electron acceptor) organic matter during respiration. This reduces nitrates through a series of steps:

$$NO_3^- \rightarrow NO_2^- \rightarrow NO\ (gas) \rightarrow N_2O\ (gas) \rightarrow N_2\ (gas)$$

While nitrogen gas is the usual end result, intermediate nitrogen oxides also make it into the atmosphere. Nitrogen oxides are greenhouse gases some 300 times more potent than carbon dioxide in trapping heat in the atmosphere, so contribute to global climate change. They also deplete ozone in the stratosphere, a gas that intercepts harmful ultraviolet radiation. Agriculture is the biggest source of nitrogen oxides in the atmosphere: nitrous oxide emissions from fertilizer applications and other practices are said to account for about 72 percent of such emissions worldwide.

Because denitrifying bacteria are anaerobic, the process occurs most rapidly in wet soils, wetlands, or wetland agriculture such as rice paddies. Flooded soils, such as fields underwater in the spring and overly irrigated turf, lose nitrogen by denitrification to the detriment of plant growth. However, even well-drained soils have anaerobic and other oxygen-depleted sites, such as ped interiors. Denitrification rates can be high in high-nitrogen, warm, wet soils, especially those high in organic matter, the food source for the bacteria.

While denitrification may be viewed negatively as a loss of nitrogen and a contributor to global climate change, it is often promoted to "cleanse" water of nitrates. Purposeful denitrification removes nitrates from aquariums and landscape ponds to keep water clear and for the health of fish, while controlled drainage systems, constructed wetlands, and riparian filter strips (all discussed later) prevent nitrates from entering surface bodies of water and causing environmental problems.

All these nitrogen transformations make up the biological portion of the nitrogen cycle (Figure 5–10). Note that the nitrogen cycle is really two nested cycles. In the outer cycle, nitrogen enters the soil by fixation and leaves by denitrification, recycling nitrogen between the earth and air. The inner cycle recycles nitrogen inside the soil.

Soil Aggregation

Soil microbes are important agents of soil aggregation. Fungi and actinomycetes are the most effective of these organisms. First, their threadlike hyphae twine between soil particles, pulling them together to form loose aggregates. Both organisms also produce gummy substances that glue the aggregates together. These substances resist wetting, and so peds do not fall apart when they get wet. The improved strength and wetting resistance of these soil aggregates keep soil structure sound during tillage, rainfall, and irrigation. The rule that adding organic matter "loosens" clay soils results from this function of soil microbes.

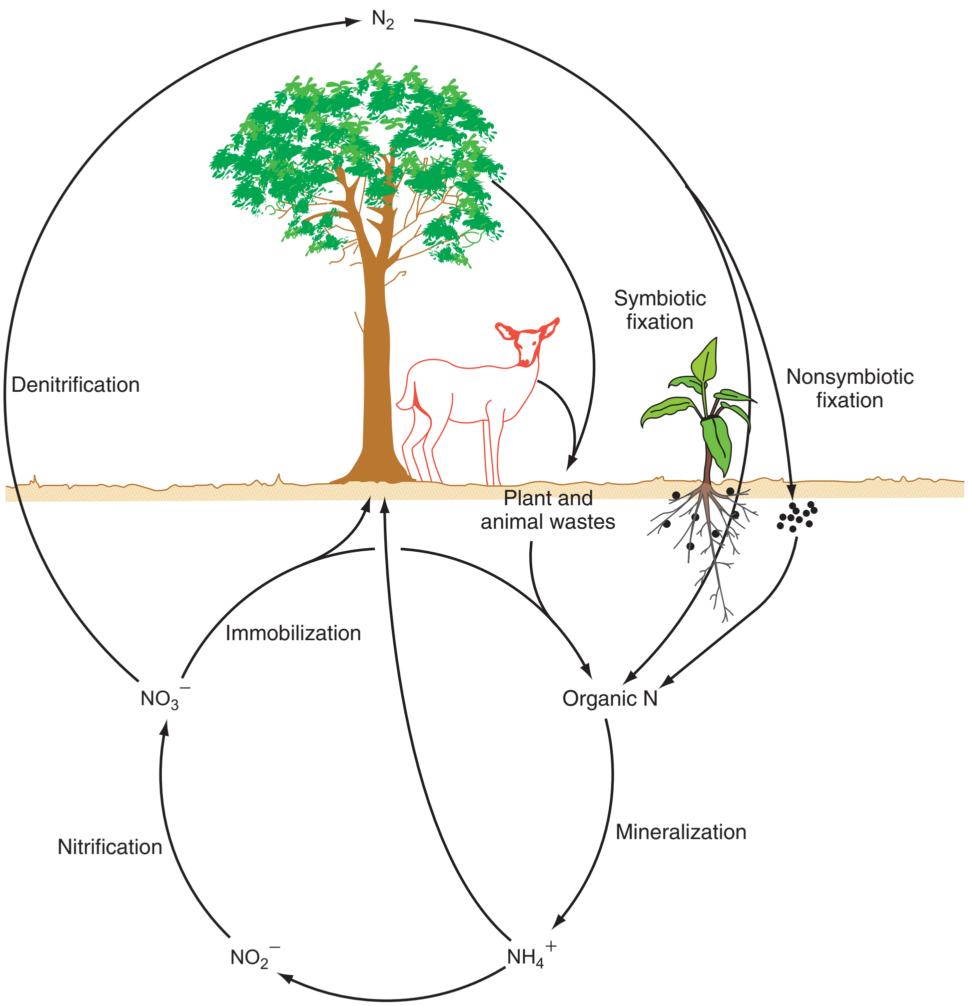


Figure 5–10
This is the core of the nitrogen cycle—natural biological transformations of nitrogen. See Figure 12–3 for the complete cycle.

Plant Growth Promotion

Some interactions of plants and microorganisms attached to their roots or occupying the rhizosphere enhance plant health and vigor. Symbiotic nitrogen fixation is an obvious example. Another example of a symbiotic relationship between plants and microbes are the fungi called **mycorrhizae**.

Mycorrhizae

Mycorrhizae are fungi that form a symbiotic relationship with plant roots, colonizing plant roots to obtain food and nutrients. In fact, infected plants shunt about 15 percent of sugars produced by leaves to their mycorrhizal symbiont. In return, the host plant gains a number of benefits:

- Roots are better able to absorb phosphorus—probably the most certain and important benefit.
- Roots are better able to absorb water, making plants more drought resistant.

- Roots are better able to absorb zinc, copper, and other nutrients.
- Infected rootlets live longer than uninfected ones.
- Some mycorrhizae protect roots from disease and probably from low levels of the toxins aluminum and heavy metals.
- Mycorrhizal fungus is particularly effective at aggregating soil particles, and so improves the physical condition of soil for plants. A complex, sticky, gooey substance, called *glomalin*, is produced by mycorrhizae that binds and protects soil aggregates.

Mycorrhizae growing on many forest trees, especially evergreens, create a thick growth, or "mantle," of fungal hyphae on the outside of the root (Figure 5–11). These fungi, called *ectomycorrhizae*, penetrate between the outer few cells of the plant root. Ectomycorrhizae, most common on woody plants, are presently used in the production of tree seedlings by artificial infection in the greenhouse. When planted in the field, these infected seedlings have better survival rates, become established

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Figure 5–11
Individual mycorrhizal hyphae grow out of the mantle into the soil, acting as efficient extensions of the host's root system. This is an example of an ectomycorrhizae.

more quickly, and grow faster than uninfected seedlings. This proves especially useful in planting heavily disturbed soils like mine tailings.

Most plants, including common crops, host mycorrhizae that grow inside root cells without forming a mantle. These fungi, called *endomycorrhizae* (the most common types are now more commonly called *arbuscular mycorrhizae*) invade plant cell walls and form associations with the cell membrane. From there hyphae extend out into the soil. These organisms most commonly associate with woody deciduous and herbaceous plants.

Both types of mycorrhizae act as extensions of the root system of the plant. Indeed, mycorrhiza means "fungus root." Hyphal strands extend from plant roots into the surrounding soil, greatly increasing the absorbing area of the root system (Figure 5–11). Because the strands are much finer than plant roots, they can grow into tinier pores than can roots. There they can forage for water, phosphorus, and other nutrients that plants cannot reach. Some mycorrhizae are also able to actively release phosphorus from insoluble sources such as organic matter and minerals. Further, it takes a lot less energy and material to make fungal hyphae than plant roots, so hyphae are more efficient to create. This function of efficiently extending the plant root system is helpful enough that most plant species form mycorrhizal associations. The root systems of infected plants, in fact, tend to be smaller than those of uninfected plants, yet explore more soil volume. The few species that do not form such associations usually posses very specialized phosphorus-absorbing root systems instead.

Two other specialized groups of mycorrhizae, while of no concern to most growers, are hosted by two specialty crops. One group, hosted specifically by orchids (family *Orchidaceae*), is an example of an obligate relationship; that is, without being infected by its fungal symbiont, orchid seeds cannot germinate nor can the plants grow. The other group infects roots of the plant family *Ericaceae*, which includes numerous important landscape plants such as rhododendron and azalea, and berries such as blueberry.

While most plant species host mycorrhizae—estimates range from 65 percent to 95 percent—the way we use soil often reduces their effectiveness. Tillage disrupts their hyphal networks, while reduced tillage systems can enhance mycorrhizal activity. Stockpiling topsoil, commonly done before construction projects, reduces infectivity as well. High phosphorus levels in soil, a common condition in farm and lawn soils because of phosphorus fertilization, suppress the growth of mycorrhizae.

Research is being done to find ways to use mycorrhizae more often in plant production. Ectomycorrhizae can be grown artificially in the laboratory. However, endomycorrhizae cannot be grown artificially, making it more difficult to produce large quantities of agriculturally important organisms. Nurseries growing forest trees often infect seedlings with mycorrhizae, and many firms now offer mycorrhizal products for a variety of landscape and other uses.

Interestingly, mycorrhizae can infect and connect neighboring plants, allowing nutrient and other transfers between the two. Even plants of different species may be connected through hyphal bridges between roots. Some species of plants, such as the forest wildflower Indian pipe (*Monotropa uniflora*), obtain food not by photosynthesis but from mycorrhizae attached to a nearby tree—the tree feeds the fungus, and the fungus feeds the Indian pipe (Figure 5–12).

Figure 5–12
The unusual forest plant Indian pipe (*Monotropa uniflora*) cannot create its own food by photosynthesis. It attaches to a certain type of mycorrhiza in the soil, which is in turn attached to a forest tree.

Plant Growth Promoting Rhizobacteria

Some rhizosphere microbes, besides those already mentioned, actively improve plant growth, and include a group called "plant growth promoting rhizobacteria." These may act by producing plant hormones and vitamins, by improving nutrient uptake, or by suppressing root disease. Some of these are now available as products that can be applied to roots and soil. These microbes need organic matter as a food source.

Breaking Down Chemicals

Fortunately for modern society, organisms inhabit the soil that can break down chemical products and refuse deposited in the soil. Chapter 1 mentioned the importance of soil in waste disposal. The cleanup of increasingly frequent oil leaks and spills is also aided by organisms that digest oil (while not soil, the Gulf oil spill of 2010 was partially cleaned up by such natural bacteria in the water). Research is identifying strains of microorganisms that are quite effective in digesting chemical wastes in soil, making possible **bioremediation**, the biological cleanup of contaminated soils.

Farms avoid a buildup of agricultural chemicals in the soil mainly because of microorganisms. While some chemicals leave the soil by leaching or by evaporation, biological decomposition is the most important means of removing chemicals. The ability of a soil to degrade a chemical depends upon the substance. Some pesticides disappear quickly, while others, such as DDT, persist in soil for years.

Interestingly, some microbes have adapted to soil chemicals so well that an herbicide or soil insecticide fails altogether because organisms break them down so fast. Until more is known, researchers suggest that where the problem has occurred, growers should use soil pesticides as little as possible, rotate crops, and rotate chemicals.

Methane Production and Absorption

Certain anaerobic organisms produce methane (CH_4) while breaking down organic matter in oxygen-free sites, a process termed **methanogenesis**. **Methane**, also known as swamp-gas, is the major component of natural gas fuel. Other aerobic soil bacteria, the *methanotrophic* bacteria, oxidize methane to carbon dioxide (CO_2) as part of their metabolism. In well-drained soils, methane may be produced in oxygen-free sites in the soil (such as ped interiors), but as the gas filters into aerobic pores, it is consumed before reaching the atmosphere. However, large areas that are entirely oxygen-free, such as wetlands, rice paddies, or landfills, can generate large amounts of methane.

While methane generation by soil microbes does not affect grower operations, it is of global concern. Methane functions as another greenhouse gas, much more potent than carbon dioxide. Atmospheric methane levels, while much lower than those of carbon dioxide, have been climbing for decades from a variety of human-made sources. Wet soils and wetland crops such as rice can be major methane generators. On the other hand, well-drained soil is the planet's main location where methane is removed from the atmosphere by methanotrophic bacteria.

It concerns climate scientists that if temperatures of the far north warm enough to start thawing tundra Gelisols, accelerated decay in these wet soils could release great amounts of methane into the atmosphere, accelerating climate change further.

MANAGING SOIL ORGANISMS

Biologic activity is an important indicator of soil quality. Not only are soil organisms key to good tilth, but failure to host a thriving population means increasing inputs like fertilizer to compensate for contributions they make to plant health. When speaking of healthy microbe populations that contribute to soil quality, we mean not only numbers of desirable organisms, but also diversity of organisms—how many different types and species of organisms are active in the soil. More diversity means more biological functions fulfilled and greater biological stability. There is evidence that soils with a rich diversity of species share some resilience to stress and disturbance.

How can we promote healthy populations? The measures to be taken fall into several broad categories: inoculating the soil with desirable organisms, improving soil conditions for the organisms, and controlling harmful organisms. Let us look at some suggestions for populating the soil with healthy numbers of beneficial organisms.

Inoculation

Inoculation is purposely infecting soil with useful organisms. As an example, there have been many attempts to speed up nonsymbiotic nitrogen fixation by soil inoculation. The market is now supplying preparations of mycorrhizae as an inoculant for landscape plants to improve transplant success. Researchers continue to explore ways to infect soil or plants with "friendly" microorganisms, but microbes introduced into a soil often do not survive in competition with or under attack from native flora.

Inoculation of legumes with *Rhizobium* bacteria, however, has long been an important farming and gardening practice. Inoculant, mixed in liquid or a peat base, can be applied to seeds or the planting furrow to ensure good nodule growth on the roots of host plants. Growers must take care to select the right strain of *Rhizobium* for the crop. Inoculants are also available for native prairie legumes, important in the increasingly common practice of planting or restoring native prairies.

Improving Soil Conditions

Improving the soil environment enhances natural populations of desirable soil microorganisms and makes the soil hospitable for those we inoculate. These improvements include supplying organic matter, improving soil conditions, and increasing variety in the field.

Supplying Organic Matter

A constant supply of fresh organic matter is needed as a food source for most soil organisms. Other factors being adequate, this is the most important factor for successful microbe populations. Organic matter comes from a variety of sources:

- Crop residues. Residues supply tons per acre of organic matter, depending on the crop, if left in the field. Residues left on the soil surface, rather than turned in, create a habitat that promotes a diverse population of organisms, and tends to favor fungi, which can more readily attack surface residues than bacteria.
- Outside sources of organic material. These can include peats, manures, composts, or sludges (see Chapter 15), as well as other locally available materials. Such materials are particularly important for urban soil users like professional gardeners, landscapers, and urban farmers.
- Cover crops. A variety of "green manures," living mulches, and other types of cover crops increase the bulk of organic materials produced in the field. Chapter 16 discusses this further.

Improving Soil Conditions

Obviously soil organisms cannot thrive unless conditions are correct. Soil microbes are sensitive to temperature, moisture, oxygen content, soil pH, and supplies of nutrients they need, and these can be managed by soil users. Good aeration supplies soil flora with the oxygen most need. While many organisms survive periods of drought by going dormant, most need moist soil to multiply and function actively. Few microbes are active below 41°F, and most grow better in much warmer soils. In cold soils, many biological activities slow, including mineralization of phosphorus and nitrification. Most organisms grow better at near neutral pH, though fungi tolerate soil acidity and actinomycetes tolerate some alkalinity. This list suggests a group of practices, or Best Management Practices (BMPs), for improving soil conditions for microbes:

- Reduced tillage. Tillage, by mixing oxygen and residues into the soil, causes an explosion of biological activity, but the food source is quickly consumed. Reducing tillage keeps a more constant food source and improves conditions for soil microbes, particularly fungi. Tillage alters soil habitat in ways that reduce the diversity of soil organisms and destroy habitat for many soil fauna. Chapter 16 describes reduced, or conservation, tillage.
- Improved drainage. Wet soils inhibit healthy microbial populations by restricting aeration. Drainage will improve the oxygen content of the soil. Chapter 9 describes drainage.
- Minimized compaction. Compaction reduces aeration and often disturbs the moisture content.
- Reduced pesticide use. The interaction of soil microbes with pesticides is complex and not thoroughly understood. Some organisms feed on a specific pesticide, and their population will rise when it is applied, while the same pesticide may be toxic to other organisms. Certainly fungicides will harm at least some soil fungi. Heavy pesticide use is likely to decrease diversity of soil microbe populations.
- Adequate nutrient, moisture, and pH levels. Soil microbes, like plants, require nutrients, which can be supplied with a variety of organic materials and fertilizers. Irrigation and lime (or where needed, some acidifying agent) maintain proper moisture and pH. Some common fertilizers have effects on salt and pH levels that may cause at least a temporary reduction in populations of some microbes. All these topics are covered in later chapters.
- Minimize fallow. Fallow is the practice of leaving the soil bare (Chapter 16) to store soil water. Organisms, such as mycorrhizae, that require association with plants most certainly suffer during fallow periods.
- Keep soil covered with mulch or plants (Figure 5–13). Chapter 4 described the effects of soil cover on soil moisture, temperature, and physical conditions; these are desirable for soil biology.

Increasing Habitat Diversity

A variety of conditions and food sources over both time—from year to year—and space—across the field, enhances diversity of organism populations. With more types of organisms, more types of things happen in the soil—more biological functions can be fulfilled. Desirable practices include:

- Crop rotation. Changing crops each year means different root systems, different rhizospheres, different residues, and different effects on the soil. This encourages a wider variety of organisms to inhabit a soil, and reduces the chances of root pathogens being carried over from year to year. Continuous row crops discourage a diverse and healthy microflora.
- Cover crops. Again, adding cover crops into a cropping system brings plant variety into the field.

Image courtesy of Ed Plaster

Figure 5–13
A "pine straw" mulch around a landscape plant in Georgia. Keeping the soil covered with a mulch promotes a healthy microbial population in the soil, one more reason to keep bare soil covered with an organic material.

- Intercropping means to grow more than one crop simultaneously in a space when both crops are meant to be harvested. An example could be rows of peas between rows of wheat. Intercropping is common in "primitive" agricultures, like the well-known corn–bean–squash intercropping of some Native American groups. It will take a lot of research to adopt intercropping to modern large-scale agriculture, but gardeners and smaller-scale growers, like urban farmers, certainly practice the option.
- Diverse landscape. That is, having more different situations on the land, including smaller fields, buffer strips, strip cropping, or even windbreaks, will bring more diversity into the cropping area.

Controlling Harmful Organisms

Part of making a soil healthy for growing desirable plants is to control harmful organisms such as plant-feeding nematodes and parasitic fungi and bacteria. In cases of severe infestation, soil may be chemically (Figure 5–14) or heat sterilized. Soil sterilant chemicals, such as methyl bromide (mostly phased from the market as an ozone-depleting chemical), are injected into the soil or washed in by irrigation. In the soil, chemical vapors penetrate pore spaces and poison soil organisms.

Pathogens may also be controlled by raising the soil temperature high enough and long enough to kill them. In greenhouses, this is typically done by steaming the soil. In the field, **solarization** may do the same. A clear plastic sheet covering the soil for several weeks during hot, sunny weather may heat the soil enough to

Image courtesy of Ed Plaster

Figure 5–14
A strawberry field in California. Here, raised beds are created, covered with plastic, and planted with berries. In the process, the beds are typically treated with a chemical sterilant to rid the soil of pathogens and weeds.

destroy undesirable organisms. Solarization works only in dependably warm, sunny climates, and may not be fully reliable even there.

Sterilizing an entire field is very expensive; therefore, the practice is reserved for high-value crops such as strawberries. In addition to the cost, sterilizing soil kills the good along with the bad. The key to controlling harmful organisms is to prevent their occurrence and to use other control methods where possible. Here are a few suggestions:

- Practice sanitation. Start with disease-free seeds and transplants, often available from seed- or plant-certification programs. Do not drag infected soil into a field on tillage equipment.
- Obey quarantines. Quarantines are intended to prevent the transportation of diseases and other pests into uninfected areas.
- Manage soil pH. For instance, potato scab is not a serious problem in acid soils.
- Rotate crops. Many pathogens decline in numbers during the years when their host crop is not being grown.
- Incorporate organic matter. Many organisms that feed on organic matter compete with, antagonize, or parasitize pathogens. Cured compost itself contains high numbers of such organisms.
- Incorporate certain plant residues. Some plant residues, such as those of members of the mustard family, contain chemicals that suppress root pathogens. Such plants may be grown in rotation or used as a cover crop.

- Use "living pesticides." A number of organisms that suppress root rot fungi are available on the market; these are most commonly used in greenhouses.
- Select varieties resistant to soil pathogens. For example, tomatoes have been bred to be resistant to a verticillium wilt and nematodes. They carry the designation VN.
- Use suppressive media in container growing. These are growing media made from materials such as certain composted bark chips that suppress soil pathogens.

Soil sterilization is a must in the greenhouse, unless media are used that contain no soil. This practice is discussed in detail in Chapter 17. Even in a greenhouse, sanitation remains one of the best defenses against soil-borne diseases.

SOIL ANIMALS

Many animals, from tiny mesofauna such as **nematodes** to larger macrofauna such as badgers, make their home in soil. Animals affect cultivated soil less than microorganisms. Undisturbed soil, which provides a better habitat than cultivated land, can be heavily changed by soil animals. In general, macrofauna function to mix and even invert the soil, as well as creating larger soil channels. Mesofauna do the same, but are also involved in the decay process by shredding raw organic matter, and contribute to soil structure. Many of the tiny structural units of soil begin as fecal pellets of mesofauna and earthworms. Let us look at some soil animals, starting with nematodes.

Nematodes

Nematodes, the dominant mesofauna, are a large and diverse group of microscopic nonsegmented worms (Figure 5–15) that occur in many habitats, but are especially numerous in soil. While microscopic, they are relatively large compared to other microscopic creatures, and tend to occupy water films in larger pores, where they can move around. Undisturbed soils in forests or grasslands support much higher populations than do agricultural soils.

Nematodes may be divided into classes based on their diet, or their place in the soil food web. The two largest groups are plant-feeders and bacteria-feeders. Plant feeders attach themselves to plant roots, and puncture plant cells with a needle-like stylet mouthpart (Figure 5–15). Bacteria-feeders graze on bacteria; their mouthpart is simply a hollow tube to suck them in.

Other nematode groups include fungi-feeders, which also pierce the fungal cell wall with a stylet, and predatory nematodes that feed on protozoa and other nematodes. A smaller group invades insect bodies, releasing bacteria that turn the insect's insides to a nutritious soup for reproducing nematodes. Several manufacturers now offer preparations of these as commercially available "living insecticides."

Growers are most concerned with plant-feeding nematodes. These animals infest plant roots, sapping plants or strength and reducing yields (Figure 5–16). The tiny puncture wounds also provide entry for other fungal or bacterial diseases. For that reason, nematode feeding is often related to infections by other soil-borne diseases. In addition, certain genera of nematodes vector plant viruses.

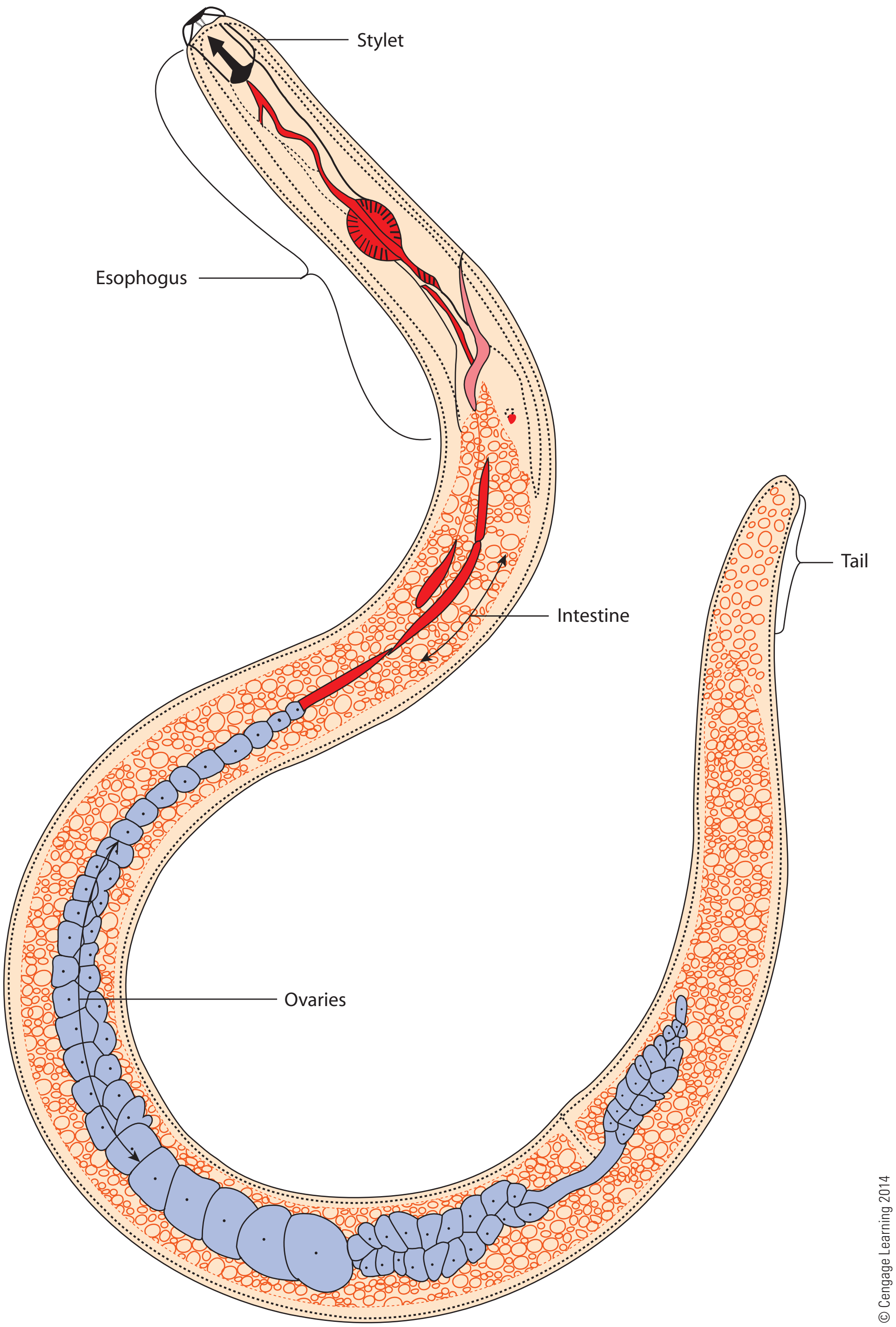

Figure 5–15
Plant parasitic nematodes are simple organisms that feed on plant roots with a needle-like mouthpart called the stylet. Feeding weakens the plant and creates minute holes in roots that can be invaded by other pathogens.

Other nematode groups may be viewed as generally beneficial, and their activity has been proposed as an indicator of soil quality. Those that prey on bacteria, fungi, or other organisms regulate the populations of their prey. However, in higher numbers, they might inhibit desirable bacterial processes and mycorrhizal infections. Like protozoa, nematodes feeding on bacteria and fungi release plant-usable ammonium nitrogen into the soil because their bodies do not need all the nitrogen the microbes provide.

Figure 5–16
The small white cysts on the roots in the lower part of the root system are soybean cyst nematodes. By feeding on plant roots, they weaken the plant and cause a poor stand in infested fields. The large nodules are nitrogen-fixing nodules.

Managing soil nematodes is much like managing other soil microbes, as discussed earlier. Frequent additions of fresh organic matter through amendments, green manures, or cover crops favor desirable nematodes over plant-feeding ones. Interestingly, a number of plants actively suppress at least some plant-feeding nematodes, including marigolds, sesame, mustard family plants such as rapeseed, and others. These may be incorporated into some cropping systems to reduce nematode problems. Crop rotations and other practices listed earlier are also helpful.

Nematode pests may also be killed by heat or chemical sterilization, as described for microbes. Pesticides, called *nematocides*, may also be applied to the soil. A word of warning, however: nematocides as a group are highly toxic to people and wildlife.

Arthropods

Mites, millipedes, centipedes, billbugs, and insects are the most common soil **arthropods**. The smallest arthropods, such as the smallest mites, are classified as mesofauna, while the readily visible ones are classified as macrofauna. Arthropods are easily recognized because they have jointed legs and a hard outside skeleton. Many arthropods, such as some mites, millipedes, and insects, are detritovores that feed on decaying organic matter and the bacteria and fungi growing on it. Such mesofauna play an important role in the decay of organic matter by shredding raw organic materials. Others, such as centipedes and some mites and insects, feed on other soil fauna. A number of arthropods feed on plant roots. June and Japanese beetle larvae, or grubs, often injure crop and turf areas by feeding on plant roots.

Ants and some termite species alter soil more than other insects by their tunneling behavior. Tunneling mixes the soil, a subject to be considered later. Ant and termite burrows also aid soil aeration.

Arthropods tend to inhabit surface litter, and will be most numerous in undisturbed soils in natural ecosystems. Tillage both reduces surface litter and directly kills many arthropods, so reduced tillage helps maintain high populations. Fallowing removes their entire food source, and essentially eradicates them, while cover cropping improves their habitat.

Earthworms

Earthworms, the dominant macrofauna of most soils, feed on organic matter and its load of fungi and bacteria. It passes through the gut of the worm, where it is worked on by bacteria resident in the gut. The digested matter is excreted as “casts,” consisting of small structural units mostly 0.5 to 2 millimeters in size. In doing so, decay and nutrient cycling is greatly accelerated and nutrients become more available to plants. The casts are rich in nutrients, especially available phosphorus, which is made soluble by bacterial enzymes. Earthworm burrows aerate the soil and both burrows and casts improve soil structure. Species of worms that feed on surface debris dramatically improve moisture infiltration by extending tunnels to the surface.

Earthworms can be classified into three broad classes based on their mode of living. Litter dwellers reside entirely in surface litter, so require a constant supply of surface litter to survive. Shallow soil dwellers live entirely in the shallow soil, digesting soil and organic matter, and in the process aerating the soil and helping to create structure. Deep soil dwellers, such as nightcrawlers, reside deep in the soil but tunnel to the surface and drag plant debris into their burrows. In the process, they create biopores open to the surface. Like the litter dwellers, these worms are detritovores.

Earthworms develop best in moist fine loams with a good supply of fresh organic matter and neutral pH. Between 200 and 1,000 pounds of earthworms may occupy an acre of soil. Earthworm populations are a visible sign of soil health, because conditions in which earthworms thrive are also good for other soil flora and fauna and plant roots.

Farming and gardening practices that promote soil organic matter levels and structure are good for earthworms. These practices include crop rotation, minimum tillage, and additions of organic matter. Tillage not only kills earthworms directly, but also buries plant litter, discouraging litter and deep dwellers. Tillage also erases the burrow openings of the deep dwellers. Liming acid soils also helps. Organic mulches benefit earthworms by providing a continuous food source, preventing rapid deep-freezing of soil in the winter, and preventing high soil temperatures in the summer.

While earthworms are beneficial in agricultural soils, they may be problematic in other settings. In lawns, earthworms prevent thatch buildup (a layer of dead and living stems and roots between green vegetation and the soil surface) by feeding on it. However, homeowners often object to casts that mar the surface of the turf, and on golf courses, casts hinder playability. Earthworms may also attract moles, whose burrows can severely damage a lawn.

Recent evidence suggests that earthworms harm northern deciduous forests. The last glacial advance eradicated earthworms in its path, so earthworms in glaciated areas are foreign, mostly from Europe and Asia. Forests of these areas developed in the absence of the worms.

Earthworms in the forest dramatically accelerate the decay of surface litter. Loss of surface litter in forests sets off a cascade of effects. By the middle of the summer, surface litter is gone, leaving only a surface of mineral soil and worm casts. This accelerates erosion. Most fine roots of young seedlings and herbaceous plants inhabit the litter; these roots dehydrate when exposed and the plant dies. Seeds of many forest species germinate in leaf duff; without it, reproduction declines drastically. Without the insulating mulch, greater temperature extremes occur in surface soils. As a consequence, while older trees survive, the forest floor is denuded of its vegetative cover of tree seedlings and herbaceous plants (Figures 5–17 and 5–18). Ultimately, as older trees die, the nature of the forest population will change radically. Many forests of northern states are struggling in response to climate change, deer browsing, and earthworm infestations.

Image courtesy of Ed Plaster

Figure 5–17

A bit of sugar maple forest in Minnesota not yet severely affected by earthworms. There is a rich ground layer of vegetation.

Image courtesy of Ed Plaster

Figure 5–18
Another section of the same forest affected by earthworms. Notice the lack of ground-layer vegetation, as well as a rapidly thinning layer of leaf duff.

Courtesy of Maurice Northrup

Figure 5–19
Prairie dogs mixed the soil of the western prairies, renewing the soil.

Mammals

Mammals affect soil by burrowing. The greatest number of burrowing mammals are rodents, such as gophers, woodchucks, and prairie dogs. Their population is highest in undisturbed soils such as pastures, forests, and prairie.

Rodent digging, like that of ants, alters soil by mixing the layers. The mixing counteracts, to some degree, the natural soil aging process in which clay particles and nutrients leach into the B horizon. Mixing has the effect of rejuvenating soil. Native prairie of the western United States, before its use as agricultural land, was continuously churned by soil-mixing activities of burrowing animals. An important part of the animal community was the prairie dog town. Prairie dog burrows extend some 5 feet into the ground. In digging the burrows, prairie dogs carried a lot of subsoil to the surface and piled it on the topsoil (Figure 5–19). As a result, subsoil was mixed with the topsoil. Soils of these areas are surprisingly high in clay.

Soil mixers, whether mammals, earthworms, or insects, modify the soil profile. Conditions that favor soil mixers tend to produce soils with a deep A horizon atop a B horizon. Conditions that do not favor soil mixers are more likely to produce shallow A horizons with an E horizon between it and the deeper B horizon.

SUMMARY

More than 2 tons of living creatures inhabit an acre of soil. An important role of microorganisms is the decay of organic matter. In this process, nutrients are returned to the soil, and the level of humus is improved. An even more essential result of decomposition is the return of carbon from plants to the atmosphere.

The most numerous soil microflora are bacteria. Most bacteria decay organic matter, though a few cause plant diseases. Important bacteria include the symbiotic nitrogen fixers *Rhizobia,* nonsymbiotic nitrogen fixers, and other bacteria involved in the nitrogen cycle. Both fungi and actinomycetes are excellent decay organisms and help preserve soil structure. Some actinomycetes fix nitrogen and some produce antibiotics. Mycorrhizae, which help plants absorb water and nutrients, are fungi. Algae add organic matter to the soil by being primary producers. Protozoans, the soil's microfauna, regulate soil bacterial populations and release plant-usable nitrogen. Microbes, by generating, absorbing, or degrading such greenhouse gases as carbon dioxide, nitrous oxide, and methane, also interact with global climate.

Most soil life occupies the surface layer of soil, where it shares space with most plant roots. Powerful interactions between numerous microorganisms and plant roots occur in the rhizosphere, a zone surrounding plant roots supported by root exudates. Rhizosphere soil differs greatly from bulk soil and rhizosphere processes profoundly affect the soil, plant growth, and even natural ecosystems.

Microorganisms need proper soil conditions to grow and multiply. The most basic requirements are a constant supply of fresh organic matter, good soil aeration, and enough moisture. The growth of organisms is further influenced by pH, nutrient levels, and warmth. Beneficial organisms can be further promoted by maintaining diversity in the field and, in some cases, inoculation of soil, seed, or roots.

Common soil mesofauna and macrofauna include nematodes, arthropods, and earthworms. Some nematodes are helpful, but growers are concerned primarily about the types that cause plant disease. Earthworms feed on fresh organic matter, making nutrients more available to plants. They also improve soil permeability and structure, but damage northern forests. The burrowing of worms, ants, and larger soil mammals mixes the soil layers. This slows the "aging" of a mature soil and helps keep it fertile.

In general, conventional tillage and plowing favors bacteria and their predators, protozoa and nematodes. Conservation tillage, with fewer or no tillage operations, leaves more residues on the soil surface and enhances populations of fungi, small insects, and earthworms.

Biological activity is an important indicator of soil quality; active and diverse populations of soil organisms improve tilth, preserve soil nutrients, and reduce inputs required of a grower. Soil biology also affects such important aspects of natural ecosystems as nutrient cycling and soil structure. Human-caused alterations in natural ecosystems that affect soil biology, such as earthworm and exotic plant invasions, can greatly alter those habitats.

REVIEW

1. How do protista and many nematodes fit into the nitrogen cycle described in this chapter? How do they fit into the detrital food chain?
2. After enjoying a day of fishing on one of the many lakes in the author's home state, you wonder what to do with leftover angleworms. Should you throw them into the nearby woods? Explain your reasoning.
3. Pocket gophers, which tunnel in the soil, eating plant roots and leaving piles of soil above ground, are considered a pest of pastures, lawns, orchards, and many other settings. Could they be considered desirable to soil? Explain.
4. Make two lists: a list of practices that promote healthy and diverse populations of living things in the soil, and a list of practices that do harm.
5. In no-till agriculture, one does not plow or cultivate the soil, and residues are left as a mulch on the surface. How might this affect earthworm populations, and would it be beneficial? (*Hint:* Think also about biopores.)
6. Is Indian pipe (Figure 5–12), mentioned in this chapter, autotrophic or heterotrophic? What plant pigment is obviously missing? How does it make its living? Does this make it an unusual plant?
7. Discuss symbiotic plant–microbe relationships described in the text and state why they are important.
8. Discuss two biological processes in the soil that might contribute to climate change. Where are they most likely to occur? How might they be avoided, if possible?
9. Describe the biological part of the nitrogen cycle.
10. Distinguish the type of mycorrhizae that would be typical of forest trees and those typical of most crops.

ENRICHMENT ACTIVITIES

1. Isolate nematodes from a soil sample and examine them under a microscope. Test kits for this purpose are available.
2. Culture soil microorganisms on an agar medium and observe them under a microscope.
3. Grow several soybeans or other legume plants in sterilized soil. Inoculate one group with the correct *Rhizobium*, but not the other. Compare the plants' growth. When the experiment is over, carefully wash soil off the roots and note the difference between the two root systems.
4. For general Web sites on soil biology, with some photography, visit the National Science and Technology Center's website on Soil Biological Communities at http://www.blm.gov/nstc/soil/index.html, or check the USDA's *Soil Biology Primer*, available in hard copy for purchase or on the Internet through NRCS' website at http://soils.usda.gov/sqi/concepts/soil_biology/biology.html.

5. The Unniversity of Minnesota Extension's website has a bulletin called "Soil Biology and Management": http://www.extension.umn.edu/ distribution/cropsystems/DC7403.html. What does it suggest as cultural practices to promote healthy microbe populations?
6. The University of Minnesota *Rhizobium* Research Laboratory's website has information on the process of inoculating legumes: http://www.rhizobium.umn.edu. Select FAQ.
7. The Dr. Fred T. Davies, Jr.'s website at Texas A&M University is a site on mycorrhiza: http://aggie-horticulture.tamu.edu/faculty/davies/research/mycorrhizae.html.
8. Mycorrhiza have been offered for improving survival and performance in landscape plants, particularly in difficult settings. The Nursery Management website discusses inoculating nursery plants for this use: https://www.nurserymanagementonline.com/nursery-0111-from-bottom-up-fertility-irrigation.aspx.
9. For an elegant story of nutrient recycling in the natural environment, comparing to the agricultural environment in the 1930s, read the elegant story "Odyssey" in Aldo Leopold's book *Sand County Almanac*, available in numerous editions in any book store. While the book was written in the 1930s, the fate of nutrient molecules has not changed all that much. Highly recommended reading.
10. A couple of good books about soil biology include *Life in the Soil: A Guide for Naturalists and Gardeners* (2007) by James Nardi, and especially for those of an organic gardening or farming bent, *Teaming with Microbes—A Gardener's Guide to the Soil Food Web* (2010) by Jeff Lowenfels and Wayne Lewis.

CHAPTER 6

Organic Matter

TERMS TO KNOW

allelopathy
amino acid
carbon–nitrogen ratio (C:N ratio)
cellulose
chelate
colloid
compost
cover crop
fibric
green manure
hemic
hemicellulose
humification
humus
labile
lignin
muck
nitrogen depression period
organic matter
organic soil
peat
prime farmland
protein
recalcitrant
sapric
starch
subsidence

OBJECTIVES

After completing this chapter, you should be able to:

- explain what organic matter is and how it forms
- describe what organic matter does in the soil
- list several ways to maintain soil organic matter
- discuss the problem of nitrogen immobilization
- define organic soil, and list its uses and problems
- discuss soil organic matter and climate

Early settlers in America cleared the woodlands of the eastern colonies to create their farms, but many of those farms were later abandoned and have since returned to forest, the original vegetation under which these soils developed. By the middle of the nineteenth century, pioneering farmers were turning over the prairie sod of the Midwest. Farming in the Midwest continued to expand until the prairie retreated to a few preserved areas.

Why could soils of the grassland better support long-term agriculture than eastern woodland soils? One difference is the high organic matter content of the prairie Mollisols (Figure 6–1) of the Midwest compared to the lower organic matter content of the Spodosols, Entisols, and Inceptisols common to many of the original colonies.

THE NATURE OF ORGANIC MATTER

Organic matter is the portion of soil that includes animal and plant remains at various stages of decay. We recognize three components of soil organic matter. First, it begins as living biota, the roots, microbes, and

Figure 6–1
Rich prairie soils of the Corn Belt, here in Iowa, are high in organic matter, lending them dark color.

other organisms that occupy soil. Second are the fragments of plant and animal remains in various stages of decay, such as fallen leaves, dead organisms, animal excretia, or crop residues. Third are the residues of active decay, organic compounds remaining in the soil that we call humus.

Chemical Makeup of Detritus

Organic matter consists of complex, carbon-containing compounds. Carbon atoms, unlike other elements, naturally form long chains. These long chains provide a framework upon which are attached other elements such as hydrogen, oxygen, nitrogen, and sulfur, to make the wide array of organic compounds necessary to life. Soil organic matter begins as detritus like fallen leaves, which largely consist of compounds such as sugars, starches, cellulose, hemicellulose, protein, fats and waxes, and lignins.

Sugars, starches, cellulose, and hemicellulose, all carbohydrates, make up the bulk of plant dry matter. Most plant sugars are short carbon chains of five or six carbons with many oxygen and hydrogen atoms attached. These sugar molecules can themselves link together to form various long chains to make more complex carbohydrates. One version is **starch**, which we consume in such foods as potatoes or bread, and acts as food storage for the plant. Another is **cellulose**, which forms various fibers, makes up the bulk of plant cell walls, and constitutes the main structural element of the plant. Humans digest cellulose poorly, so it is fiber in our diet. Wood and paper are mostly cellulose. **Hemicelluloses** are a group of several different carbohydrates of complex structure, which bind the cellulose fibers of cell walls together.

Proteins are also long chain structures made up of individual units called **amino acids**. Amino acids, unlike sugars, are rich in nitrogen and sulfur. Enzymes are protein, as is much of muscle tissue in animals. Most of the nitrogen in soil organic matter derives from protein in litter.

Fats and waxes include a variety of long carbon chains with mostly hydrogen atoms attached. Fats can be high-energy compounds in seeds and are important in cell membranes. Waxes usually coat leaves to form a protective layer and may occur in other parts of plants as well.

Lignins can be 10 percent to 30 percent of plant tissue and act as a structural component of plants. Lignins glue together cellulose fibers in cell walls to make wood, coat cellulose to protect it from microbial attack, and lend rigidity to plant tissue. They are large, highly complex molecules of almost random structure, with many rings and branches, and are resistant to attack by microorganisms, especially bacteria. Lignins contain no nitrogen.

These compounds vary in how readily they can be attacked by microbes. Sugars, amino acids, and starches make ready food sources, followed in order by protein, hemicellulose, cellulose, fats, waxes, and lignin. Easily decayed materials, such as starch, are said to be **labile**, while difficult materials, such as lignin, are **recalcitrant**. Recalcitrant materials may contain lots of decay-resistant chemicals like lignins, may be low in the nitrogen needed by microbes, or may actually contain chemicals that are toxic to decay organisms. Pine needles, for instance, resist decay because they have high lignin, low nitrogen, and are high in toxins called tannins.

The Process of Decay

Fresh detritus becomes soil organic matter by the process of decay, essentially the biological oxidation of carbon for energy. That is, microbes use organic matter as a food source, and decay is the result of microbial respiration. Decay follows a series of four overlapping steps we can call solution, fragmentation, decay, and humification.

During *solution*, free amino acids and sugars, as well as potassium and other water-soluble components, quickly dissolve out of litter into nearby soil water. Soil microbes rapidly exploit this food source and colonize the detritus (Figure 6–2).

Figure 6–2
Soil organic matter in the forest derives mostly from litter deposited on the soil surface. Here we see decay beginning, as fungi and bacteria colonize fallen leaves and shredders begin their work.

Soil meso- and macrofauna, like tiny mites and even earthworms, now *shred* the material, feeding on both the organic matter and microbes inhabiting it. This fragmentation breaks through protective lignin and wax coatings, and increases the surface area available to attack by bacteria and fungi during decay.

During *decay*, labile materials break down quickly, while recalcitrant ones do so much more slowly Complex molecules are split into smaller units and become increasingly oxidized, carbon dioxide is produced, and nutrients like nitrogen are liberated in mineralized forms.

Humification follows a different path. As decay proceeds, labile materials disappear while recalcitrant ones such as lignin remain at least partially intact. Chemical reactions occur in the soil in which soil nitrogen from the more labile protein reacts with lignin and other remains of decay to form new compounds that, like lignin, are large, highly complex, and resistant to attack but are rich in nitrogen. This material is called **humus**, the resistant residue from decay. Humification is largely a chemical, rather than biological, soil process, though microorganisms play some role. Humus is essentially constructed in the soil.

The chemical nature of humus is extremely complex; that very complexity renders it resistant to attack by fungal and bacterial enzymes. By weight, it is about 50 percent carbon and 5 percent nitrogen; it has a carbon–nitrogen ratio of about 10:1. It coats mineral soil particles, is very dark colored, and in the solid state appears as tiny particles of clay size. We recognize several classes of humus not described here. One group of lightweight humic material is water soluble; this often stains streams that flow through bogs with a tea color.

The decay process begins very rapidly, but slows over time. At first, in labile materials, half the material may decay in a week under favorable conditions, but decay slows as the supply of labile materials declines. Humus itself continues to oxidize, but this is a very slow process: about 1 percent to 3 percent of soil humus in a well-drained soil is lost annually. Because decay is mostly a biological process, it slows when soil organisms experience adverse conditions, such as pH extremes, highly salty soil, or soil that is cold, wet, or very dry. Warm, moist soil well supplied with oxygen creates favorable conditions for rapid decay.

This sequence creates soil organic matter in several different states. Material undergoing rapid decay can be called the *active fraction*. The most active part of this fraction lasts from a few weeks to a few years. It results in a slower fraction—*particulate organic matter (POM),* consisting of fine organic particles—that can persist for decades. The active fraction is most responsible for soil aggregation and nutrient recycling, and POM content can be used as a measure of soil fertility and quality.

Highly stable humus, the largest fraction of organic matter in the soil, is considered the *passive fraction*. It no longer undergoes rapid biological activity, but is largely responsible for acting as storage sites for certain nutrients, and as a chemically active colloidal material that can lightly bind plant nutrients (Chapter 10). It can persist for centuries, even thousands of years when protected by binding with clay inside soil aggregates.

The decay process just described occurs under aerobic conditions, where oxygen acts as the oxidizing agent (i.e., the electron acceptor) for microbial respiration. In waterlogged soils, there is no oxygen available, but decay proceeds using other electron acceptors such as nitrates (denitrification), ferric iron, and others. This process is much slower and gives rise to a variety of less desirable chemicals such as organic acids, methane, and the sulfides that give wet soil its rotten-egg smell. It also creates the gleyed color of wet subsoils.

Factors Affecting Organic Matter

Five major factors directly affect the amount of organic matter in the soil: vegetation, climate, soil texture, drainage, and tillage.

In well-drained upland soils, prairies generate the most soil organic matter because the extensive fibrous root systems of prairie grasses generate great quantities of underground organic material (Figure 6–3). Root masses in a humid tallgrass prairie sum between 5.8 and 7.6 tons per acre. In a North Dakota mixed prairie, growth each year generates about 1.4 tons of shoots and about 4 tons of roots. Note that in native grasslands, most of the growth is in the soil, where natural turnover of roots enriches soil organic matter.

In contrast, forests generate organic matter as litter on the soil surface (Figure 6–2). The litter decays into a thin organic layer, the O horizon, on the surface. Insects, worms, and other animals mix the material into the top few inches of soil, making a shallow, humus-rich A horizon. The needles of conifers are especially recalcitrant, so conifer forests have even less organic matter than other woods, and may have no A horizon at all.

Prairie plants also die back each year, while trees do not. This means most of a prairie plant returns to the soil each year. The differing growth of grasses and trees causes the following differences in prairies and woodlands and their soils (see Figure 6–4):

Photo courtesy of USDA Natural Resources Conservation Service

Figure 6–3
These gentlemen are examining roots of Eastern gammagrass (*Tripsacum dactyloides*) in New York. Root systems like these contribute to the deep, high organic matter soils of the prairies.

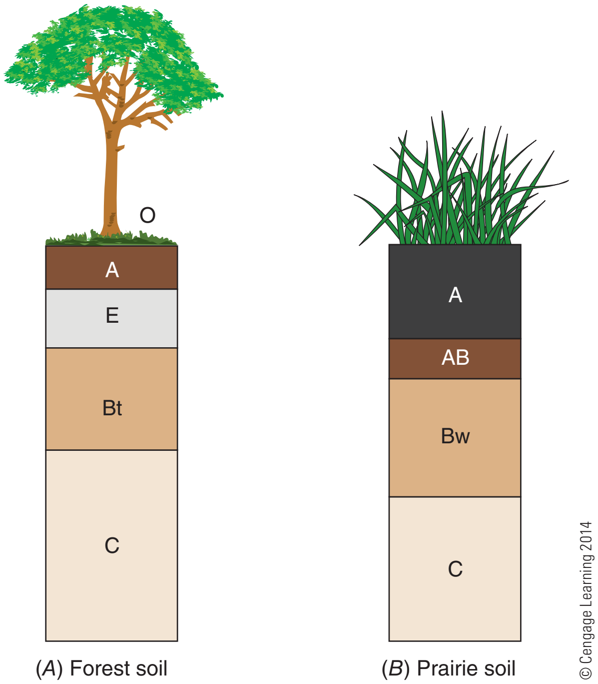

Figure 6–4
Typical soil profiles of a prairie and a forest soil. *(A)* Forest soil with a thin O horizon over a thin A horizon. The A horizon is thin because little of the litter mixes deeply into the soil. *(B)* Prairie soil has a deep A horizon because dense fibrous roots decay deeper in the soil.

- There is about twice as much organic matter in grassland soil as in an otherwise similar woodland soil.
- Organic matter extends deeper into prairie soil, because grass roots can decay deep in the soil while organic matter in forest soils comes mainly from the decay of surface litter.
- Most organic matter of the prairie is in the soil. In forests, most of the organic matter resides in standing trees.

Because soils in arid climates support little vegetation, they are lower in organic matter than either prairie or forest soils. Arid soils, unlike other soils, may gain organic matter under cultivation when irrigated. The gain results from the greater amount of green matter growing under irrigated cultivation.

Temperature and rainfall are key climatic factors that affect soil organic matter. The more rainfall there is, the greater the total amount of vegetation. Thus, soils in high-rainfall areas tend to develop more organic matter than those in drier sites. This is obscured, however, by the tendency of soils in drier climates to host grassland vegetation.

High average temperatures also promote plant growth. However, organic matter decays more rapidly at higher temperatures, so soils in warmer climates tend to contain less organic matter than those in cooler climates. As a simple guide, organic matter is generated faster than decay when soil temperatures are below 77°F (25°C), and decay almost stops below 41°F (5°C). In these cooler soils, organic matter can accumulate.

Fine-textured soils tend to have more organic matter than coarse soils such as sand. Finer soils grow a large supply of plant materials because they hold water and nutrients well. Because coarse soils are better aerated than fine-textured soils, they have a better supply of oxygen and, as a result, organic matter decay is more rapid in sandy or coarse soils. Fine-textured soils also tend to contain more organic matter because clay protects humus from further decay and because organic matter can be preserved inside anaerobic ped interiors.

Soil drainage has the most dramatic effect on soil organic matter levels. The wetter the soil is, the less oxygen is available to fuel decay and the more organic matter accumulates. The wettest soils usually have a layer of black, decaying material, an O horizon, on the surface with a very dark A horizon underneath.

Virgin soils lose organic matter when they begin to be farmed. Organic matter levels drop rapidly at first, but eventually the loss of humus slows and a new balance is reached. Loss occurs partly because erosion washes away some humus along with topsoil. Cropping usually returns less organic matter to the soil than does native vegetation. Interestingly, cultivated crops reverse the root-to-shoot ratio noted previously for grasslands. That is, crops produce far more mass above ground than roots; after harvest, less root mass is left to contribute organic matter to the soil.

Most important, tillage stirs oxygen into the soil and raises its average temperature. Tillage also tends to break down soil aggregates, which contain organic matter protected from decay organisms. In one study in the Great Plains, 42 percent of soil carbon was lost after 36 years of cultivation.

FUNCTIONS OF ORGANIC MATTER

Organic matter content can be taken as an important measure of soil quality. While there is no ideal organic content, we would say that a soil losing organic matter is losing quality, while one gaining carbon content is becoming a higher-quality soil. There are, in fact, few soil management practices so reliably beneficial as the addition of organic matter. Improvement of degraded urban soils almost always begins with the addition of organic matter.

Organic matter improves conditions of all mineral soils for many reasons. Organic matter helps sandy soils by increasing their water- and nutrient-holding capacity. It improves clay soils by loosening them and improving their tilth through the improvement in soil structure. Organic matter, of course, also feeds a variety of desirable soil oganisms. In a 2005 study, consistent applications of organic matter increased production and nutritional status of crops on sandy soils, improved soil quality, and reduced the need for fertilization.[1] This section describes these and other functions of organic matter in the soil.

Nutrient and Water Storage

Organic matter stores nutrients used by plants in two different ways. The first method of storage results from the size of humus particles. Like clay particles, humus particles are extremely small with a relatively large surface area. Particles of this size are called **colloids**. Water and nutrients cling to the large surface area of the colloids, a process described later in the text. The passive fraction of organic matter most serves this function.

[1]Ozores-Hampton, M. et al. (2005). Effects of long-term organic amendments and soil solarization on pepper and watermelon growth, yield, and soil fertility. *HortScience, 40*(1), 80–84.

Second, organic matter stores nutrients as part of its own chemical makeup, released for plant use by decay. Humus contains most of the soil's supply of nitrogen, boron, and molybdenum, about 60 percent of its phosphorus, and 80 percent of soil sulfur. Organic matter acts as a major reservoir of soil nutrients. In fact, in conventional tillage systems, tillage is a form of fertilization. Each time a field is tilled, a burst of biological activity consumes some humus, liberating nitrogen for plant growth. Before the use of nitrogen fertilizers, tillage was a major source of plant-available nitrogen, to the detriment of long-term soil quality.

Both fresh organic matter and humus absorb water like a sponge, holding about six times their own weight in water. This is extremely important in naturally dry and sandy soils. In fact, the water- and nutrient-holding capacity of organic matter is its major benefit in sandy soils.

While not nutrients, some humic compounds have been shown to stimulate root and plant growth directly. Preparations of such humic compounds are now available on the market as plant growth promoters.

Nutrient Availability

Humus not only stores nutrients, but also makes several nutrients more available for plant use. As organic matter decays it releases mild organic acids, which dissolve soil minerals, freeing them for plant use. Soil phosphorus tends to form compounds that do not dissolve in water. These forms cannot move in the soil, nor can plant roots absorb them. Organic acids act on these compounds, making phosphorus more available for plant use.

Some metallic nutrients, such as iron and zinc, react with other soil chemicals to form insoluble compounds. Certain humus molecules form a ring around the metal atom in the process called chelation (key-lay-shun). These **chelates** protect metal atoms from being locked in the soil, helping keep iron, zinc, and others more available to plants. Copper, on the other hand, is so tightly bound to humus that it is least available in high organic matter soils.

Soil Aggregation

As mentioned earlier, organic matter causes soil particles to clump together to form soil aggregates, and gummy substances produced by soil organisms bind the soil clumps. Humus particles that coat mineral particles also bind those particles together.

> Organic matter has high water-holding capacity as measured *by weight*. Because it is so light, there is not much weight to a volume of organic matter, so it does not have so high a water-holding capacity *by volume*. This can mislead individuals growing plants in containers. These growing media are often largely organic materials, and the actual weight of them in a pot can be slight. Therefore a container might be capable of holding much less water than expected. This also applies to, say, a containerized shrub planted in a yard. The soil mass holding the roots may dry out much more quickly than the surrounding soil, causing great and unexpected water stress. Such plants must be tended with care until roots grow out into the surrounding soil.

Better aggregation improves soil tilth and permeability. The soil is easier to work, is better aerated, and absorbs water more readily. Better aggregated soils also better resist compaction. This may be the most important way that heavy clay soils respond to organic matter. The active fraction of organic matter most serves this purpose.

Preventing Runoff and Erosion

Soils kept supplied with organic matter have an improved structure that greatly improves water infiltration. Because water infiltrates soils high in organic matter more quickly during rainstorms, less water runs off—water that can remove soil from the field. Data used in the Universal Soil Loss Equation (a tool for predicting erosion rates, described in Chapter 18) indicate that increasing a soil's organic matter from 1 percent to 3 percent can reduce erosion by one-third to one-fifth. An equivalent loss of organic matter would increase erosion. Because runoff and erosion carry sediments and agricultural pollutants into streams, a loss of organic matter can actually harm the surrounding environment.

Undesirable Effects

Two undesirable but temporary effects can occur during decay of fresh organic matter. The first effect is that nitrogen is tied up in the bodies of microbes during the decay process. Nitrogen is immobilized and is not available for use by plants, an effect covered in more detail later in the chapter.

A second effect is that certain plant residues are toxic to other plants. Some plants exude chemicals into their rhizospheres that inhibit the growth of other plants, and their residues will be toxic as well. The term for this toxic effect is **allelopathy**. Dead quackgrass roots, for instance, until completely decomposed, may slow the growth of crop plants. The tree black walnut (*Juglans nigra*) is famous for this, exuding a chemical called juglone into the soil. Homeowners or landscapers planting into yards containing black walnut need to consult lists of resistant plants. The invasive shrub buckthorn, mentioned in the last chapter for its damage to forests, is also allelopathic, as are its residues, challenging forest restoration projects after buckthorn removal.

MAINTAINING SOIL ORGANIC MATTER

It should be a goal of all growers to maintain organic matter at the highest practical level. Equally important is the frequent addition of fresh organic matter. It is new organic matter that provides most nourishment for soil microbes and releases nutrients rapidly.

The active fraction, most responsible for soil aggregation and plant-available nitrogen, forms a small percentage of total soil organic matter, 10 percent to 20 percent. Annual additions of organic matter readily maintain or even improve this level; on the other hand, reducing the amounts of new organic matter or intensified tillage shrink it quickly as well. Relatively small changes in the active fraction have a strong effect on soil quality, even if total soil organic matter fails to rise dramatically.

The amount of organic matter in soil depends on the balance between organic matter inputs and losses. Inputs include crop residues, manures, mulches, and others. Losses include erosion and decay. Therefore, growers should aim to maximize additions of organic matter while minimizing erosion and slowing decay.

Conservation Tillage

Moldboard plowing drastically loosens soil while burying crop residues. The sudden increase in soil oxygen accelerates the oxidation of humus, and close contact between residues, microorganisms, moisture, and oxygen stokes an explosion of rapid decay that consumes new organic matter quickly. At the same time, the bare soil that remains is exposed to erosion. The active fraction of soil organic matter, which contributes so much to soil quality, is most rapidly depleted by tillage.

Conservation tillage, especially no-till, reduces the influx of oxygen into the soil. Much of crop residue remains on the soil surface to decay slowly. Because the soil is covered with organic litter, erosion is reduced. No-till farming, which disturbs the soil and residue cover the least (Figure 6–5), has the most powerful effect. Research has shown that no-till in certain cropping systems can increase soil organic matter up to a ton per acre per year for several years, so significant improvements in organic matter content are feasible under conservation tillage.

Conservation tillage concentrates organic matter in the top few inches of soil, especially the top inch. Better soil conditions near the surface improve moisture infiltration, reduce crusting and erosion, and make nutrients available where roots are most numerous. Chapter 16 covers conventional and conservation tillage.

Crop Residues

Conserving crop residues is a simple Best Management Practice (BMP) for maintaining organic matter levels.

Photo by Tim McCabe, USDA Natural Resources Conservation Service

Figure 6–5

Arkansas no-till soybeans in wheat crop residue. Crop residue acts as a mulch and improves soil organic matter content.

Simply leaving residues in the soil is an easy way to provide organic matter. With the exception of root crops, such as carrots and nursery stock, plant roots automatically stay in the field after harvest. The aboveground parts of crops for which only the seed is harvested are also usually left in the field. Nationally, growers harvest about one-third of crop residue for feed, animal bedding, or fuel. While there may be good economic reasons for harvesting or burning crop debris, the practice results in a loss of organic materials for the soil.

Growers can increase the quantity of residues being returned to the soil by proper nutrient management. A well-fertilized crop produces a greater bulk of vegetation, both roots and tops, resulting in more organic matter for the soil. Placing more crops that yield high residue levels into a cropping system also helps. Wheat, for instance, grows twice the organic bulk of a soybean crop.

The homeowner's version of preserving residues is leaving grass clippings to decay on the lawn, rather than removing them. They decay readily and do not contribute to thatch, contrary to popular thought. As a bonus, these clippings can substitute for one lawn fertilization each year.

Green Manuring and Cover Cropping

Some vegetation is planted strictly as a soil management tool, rather than as a crop to be harvested. One management goal of these practices, among others, can be to add organic matter to the field.

Green manure may be incorporated into four broad systems of production. First is traditional green manure, planted as a main crop for later plowdown (though killing the crop and planting into it no-till works even better). This method is particularly useful to reduce erosion and weed growth on land that has been idled. Otherwise, the loss of a paying crop for one season seldom justifies the practice for most growers. However, it is a standard and important practice for nursery growers to renew organic matter between crops of trees and shrubs.

Two types of plants can be grown as green manures. Legumes such as clover or vetch are useful because, in addition to the organic matter they leave behind, the nitrogen they fix supplies later crops. To get the most bulk of organic matter at the least cost, or if nitrogen additions are undesirable, grasses such as oats or rye may be used. Sudangrass, a tropical grass that grows to 6 feet, develops the greatest amount of green matter and is particularly popular with nursery growers.

Where winter erosion is a problem, a **cover crop** may be planted in the fall after the main crop is harvested. The green cover protects soil during the fall, winter, and

Yard Recycling

Your author uses a mulching mower to recycle yard waste right in the lawn. Weeds from the garden, twigs that fall from the shade trees, and fall leaves get tossed on the lawn and chopped up finely by the mower. Chopped up finely, it degrades quickly. Why waste perfectly good organic matter, with its nutrients, by leaving it bagged on the curb?

early spring when it is most erosion prone. The cover crop is then tilled in the following spring, or even better, simply killed with an herbicide and planted into no-till. Winter rye and other winter crops work quite well for this purpose. The same practice can be applied to flower beds (Figure 6–6).

A cover crop may also be planted immediately after harvest of a rapidly maturing crop, like oats following peas in the same season. The crop could be fall-plowed. If left until the following spring, this method also provides winter protection of the soil.

Last, a cover crop may be planted between rows of the main crop. This cover is sometimes called a companion crop or living mulch. The cover crop may be planted later in the development of the main crop to reduce yield losses from competition. Again, planting no-till into the killed material the following spring increases the benefits over plowing it down.

Crop Rotation

Economic factors often cause growers to avoid rotating crops, because it means growing less profitable crops a few years. However, crop rotation improves soil humus. Studies show that continuous cropping of row crops such as corn causes the greatest decline in soil organic matter. Grains cause smaller loss, while meadow or hay legumes (e.g., alfalfa and clover) actually increase organic matter levels. Thus, a rotation of row crops, small grains, and legume hay is better than continuous cultivation of row crops.

Courtesy of Minnesota Landscape Arboretum

Figure 6–6
These gardens at the Minnesota Landscape Arboretum were planted to winter rye as a cover crop to protect the soil over winter and to grow organic matter in the soil. Cover cropping is not just for agriculture.

Organic Matter Additions

The sources of organic matter described so far are all grown in the field. Many growers or gardeners can import other organic materials into their fields, including animal manures, organic wastes, sewage sludge, or **compost**. Compost is organic material that has been allowed to decay above ground. The availability of these materials depends on the kind of operation and the presence of local organic waste producers.

Manure is an important source of both organic matter and plant nutrients. For the farming operation that both grows crops and feeds animals, manuring recycles nutrients and organic carbon on the farm. The cycle may be broken, however, if the feeding of animals and the growing of feed crops are separated, as in some large feedlot operations.

Many industries generate organic wastes that may be locally useful. Forestry by-products, such as sawdust or wood chips, may be available. Meatpacking operations and canneries also produce organic wastes. Yard and municipal wastes and sewage sludge may also be available near cities. These organic materials are usually composted before use. Because these sources can generate large amounts of compost, they are useful to landscapers and others who might want to amend soils. It has been shown, for instance, that tilling a 2-inch layer of compost into a clay soil greatly improves the establishment and growth of new sod in the landscape.

Homeowners usually have leaves, grass clippings, or other sources of organic matter in their gardens. Some gardeners compost the leaves, clippings, and even table scraps for their own use. Garden centers usually sell bagged composted manures and peat moss, both useful for the home garden. People should note that manure-based composts can be too salty for liberal applications; materials like leaf composts can be used much more freely.

Chapter 15 covers the production and use of manure, compost, and sewage sludge, the three main classes of organic amendments, in detail.

Mulches

Home gardeners often mulch their gardens by spreading straw, sawdust, wood chips, or other materials several inches deep on the ground. Landscape shrub beds, as well as newly planted trees are also often mulched with organic materials like wood chips or pine straw (Figure 5–13). As the organic matter decays during the growing season, it enriches the humus content of the top few inches of soil. Besides adding organic matter, mulches have other benefits:

- Thick mulches smother annual weeds. More aggressive perennial weeds may grow through normal mulches.
- Mulched soil absorbs water much more readily than bare soil, improving soil-water content and reducing erosion.
- Mulches limit water evaporation from the soil surface, improving the water content of the soil.
- Organic mulches moderate soil temperature.

The financial returns on typical farm crops such as corn do not justify mulching. Conservation tillage, however, does leave a mulch of crop residue on the soil surface

(Figure 6–5). Many growers mulch high-value crops such as berries or nursery stock. Mulches almost always make striking improvements in the yields of blueberries, strawberries, raspberries, and tree fruits.

Managing Soil Moisture

Any of the methods of water conservation or irrigation described in Chapters 8 and 9 increases the bulk of organic matter growing in the field. The more the green matter, the greater the amount of organic matter returned to the soil.

Maximum Cropping

As much as possible, soil should be covered with crops. Soils will be cooler, and more organic matter will be produced. Where possible, double-cropping, or the production of two crops a year, is desirable. Avoid fallowing as much as possible.

Permanent Perennial Cover

Permanent soil cover of perennial plants, particularly grasses, greatly enhances soil quality and soil carbon. While difficult to incorporate into many farming rotations as currently practiced, there is a place for this. Land being protected under the Conservation Reserve Program (Chapter 20) must be planted to such cover. Well-managed pasture is a perennial cover, as are many natural restoration projects. A new system of growing plants and crops called *permaculture* emphasizes perennial covers.

NITROGEN IMMOBILIZATION

Soil flora need both carbon and nitrogen in their diet to grow and multiply. When fresh organic matter is added to the soil—whether it be crop residues, green manure, or manure—the number of organisms rises because of the new food. These organisms may compete with crop plants for nitrogen, causing a slowing of crop growth.

The organic matter of greatest concern contains a lot of carbon compared with nitrogen. This can be measured by the **carbon–nitrogen ratio** (C:N ratio) of the material. The C:N ratio of well-rotted manure is about 20:1, meaning that there are 20 parts of carbon for each part of nitrogen. Figure 6–7 shows the C:N ratio for soil and several common organic materials. Matter with a low C:N ratio is nitrogen-rich; material with a high C:N ratio is nitrogen-poor.

Young, fresh, green matter usually has a lower C:N ratio than older and dead (brown) material. As a leaf ages, its cellulose (carbon) content rises while its protein (nitrogen) content declines. As a leaf reaches the end of its life, most of the nitrogen is translocated out of the leaf for use in other parts of the plant, so brown plant material tends to have high C:N ratios. The effect of tissue age can be seen by comparing the C:N ratios of young and mature alfalfa in Figure 6–7.

Let us see what happens when a large amount of fresh, nitrogen-poor material begins to decay in the soil. In response to the new food source, the population of decay organisms rises rapidly (Figure 6–8). Soil microflora average a low C:N ratio of about 8:1, lower for bacteria and higher for fungi, so they need to incorporate a lot of nitrogen into their bodies. Microflora feed on both carbon and nitrogen in the

Material	C:N Ratio
Soil microflora, average	8
Sewage sludge	7
Garden soil	12–15
Young alfalfa	13
Mature alfalfa	25
Compost	15–20
Rotted manure	20
Lawn clippings, fresh	31
Corn stover	60
Straw or leaves	60
Newspaper	120
Pine needles	225
Sawdust	400–600

Figure 6–7
Carbon–nitrogen (C:N) ratios of several materials. The lower the ratio, the richer its nitrogen content.

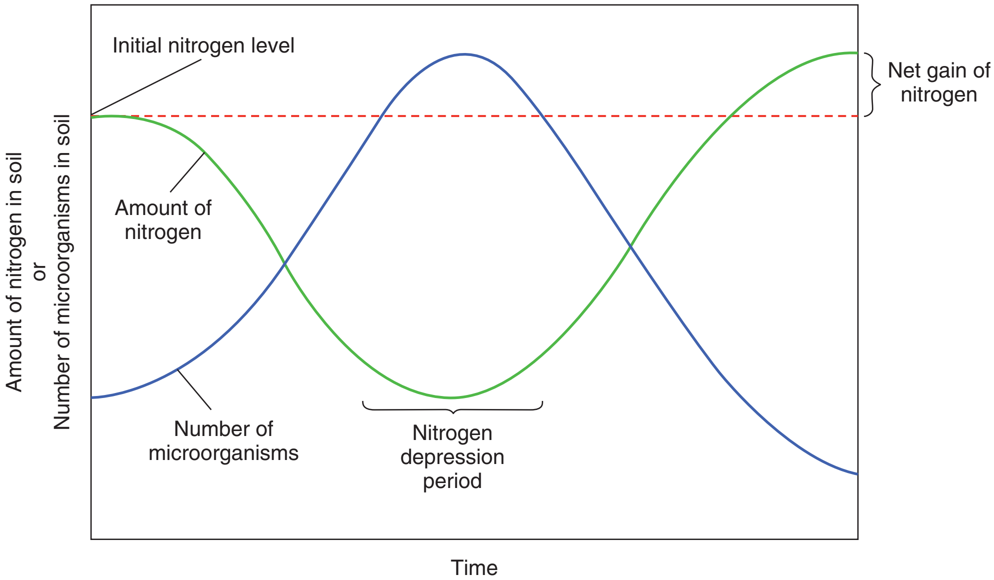

Figure 6–8
When nitrogen-poor materials begin to decay, the rising number of microbes robs soil of nitrogen. During the nitrogen depression period, nitrogen is tied up (immobilized) faster than it is released (mineralized). As decay slows, the number of organisms declines and nitrogen is released.

material, but with high-C:N materials, nitrogen is quickly used up. To make up the difference, flora draw nitrogen from the soil. In the initial stages of decay, then, soil nitrogen is rapidly tied up or immobilized.

During the period when nitrogen is being immobilized, there is a temporary loss of free nitrogen, and plants growing on the soil suffer a nitrogen shortage. Growth may slow, and plants may exhibit nitrogen shortage symptoms. This period of decay is the **nitrogen depression period**.

After a time, most of the food is used up and the process reverses. Microorganism populations decline and, when microorganisms die, the nitrogen stored in their bodies is released to the soil. In other words, nitrogen is being mineralized. When decay is complete, the net gain in soil nitrogen can be measured—the original nitrogen plus that in the new organic matter.

Nitrogen tie-up can be viewed in terms of the balance between nitrogen immobilization (which makes it unavailable) and mineralization (which makes it available). Both processes occur at the same time but not at the same rate. While soil microflora have the very low C:N ratio of 8:1, they need to take in more carbon to fuel respiration for their energy needs, and so take in material at a ratio of about 24:1. Materials with a greater C:N ratio than around 30:1 favor immobilization; those with a ratio of less than 20:1 favor mineralization. At rates between 20:1 and 30:1, the two processes roughly balance. It is therefore materials with C:N ratios higher than 30:1 that induce nitrogen immobilization.

Phosphorus, sulfur, and some other nutrients undergo a similar process when organic matter is added to soil. Nitrogen tie-up, however, produces the most noticeable effect.

Nitrogen tie-up occurs largely when low-nitrogen materials are turned into the soil and rapid decay quickly depletes nitrogen in the root zone. Organic materials lying on the soil surface—mulches and unincorporated crop residues—tie up less nitrogen because they are isolated from soil bacteria, soil water, and soil nutrients. Fungi do grow hyphae out of the soil up into surface litter, but not enough to make nitrogen immobilization a commonly serious problem.

Nitrogen tie-up can be avoided in several ways. One way is to plant after the nitrogen depression period is over—when the decay of previous crop residues is mostly complete. Another is to fertilize with enough extra nitrogen to provide for the needs of the microorganisms. For instance, if sawdust is being used to amend soil, some additional nitrogen fertilizer can be added as well. However, fertilization tends not to fully compensate for nitrogen withdrawal during decay. Minimum tillage should also reduce nitrogen tie-up because the grower leaves more residue on the surface.

Fully composting organic residues before incorporating them into the soil eliminates nitrogen tie-up. Composting ideally mixes high-carbon residues (such as dead leaves or wood chips) with high-nitrogen residues (such as manure or green grass clippings) in ways that promote rapid decay. When complete, the C:N ratio falls to about 15:1, a safe addition to the soil. Furthermore, the percentage of this organic matter that remains in the soil long term will be much higher than with typical organic materials. Chapter 15 describes the composting process in detail.

ORGANIC SOILS

So far, we have discussed the organic matter of soils whose traits are largely set by their mineral particles. These mineral soils contain only a small percentage of organic matter. Soils containing more than 20 percent to 30 percent organic matter are called **organic so ils** and are mostly classified as Histosols. These soils are much different than mineral soils. In organic soils, soil traits are set by the organic matter. Approximately 1 of every 200 acres of American soil is organic. The five states with the most organic soil are Alaska, Minnesota, Michigan, Florida, and Wisconsin.

Organic soils form in marshes, bogs, and swamps. As aquatic vegetation, such as reeds or cattails, dies each season, it sinks to the bottom. Lacking the air needed for rapid aerobic decay and oxidation, material builds up on the floor of the wetland. Eventually wetlands may be completely filled in by organic deposits reaching depths ranging from 1 foot to as much as 80 feet. Figure 6–9 shows a common organic soil profile, and Figure 6–10 shows a profile in an Irish peat bog exposed by peat cutting.

Organic soils in which plant remains are only slightly decayed are commonly called **peat**. If the deposit consists primarily of fully decayed materials, it is called **muck**. Squeezing a handful of fresh, wet soil can often tell them apart. Water that may be brown, but not muddy, squeezes out of a handful of peat. Muddy water runs out of muck. Furthermore, peat contains plant remains that are at least partially identifiable; muck does not. Soil scientists term slightly decayed plant remains **fibric**, moderately decomposed ones **hemic**, and mostly decayed materials **sapric**. Organic soil horizons carry the designation “O”, and the type of material is designated by the subscripts “i” (fibric), “e” (hemic), or “a” (sapric).

The nature of organic soils varies not only by the degree of decay, but also by the types of plants the peat derives from. Sphagnum peat forms from sphagnum moss (Figure 6–11); it is very acidic. Hypnum peat contains hypnum moss; compared to

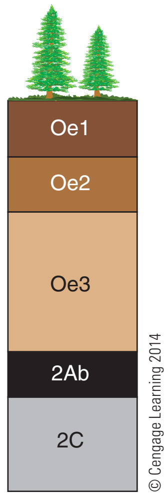

Figure 6–9
Profile of a typical organic soil formed in a black spruce–sphagnum moss bog. Growth of different types of vegetation at different periods results in the several layers of organic material shown. The lower horizons are old horizons buried by vegetation as the bog formed.

© Michael Steden/www.Shutterstock.com

Figure 6–10
Peat cutting in Connemara, Ireland. Note the layers that reflect different vegetation and conditions and different times. The browner fibric material is more suitable for horticultural peat than the blacker sapric layer.


© Gordana Sermek/www.Shutterstock.com

Figure 6–11

Sphagnum moss, the main vegetation in a sphagnum peat bog. Years of accumulation and partial decay lead to peat.

sphagnum moss, it contains more lime and nitrogen and is less acidic. Reed-sedge peat forms in marshes full of reeds and sedges; it is less acidic and more decomposed than the other types. There are also woody peats that form in wooded swamps. Mucks from marshes are also widely mixed into "black dirt" or "topsoil" (two imprecise terms often of variable and ambiguous content) sold to topdress yards before planting sod.

Organic soils are very light, porous, and loose. A cubic foot of fibric peat can weigh as little as a twentieth of a mineral soil. More decomposed types, such as sapric muck, weigh more, as do soils that have been cultivated. The heaviest organic soils may weigh about a third of mineral soils.

These soils can soak up great amounts of water. Sphagnum peat can hold 10 to 20 times its own weight in water, reed-sedge about 5 times, and cultivated mucks about twice their weight. Peats are often added to soil to improve its water-holding capacity and are almost universal amendments to potting mixes.

Before fertilization, many organic soils are quite low in plant nutrients. Muck soils are nitrogen-rich, but are generally low in phosphorus and potassium. Sphagnum peat is low in most nutrients. However, once fertilized, organic soils retain nutrients well.

Organic soils are excellent for the production of certain vegetables, including onions, celery, lettuce, carrots, and other root crops. Warm-season vegetables such as tomatoes and melons do not perform as well. Mint, hay, and turfgrass seed are also favorite crops for peats. Peats are especially valued for sod production because of easy harvest and light weight. About 700,000 acres of organic soils are planted to these specialty crops, for a gross value of about $1 billion annually.

Unfortunately, peat presents some interesting challenges. After peatland is cleared of brush and drained, exposure to air speeds decay. Soil begins to disappear, changing to carbon dioxide. Added to compaction and wind erosion, the land sinks, a process called **subsidence**. The warmer the climate, the more rapid the loss. In some parts of Florida, soils may lose as much as 2.5 inches of depth annually. And of course, since the decay process emits the greenhouse gas carbon dioxide, using peat soils contributes to global climate change.

In addition, organic soils are flammable, and peat fires are notoriously hard to put out. Being loose and light, wind carries off organic particles easily. Because peats are at low elevation, they are often frost pockets, making it difficult to grow tender plants. Last, the black soil can get so hot during warm, sunny days that young seedlings may be damaged.

The following practices can help avoid these problems:

- Design drainage systems that keep the water table as high as possible. This will reduce subsidence by decay.
- Install sprinkler systems. They can be used to control frost, cool the soil on hot days, wet soil to reduce wind erosion, or even to drench peat fires.
- Use wind erosion control techniques (see Chapter 18), but avoid tall windbreaks that reduce air movement. That increases the chance of frost and can increase soil temperature.

Harvesting Peat

Peat, mostly sphagnum peat, is harvested for two purposes: energy and horticulture. Peat is, in a sense, a precursor of coal and can be harvested and burned as a fuel source. Several European countries, most notably Finland and Ireland, harvest peat for fuel (Figure 6–10). Because of fear of ecological damage, neither Canada, which has very extensive peat deposits, nor the United States currently harvest peat for fuel.

Horticultural peat, however, is widely harvested in North America, especially in Canada, which harvested over 10 million cubic meters (close to a cubic yard) of horticultural peat in 1999. Peat, particularly sphagnum peat, possesses properties desirable for inclusion in potting mixes and as soil amendments, mulches, and shipping materials for nursery stock. The acidity of sphagnum peat lends itself well as a soil amendment for acid-loving plants such as azaleas.

To harvest peat, a bog is cleared and drained. The soil is then plowed and disked or otherwise stirred to promote drying of the surface layer. The dried peat can then be picked up and stockpiled and bagged for sale (Figure 6–12).

Of course, all commercial uses of organic soils, whether for growing, energy, or horticultural peat, present environmental challenges. Before commercial use, these were wetland ecosystems, with important ecosystem functions described in Chapter 9. Because of those functions, governments have issued regulations governing their conversion to agriculture or other human use. Peat can be a slowly renewable resource, so long as it is harvested at a low enough rate and bogs are correctly restored. However, some would argue that there is no use of peat sustainable over the long term except leaving it in place as part of the ecosystem. Partly for this reason (as well as supply shortages), most container growers have at least partially replaced peat with other materials like coconut fiber (Chapter 17).

Courtesy of Premier Tech

Figure 6–12
After preparation of the top layer of the bog for harvest, the dried moss is harvested by this giant vacuum cleaner and bagged for sale as a soil amendment.

SOIL ORGANIC MATTER AND GLOBAL CLIMATE

Let us close this chapter with the observation that soil organic matter affects not only ecosystems and growers, but also global climate itself. Soil organic matter interests climate researchers because it is one of the earth's largest reservoirs of carbon. When it decays, carbon dioxide, the main greenhouse gas, is released into the atmosphere. When more soil organic matter is created, carbon dioxide is removed from the atmosphere. Thus, the fate of soil carbon affects global climate.

If the earth warms, decay rates should speed up, releasing more carbon dioxide and increasing climate change even more. On the other hand, maybe higher carbon dioxide levels will increase plant growth, and more carbon will be returned to the soil. Unfortunately, models suggest that the former is more likely.

In the meantime, we can recognize that growers, by affecting the carbon content of their soils, actually have some influence on global climate. As mentioned in Chapter 1, as serious efforts to reduce carbon dioxide in the atmosphere begin, soil users may be asked to "grow carbon" in their soils, to increase their role in carbon sequestration. We are beginning to understand how that might work. For instance, computer modeling indicates that switching from conventional tillage to no-till might, on average, sequester 90 to 230 pounds of carbon per year per acre (0.1 to 0.26 metric tons per hectare), and reduced tillage about half that much. In the same study, switching from cropping of continuous annuals to permanent hay or pasture sequesters about 450 to 1,400 pounds of carbon per acre per year (0.5 to 1.5 metric tons per hectare).[2] The greatest potential lies in fine-textured soils that preserve soil carbon more readily than coarse-textured ones.

Two simple objectives would go a long way toward sequestering more carbon in farmland soil: manage **prime farmland** for conservation of soil carbon, and convert marginal farmland to permanent vegetative cover.

While much carbon can be stored in agricultural soils, the amount is limited. Any particular soil can hold only so much carbon. With changes in cropping practices to store carbon, soil organic matter content rises until it reaches a new equilibrium; beyond that, further increases are not practical. Furthermore, if cropping practices change again, for instance, converting Conservation Reserve Program (Chapter 20) land to corn production, the previously stored carbon reenters the atmosphere.

Histosols and Gelisols present a particular concern. Both are gigantic carbon reservoirs held in place by cold or wetness. Histosols alone contain about 20 percent of the world's soil carbon. Both climatic warming and drying could result in the release of substantial amounts of greenhouse gases such as carbon dioxide and methane. This would further accelerate climate change. Drainage of wetlands for agriculture or peat harvest presents the same possibility.

[2]Eve, M. et al. (2002). Predicted impact of management changes on soil carbon storage for each cropland region of the coterminous United States. *Journal of Soil and Water Conservation, 57*, 196–203.

SUMMARY

Detritus, the remains of plant and animal material, is made of such compounds as carbohydrates, lignins, and protein. Microorganisms decay these materials into carbon dioxide and the more resistant residue, humus. During the decay process, microbes can tie up soil nitrogen.

The amount of organic matter in soil depends on vegetation, climate, soil texture, soil drainage, and tillage. The highest organic matter mineral soils are usually virgin prairie soils formed under fairly cool, moist conditions. Forest soils and those of warm climates are lower in organic matter.

Organic matter and humus store many soil nutrients. They also improve soil structure, loosen clay soils, help prevent erosion, and improve the water- and nutrient-holding capacity of coarse or sandy soils.

Organic matter comes from crop residues, animal and green manures, compost, and other organic materials. Some residues can have allelopathic affects that hinder the growth of other plants, and improper incorporation of high-carbon organic materials can rob the soil of free nitrogen. Proper fertilization, conservation tillage, and crop rotation help preserve organic matter. Organic soils, widely used for vegetable and sod production, form under the low-oxygen conditions of a swamp or bog. Peat is light and porous, and holds water well. Once the swamp or bog is drained, however, peat slowly disappears by oxidation and wind erosion.

Because soil organic matter is a large reservoir of carbon that can feed carbon dioxide into the atmosphere or withdraw it, soil organic matter is a subject of global climate change research.

REVIEW

1. Name crops commonly grown on organic soils. Why is such a soil particularly well suited to these crops? What is likely to happen to this soil with continuous use?
2. Compare the effects on the degree of nitrogen tie-up of turning sawdust into the soil, turning alfalfa hay into the soil, and mulching with straw. Speak in terms of mineralization and immobilization.
3. Other things being equal, which would you expect to have the greatest organic matter content, clay loam or sandy loam? Why?
4. Explain the role of small insects in the decay of fresh organic matter.
5. Could no-till agriculture help reduce global warming? How about switching from grain-fed to grass-fed beef? Explain your answer.
6. Maple leaves decay more readily than oak leaves, or are more labile. Speculate on reasons why that might be.
7. Describe the full decay process whereby humus is created from fresh leaves on the forest floor. What soil horizons result?
8. How does soil organic matter affect plant growth?
9. Describe ways of using cover crops. Do you think there are benefits besides maintaining soil organic matter levels?
10. What might be the undesirable side effects of harvesting horticultural peat? For help, you can check the Internet site of the Irish Peatland Conservation Council at http://www.ipcc.ie or numerous other sites that can be found with your browser.
11. A firm that sells specialized soil amendments for landscapers, cities, and the like offers a special mix for clay soil: 35 percent composted pine bark, 25 percent compost, 20 percent peat, and 20 percent coarse sand. It recommends mixing this material 50:50 with the native clay soil. Evaluate the usefulness of this product. Would it matter if the material was not composted?

ENRICHMENT ACTIVITIES

1. Observe the effects of nitrogen tie-up by growing corn in pots using two different soil mixes. Grow one group of plants in a normal but unsterilized soil mix. Grow another group in a mix that is half fresh sawdust. Note differences in plant appearance or growth.
2. The Soil Science Society of America has a position statement on carbon storage in soils, the effects of management, and possible climatic effects. It is at https://www.soils.org/files/about-society/carbon-sequestration-paper.pdf.
3. Investigate information on peatlands using the Internet.
4. There is good information in the University of Minnesota extension bulletin in an article titled "Why Manage Soil Organic Matter?" at http://www.extension.umn.edu/distribution/cropsystems/DC7402.html.

CHAPTER 7

Soil Water

TERMS TO KNOW

adhesion
adhesion water
anaerobic
available water
capillary
capillary rise
capillary water
cohesion
cohesion water
contour
field capacity
gravitational flow
gravitational potential
gravitational water
hydrogen bond
hygroscopic water
matric potential
osmotic potential
permanent wilting point
potentiometer
preferential flow
resistance block
saturated flow
saturation
soil-moisture tension (SMT)
soil-water potential
temporary wilting point
unsaturated flow
volumetric water content
water content

OBJECTIVES

After completing this chapter, you should be able to:

- identify the role of water in plant growth
- define the forces that act on soil water
- classify types of soil water
- discuss how water moves in and over the soil
- explain how plant roots remove water from the soil
- describe how to measure soil-water content

We have all watered plants, whether it be a corn field, a home lawn, or houseplant on a windowsill. We all know that plants, above all, need water. Forget to fertilize your houseplant, it survives; forget to water, it dies. We take watering for granted without understanding what is happening in the soil. Why exactly does the water from the lawn sprinkler enter the soil, and not just puddle on top? One might answer that gravity pulls the water *down*, but then why can you water a houseplant by setting it in a pan of water, asking the water to move *up*? Does the homeowner with the sandy soil water as much or as often as the one with the clay soil in the yard?

This chapter begins a sequence of three chapters concerned with soil water. In this chapter we talk about how plants use water, how water behaves in the soil, how we can measure it, and even the shape of the water molecule—in short, the basics. The reader may want to review Appendix 1, especially the concept of a *gradient*.

HOW PLANTS USE WATER

On the average, plants consume 500 to 700 pounds of water to produce a single pound of dry plant matter; a single corn plant may absorb as much as 50 gallons of water during the growing season, a tomato plant over 30. In the author's region of the country, vast corn fields actually raise humidity of the air by their transpiration; in tropical rainforest regions, deforestation creates a drier climate because of the loss of transpired water. Obviously, most plants require very large amounts of water, and water deficiency commonly limits growth and productivity. Water availability also partly defines what plants occupy which natural ecosystems (refer to Figure 1–16). Water is vital to growers—and ecosystems—because of several functions it serves in plant growth:

- Plant cells are largely made up of water. Plant tissue is 50 percent to 90 percent water, depending upon the type of tissue.
- When plant cells are full of water, plant tissue is turgid (stiff) because of internal water pressure. This keeps stems upright and leaves expanded to receive sunlight.
- The internal water pressure causes cells to expand, promoting larger leaves, longer internodes, and rapid growth. Photosynthesis uses water as a building block in the manufacture of carbohydrates.
- Transpiration, or evaporation of water from the leaf, cools the plant.
- Plant nutrients dissolved in soil water move toward roots through the water. Water is thus important in making nutrients available to plants.
- Water carries materials such as nutrients and carbohydrates throughout the plant.
- Water is the solvent in which chemical reactions occur in the plant.
- Moist soil has lower strength than dry soil, easing root growth.
- Moisture is required for microbial activity.

Effect of Water Stress

Water stress is caused by a shortage of water in plant tissue. Stress occurs even at moisture levels that do not cause wilting because as soil dries, it becomes increasingly difficult for a plant to absorb moisture. As the plant becomes deficient in water, guard cells begin to close stomata, slowing exchange of oxygen and carbon dioxide. Reduced exchange of the two gases slows photosynthesis and plant growth is inhibited.

As soil dries further, the plant becomes even more water deficient. The plant begins to lose water faster than it can be absorbed and it temporarily wilts. At this **temporary wilting point**, the plant recovers when conditions improve. Wetter soil, cooler temperatures, a more humid atmosphere, shade, or less wind help the plant recover. Although the plant recovers, episodes of water stress reduce growth and yields. With further drying, soil becomes too dry for the plant to access any water, and the **permanent wilting point** is reached. Now the plant will not recover even if conditions improve. Note that the permanent wilting point is simply a function of soil, while the temporary wilting point occurs when one plant process (transpiration) exceeds another (water absorption).

Plants suffering from chronic water stress exhibit a variety of symptoms, including small, poorly colored leaves, loss of leaf turgor, and reduced growth. Old leaves often turn yellow and drop off. Some plants show specific symptoms of water stress.

For example, the leaves of corn plants curl when they need water, and the leaves of sugar maple trees scorch. Water stress can dispose plants to other stresses and problems. For example, the combination of dry soil and humid air leads to powdery mildew infections in plants such as garden phlox (*Phlox paniculata*).

Seed germination is very sensitive to water shortage. While seeds efficiently absorb moisture through the seed coat, the emerging seedling is easily injured by dry soil.

Effect of Excess Water

Excess moisture displaces air from soil pores. While small amounts of oxygen are dissolved in water, it is quickly used up by soil organisms. While oxygen can diffuse through water-filled pores, it does so about 10,000 times more slowly than through air-filled pores, so wet soil rapidly becomes oxygen deficient, or **anaerobic**.

Plant roots require oxygen for respiration. Roots lacking oxygen fail to take up water and nutrients properly, so plants growing in wet soil often exhibit symptoms of nutrient deficiency or even wilt. Fungal diseases attack the damaged roots, causing root rot. Carbon dioxide and toxic materials often build up in the soil, further damaging roots. Symptoms of overwatering can resemble those of underwatering, but it is slower to develop, and often more difficult to recognize and treat.

Plant species vary in their tolerance of soil saturation. Wetland plants possess adaptations to soil wetness, while others, such as tomato, may die within a few hours of "wet feet." The common landscape yew is so sensitive to wet soil that it should never be placed where there is any question about drainage—like next to a downspout from the gutters.

Greenhouse growers are particularly concerned about water. Root rots and a small fly called fungus gnat easily make their home in pots that are too damp, and the excess water available to the plant stretches the cells to cause long internodes and large leaves; put another way, the plant stretches. Many greenhouse operators "grow dry"— keeping the plant on the dry side to prevent root rots and stretch, decreasing the need for pesticides and growth regulators.

FORCES ON SOIL WATER

A number of forces influence the way water behaves in the soil. The most obvious is gravitational force, which pulls water down through the soil. Other forces, called adhesion and cohesion, work against gravity to hold water in the soil. **Adhesion** is the attraction of soil water to soil particles, while **cohesion** is the attraction of water molecules to other water molecules.

Adhesion and cohesion result from the shape of the water molecule and the way an electron is shared in the oxygen–hydrogen bond. Examine the two water molecules pictured in Figure 7–1. Hydrogen consists of one proton and one electron. Each hydrogen shares its one electron with the oxygen atom. Each shared electron tends to sit between the oxygen and hydrogen atoms, leaving the positively charged protons positioned on one side of the molecule. As a result, that side has a slightly positive charge, while the oxygen side assumes a slightly negative charge. The water molecule is then like a bar magnet—positive on one end, negative on the other. We call such a molecule a polar molecule, one with a charge separation between the two ends. Like bar magnets, the opposite ends of water molecules attract.

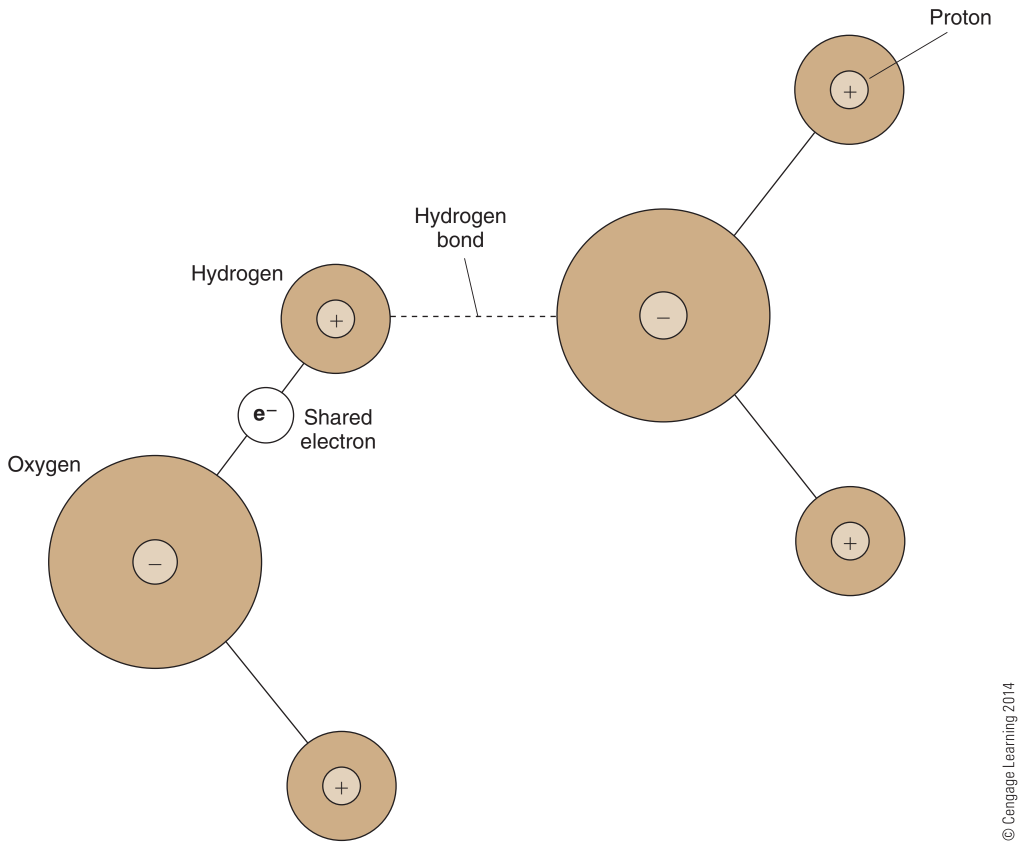

Figure 7–1
Two water molecules attract because the electrical charge is unequally distributed. The "plus" side of one molecule attracts the "minus" side of another, forming a hydrogen bond. This is cohesion.

The bond between the hydrogen of one water molecule and the oxygen of another, called a **hydrogen bond**, accounts for cohesion. Hydrogen bonding also accounts for adhesion. The main chemical in soil minerals is silica (quartz is pure silica). Silica, with the chemical formula SiO_2, has oxygen atoms on its surface that can form hydrogen bonds with soil water.

Together, adhesion and cohesion create a film of water around soil particles. The film has two parts. A thin inner film is held tightly by adhesion. **Adhesion water** is held so tightly that it cannot move. A thicker outer film of water is held in place by cohesion to the inner film. **Cohesion water**, or **capillary water**, is held more loosely, can move in the soil, and some can be absorbed by plants. Thus, plants use cohesion water that is clinging loosely to soil particles.

Capillarity

Soil water exists in small spaces in soil as a film around soil particles. The small pores can act as capillaries. A **capillary** is a very thin tube in which a liquid can move against the force of gravity, as shown in Figure 7–2. Water is attracted to the glass tube by adhesion so a thin film flows up the side of the tube, while cohesion drags more water along. The liquid rises to the point where gravity balances the adhesive and cohesive forces. The narrower the tube, the higher the water column can rise.

Capillary action, the additive effect of adhesion and cohesion, holds soil water in small pores against the force of gravity. The fact that soil water can move in

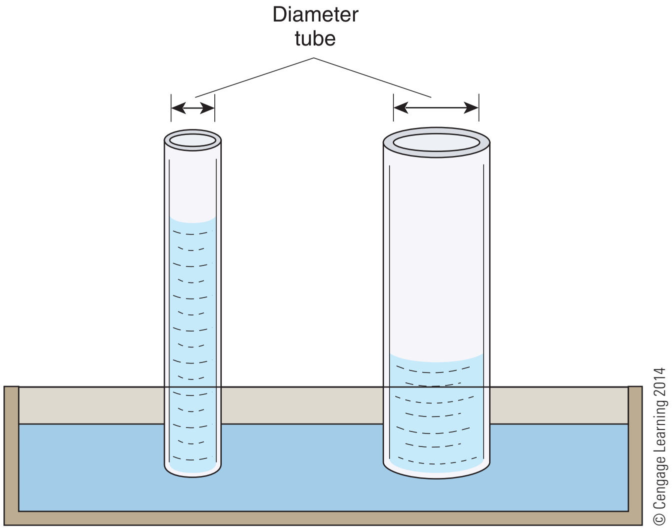

Figure 7–2
Capillary action is shown by movement of water upward against gravity in a capillary tube. The water rises because it is attracted to the glass by adhesion. The thinner the tube, the higher the water column rises. Soil pores can act as capillaries.

directions other than straight down is also due to capillary action, which also explains why you can water a potted plant from below. The smaller the pores, the greater (though slower) that movement can be.

Soil-Water Potential

Plants obtain moisture by drawing off water from films surrounding soil particles. The difficulty of the process depends on the strength of the force attracting water molecules to soil particles. Until recently, this force was measured by the **soil-moisture tension (SMT)**, which stated how much "suction" is required to pull the water away from the soil particles.

Currently, **soil-water potential** is the concept used to measure soil-water forces. Soil-water potential, which is just another way to express the forces measured by SMT, is defined as the work water can do when it moves from its present state to a pool of pure water in a defined reference state, which is assigned a potential value of zero. More simply, one can think of potential as the tendency of water to flow or move freely in the soil; the higher the water potential, the more freely it can move. The more freely it can move, the more available it is to plants.

Potential is a measure of the water's potential energy, its ability to "do work" by movement. As is the rule of energy behavior, water tends to move toward a lower energy state, or to decrease its potential. This rule dictates the behavior of water in the soil.

We can view water potential as the *relative* energy of water in a certain location compared to water in another. This is true whether we speak of water in a plant cell, in soil pore spaces, as vapor in the atmosphere, or even in cells of the reader's body. Water moves from locations of high potential to locations of low potential, from wetter to drier.

Consider raindrops falling on a dry soil. This water is capable of great movement, so has high potential. Infiltration occurs because water will readily move to a state of lower potential—and this occurs when free water enters a pore at the soil surface.

An important point about the soil-water potential concept is that what matters to a plant is not so much the *amount* of water in the soil as it is the *energy*, or potential, of that water. Potential is a measure of work the plant will have to do to extract water from the soil. While the amount of water in the soil partly defines its potential, so do other factors such as pore size and soil salt content. The consequences of this point will become apparent in this chapter.

Now consider a water molecule located far from a soil particle (Figure 7–3). At this distance, forces attracting the molecule to the particle (adhesion and cohesion) are weak, and the water molecule can move relatively freely. It has a high water potential. Compare this to a water molecule very close to a soil particle, perhaps in a tiny pore. The attractive force at this distance is very strong, and the water molecule is fixed tightly in place. It has low potential. In small pores, all the water is near a soil particle and is thus at relatively low potential; in larger pores, some water can be farther away and therefore be at higher potential. *The lower the soil-water potential, the more tightly water is attracted to soil particles and the less freely it can move.*

Soil-water potential consists of the sum of several separate forces. Three of these are sufficiently important to discuss here. In most soils, the main force is the one just described, the **matric potential**, the potential that results from the attraction of water to soil particles. Matric potential is always a negative value because of the definition of potential. Adsorbed water has less ability to do work than free water in a pool, which is defined as zero potential. Rather than being able to do work, work must be applied to adsorbed water to move it.

A second force is the **gravitational potential**. Soil water is elevated above the water table and so carries potential energy from gravity. To achieve a lower energy state, water simply percolates through the soil to a lower elevation. Gravitational potential is usually a positive value.

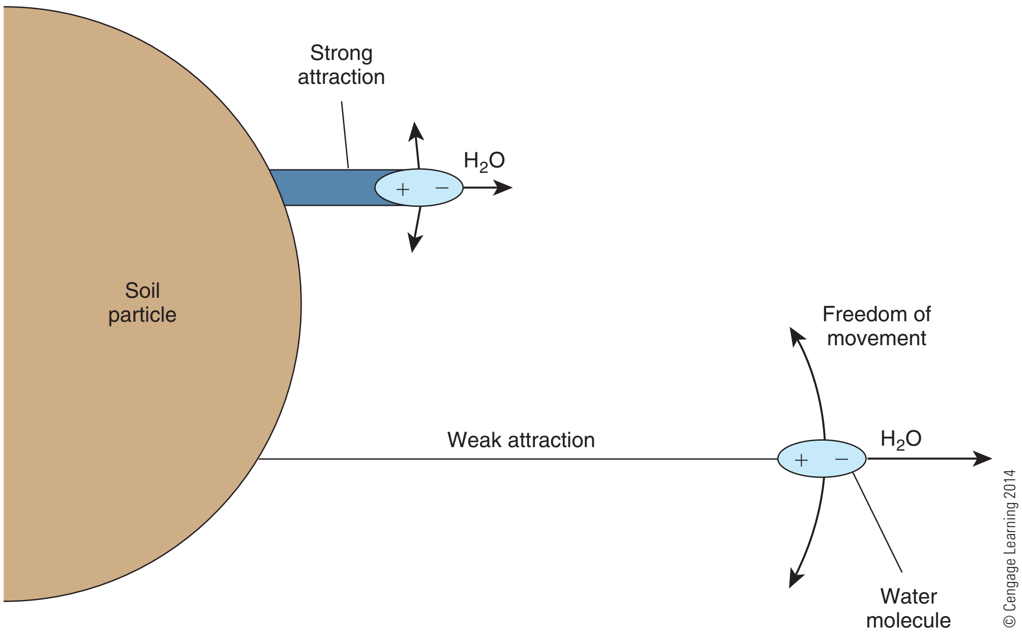

Figure 7–3
Energy level, or potential, of water molecules near a soil particle. The closer a molecule is to a soil particle, the more restricted its movement, the more tightly bound it is, and the lower its potential.

The third force, **osmotic potential**, is most important in soils of high salt content. Because water molecules are polar, they are attracted to charged salt ions. For instance, the positive end of a water molecule will be attracted to a negatively charged ion. This attraction lowers water potential. Another consequence is that ions in the soil solution are enveloped in a cloud of water molecules that are weakly attached by electrical attraction. In soils of low salt content, osmotic potential makes a minor contribution to total soil-water potential. Osmotic potential is always a negative number, because the reference state is pure water without dissolved ions.

Total water potential can be expressed by the formula:

$$\Psi_{soil} = \Psi_g + \Psi_m + \Psi_o$$

This says that total water potential is the sum of the gravitational, matric, and osmotic potentials. These values can be measured and expressed in several different units. The official unit of water potential, acceptable for scientific publications, is the *megaPascal (MPa)*. Still in common usage is the older term *bar*, which is equivalent to 0.1 MPa and is slightly less than one atmosphere pressure (14.7 pounds per square inch).

Soil-water potential is usually a negative number because its largest part, the matric potential, is a negative value. The larger the absolute value of the negative number, the lower the water potential. When we say soil-water potential is high, we mean the value is less negative, that water is loosely held, able to move readily, and easily available to plants.

Figure 7–4 shows a water film with bars of potential. The force varies through the film—the closer to the particle, the larger the negative potential, and the more work must be done to pull the water away. The potential for water in the soil, as a whole, is expressed as the most weakly held water in the soil.

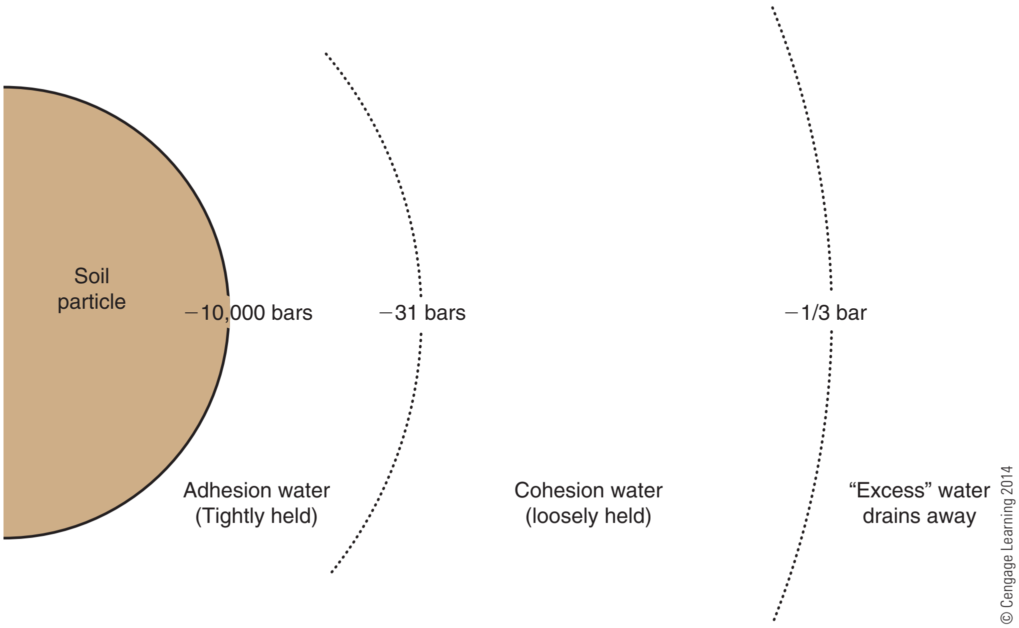

Figure 7–4
A water film showing bars of potential. A plant root must work to overcome that potential.

TYPES OF SOIL WATER

Consider what happens after a heavy rain. At first, soil pores are filled with water. This is called **saturation**; see Figure 7–5B. At saturation, matric potential is essentially zero, and gravitational potential dominates total water potential. In larger pores, some water is far enough away from the nearest surface that its gravitational potential exceeds matric potential. That is, the force of gravity can overcome the weak attraction of that water to soil particles, and it will flow downward rather than be held in place. The extra water, called **gravitational water**, drains through the soil profile, usually within 24 to 48 hours in a well-drained soil.

Eventually drainage ceases. The soil moisture level at that point is called **field capacity**. At field capacity, water films are thin enough to hold against gravity, and matric potential now balances gravitational potential. Soil-water potential is about −1/3 bar (Figure 7–5C). Air fills the interior of large pores, while micropores remain water filled, and thick films of cohesion water surround each soil particle. Plant growth is most rapid at this ideal moisture level because there is enough soil air, yet water is held loosely at high potential. We can also look at water content of soil at field capacity as that soil's capacity to hold water against gravity.

When drainage stops, water removal by plants and evaporation from the soil surface continues to deplete cohesion water, shrinking soil-water films. As water films thin, the remaining water clings more tightly, being held at lower potential (larger negative value). It becomes increasingly difficult for plant roots to absorb water. Eventually, at the permanent wilting point, most cohesion water is gone and the plant can no longer overcome the soil-water potential (Figure 7–5D). As the wilting point approaches, water becomes stuck in place; it cannot move quickly enough toward the root through the soil to support plant needs. The plant wilts and dies. The potential at this point varies according to plants and conditions, but is usually about −15 bars for typical plants. At this moisture level, water films are about 10 molecules thick. Some desert plants have adaptations that permit them to draw on water at much lower potential.

Beyond the wilting point, some cohesion water remains but is unavailable to plants. The rest of the cohesion water may also evaporate, leaving only a thin film of adhesion water. This point is called the hygroscopic coefficient, the point at which the soil is air dry. **Hygroscopic water**, as it is called, is held to particles so tightly, between −31 and −10,000 bars, that it can be removed only by drying soil in an oven. In fact, the strength of the soil-water potential is so great that if oven-dry soil is exposed to air, it will bind water vapor from the air until the soil moistens to the hygroscopic coefficient.

Available Water

Available water is that part of soil water that can be absorbed by plant roots. Gravitational water is largely unavailable because it moves out of the reach of plant roots, and if the excess water is unable to drain away, roots become short of oxygen and fail to function. Adhesion water cannot be removed by roots, so it is also unavailable to the plant. Only some cohesion water can be used by plants. Available water is defined as lying between the field capacity and the wilting point or between approximately −1/3 and −15 bars. In loamy soil, available water amounts to about 25 percent of the water held at saturation.

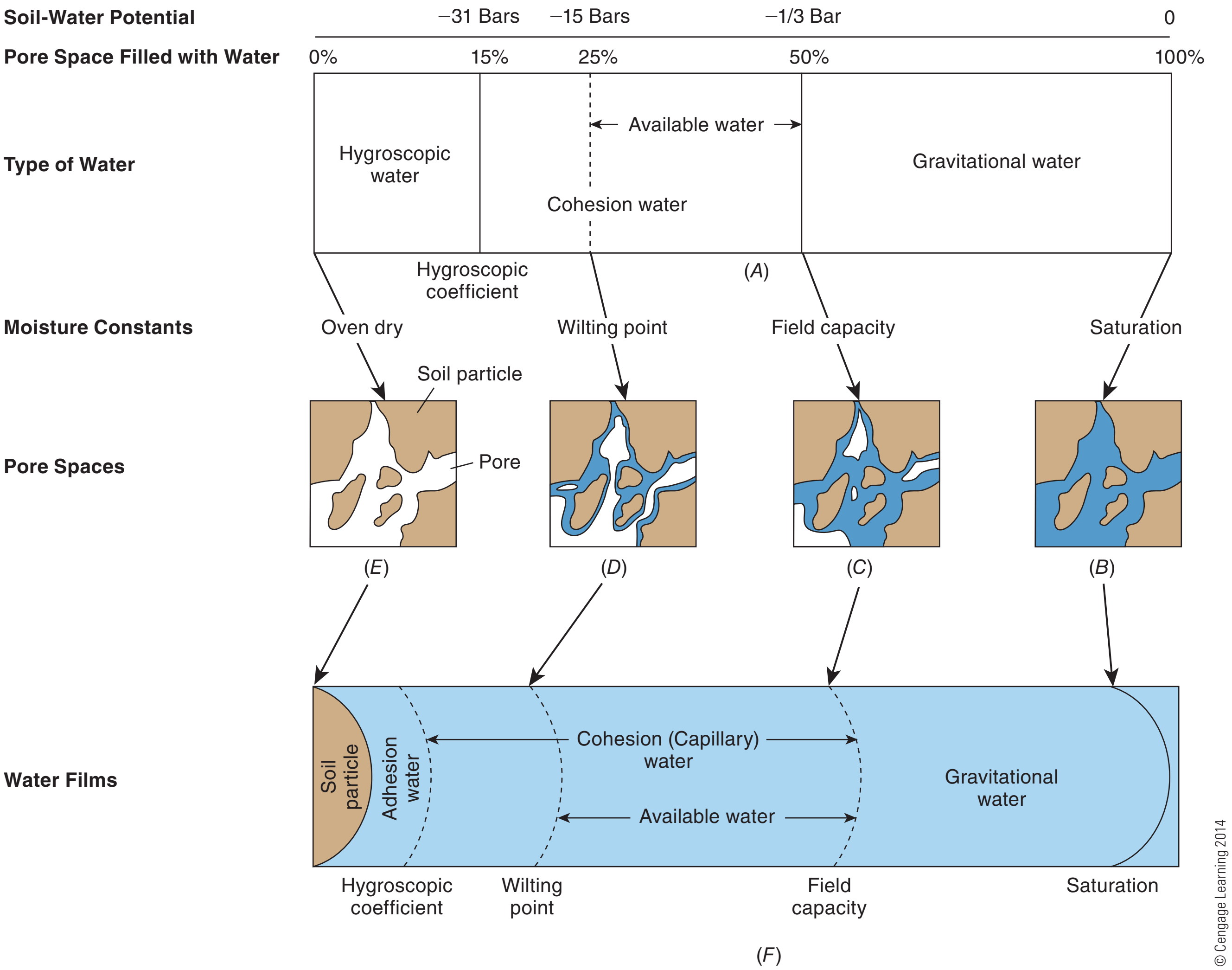

Figure 7–5

In (*A*), types of soil water are shown, plus moisture constants, corresponding soil water potential in bars, and average water-filled pore space. Parts (*B*), (*C*), (*D*) and (*E*) illustrate soil pores at each constant, and (*F*) illustrates the water films.

WATER RETENTION AND MOVEMENT

Both the retention of water and the movement of water in the soil are governed by the energy relations just described. We can begin by looking at water retention.

Water Retention

How much water can a particular soil retain and make available to plants? Actually, these are two separate questions because only the portion of soil water between field capacity and wilting point is available to plants. Both the total water-holding capacity and the available water-holding capacity are based mainly on soil texture.

Sand grains are large, so the internal surface area of a sandy soil is quite low. Thus, there is little surface to hold water films. In addition, pores are large enough that much of the volume of each pore is too far from a surface to retain water against gravity. The opposite is true of clay soils—they have small pores and a large internal surface area. Thus, soils high in sand have a low total water-holding capacity, while soils high in clay have a large water-holding capacity.

Not all this water is available to plants, however. In a soil high in clay, clay particles are crowded together tightly, leaving tiny pores. Any water molecule occupying a pore space will be close to a clay surface; therefore, it will be tightly bound at low water potential. Sand is the opposite. With large pores, much of the water can be fairly distant from a grain; therefore, it is held at high potential.

This leads to two rules. First, water in fine soils is held at low potential and water in coarse soils is held at high potential, so it is easier for plants to remove water in coarse than in fine soils. Second, because most water in high-clay soils is held at low potential, much is unavailable to plants. In contrast, most water in a sandy soil is available.

Silt and very fine sand are a special case. They are small enough that there is a high surface area to hold water. Pores are small enough to hold a large amount of cohesion water but large enough that much is held loosely at high water potentials. Thus, soils high in silt hold large amounts of plant-available water.

To hold the largest amounts of plant-available water, soil needs a mixture of large and small pores with many of the medium-sized pores caused by silt and very fine sand. Figures 7–6 and 7–7 show the effects of texture on soil-water retention. There are several important points to note in the figures:

- Fine sandy loam holds more water than regular sandy loam, reflecting the influence of very fine sand.
- Clay has the highest total water-holding capacity, but holds no more available water than a sandy loam.
- Medium-textured soil has the highest available water-holding capacity, especially silt loam.

Organic matter also influences water retention. For instance, a silt loam with 4 percent organic matter has twice the capacity of one with 1 percent organic matter. In coarse soils, organic matter can make a big difference in how much water the soil

Texture	Field Capacity (in./ft)	Permanent Wilting Point (in./ft)	Available Water (in./ft)
Fine sand	1.4	0.4	1.0
Sandy loam	1.9	0.6	1.3
Fine sandy loam	2.5	0.8	1.7
Loam	3.1	1.2	1.9
Silt loam	3.4	1.4	2.0
Clay loam	3.7	1.8	1.9
Clay	3.9	2.5	1.4

Adapted from Water: The yearbook of Agriculture, USDA, 1955

Figure 7–6
Water retention of several soil textures.

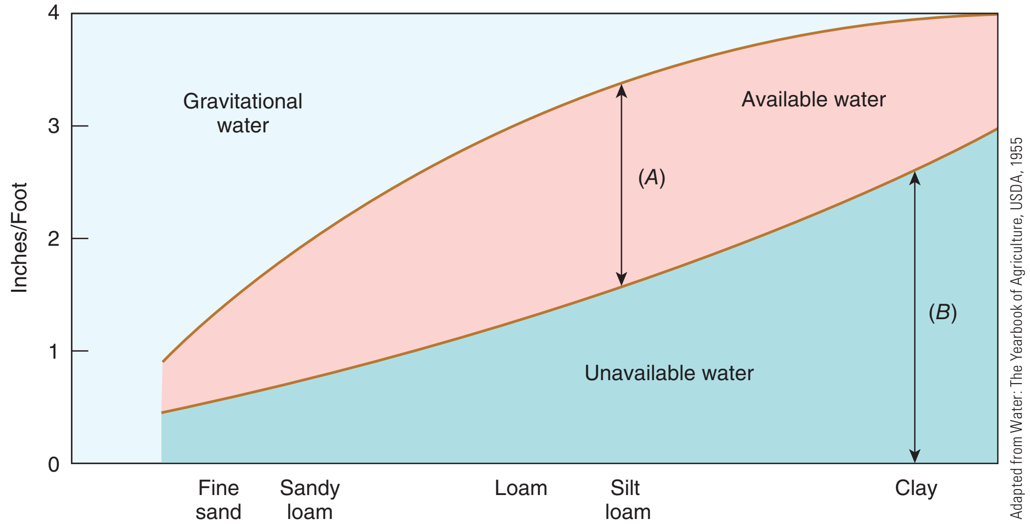

Figure 7–7
Water-holding capacity of soils at field capacity (upper curve) and wilting point (lower curve). Available water lies between the two curves. (*A*) Silt loam holds the most available water. (*B*) While clay holds the most total water, most is unavailable.

holds. Thus the rule that organic matter improves sandy soils partially by improving its water-holding capacity.

Water Movement

Horticulturists suggest that young trees be watered by letting a hose trickle on the ground. How will water move into the soil?

Figure 7–8 shows penetration of water over time for two soil textures. First, water infiltrates the soil, then it percolates downward through the soil profile. The distance, direction, and speed of travel are set by gravity, matric forces, and hydraulic conductivity.

Directly below the nozzle of the trickling hose is a column of percolating water. This water is gravitational water, moving under the influence of gravity. It is called **gravitational flow**. Gravitational flow occurs only under saturated conditions, when matric forces cannot hold water against the force of gravity. Because it occurs under such conditions, it is also called **saturated flow**. At saturation large soil pores are full of water, and water flows readily through those large interconnected pores. Most water movement occurs in the macropores, and movement is driven by differences in gravitational potential.

Saturated flow resembles the flow of water through water pipes. In a water pipe, water encounters friction as it flows along the pipe wall, causing a drop in water speed and pressure. The narrower the pipe, the greater the friction losses. Similarly, water flowing through soil suffers friction losses; the smaller the soil pores, the greater the losses. Thus, coarse soils permit more rapid water movement, or have greater hydraulic conductivity. Figure 7–8 reflects this fact.

Because gravity is directed straight down, how does water spread sideways, as it obviously does in Figure 7–8? Lateral movement is by capillary flow, the flow of cohesion water through capillary pores in the soil. Recall that water tries to achieve a low energy state. It does this by moving from areas of moist soil (high water potential) to areas of less moist soil (low water potential), or put another way, from areas

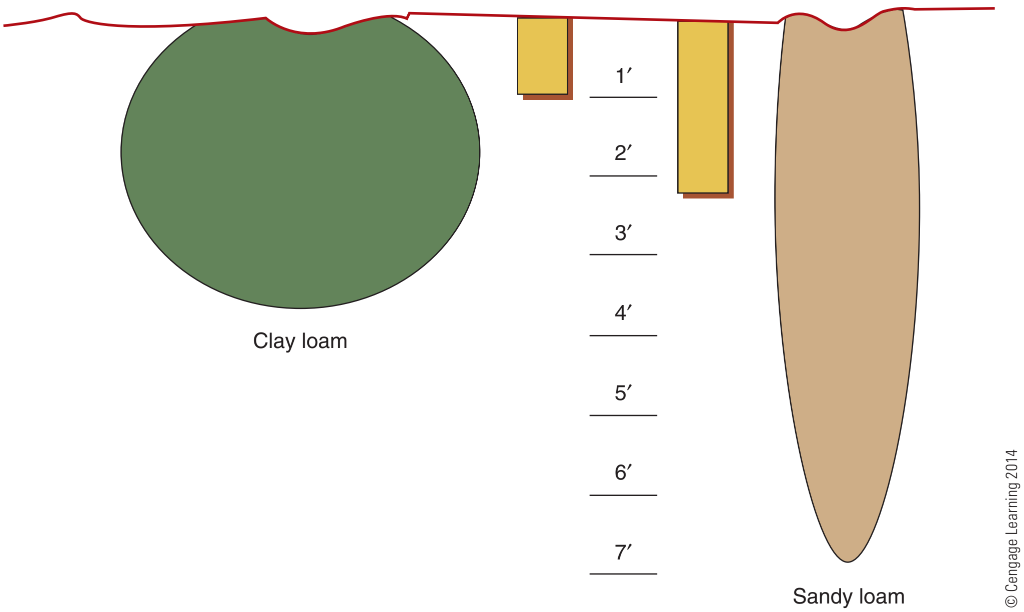

Figure 7–8

Wetting pattern in soil. This represents the way water penetrates the soil from a trickling hose. The shaded area shows penetration after 24 hours. The bars show how deep 2 inches of water penetrates for each soil texture. The figure shows that water percolates more slowly and less deeply in the clay loam but moves further laterally.

of thick water films to areas of thin films. Capillary flow can occur in any direction—up, down, or laterally (Figure 7–9). In fact, the downward movement of water is aided by capillary flow. Dry soil below pulls water downward from the wetted soil above.

Capillary flow occurs in unsaturated soil, so is called **unsaturated flow**. In unsaturated flow, the largest pores are full of air, so water has to move around these voids. Water flows through water films and smaller pores that still are full of water, closer to soil particles. Unsaturated flow is driven by differences in matric potential in the soil.

Unsaturated flow depends on unbroken films of water spreading through a series of connected capillary pores. This is like siphoning water—if a bubble gets in the siphon tube, water stops flowing. In sandy soils, large pores contain "air bubbles" that break the continuous water film. Thus, the clay loam soil in Figure 7–8 is capable of carrying water farther laterally than the sandy loam.

Water flows by capillary action most rapidly and extensively if the wet area is wetter than field capacity, and slows dramatically thereafter. As long as the hose in Figure 7–8 keeps trickling, the core of saturated soil under the hose supplies free water to keep water films thick where capillary flow is occurring. What if the hose is shut off? The column of saturated soil drains to field capacity, and the soil begins to dry. Water films thin out and become discontinuous, and unsaturated flow slows dramatically. As a result, unless there is a nearby source of saturated soil, capillary flow occurs very slowly over very short distances, often a fraction of an inch per day.

To summarize, saturated flow downward is the movement of gravitational water, usually percolation. It occurs most rapidly in coarse soils with large pores. Unsaturated flow is the movement of water from moist to dry soil (high to low potential) by capillary action, in any direction. Large pores in sand inhibit unsaturated flow.

Flow rates of water in the soil depend on how steep the potential gradient is between wet and dry locations, and how easily the soil conducts water, measured as hydraulic conductivity. Where there is a steep gradient—a large difference in wetness over a short distance—water flows relatively rapidly. Conductivity depends on friction between water and soil particle surfaces and pore constrictions and tortuosity. These are more severe in the small pores of finer-textured soils. Conductivity also declines as soil dries, because thinner films means more friction losses, the pores are less continuous, and the remaining water is more strongly attached to soil particles.

The Wetting Front

Figure 7–8 shows that water advances into the soil with a definite wetting front—wet behind a distinct line, dry ahead of it. In dry soil, thin and discontinuous water films have less ability to "pull" water deeper into the soil. Water cannot move forward until films behind the front are so thick that soil particles let go of the water. Behind the front, soil is nearly saturated; immediately ahead of the front, soil is still unwetted. One cannot "half-wet" a soil volume. Either all of a soil is wet, or else part is wet and part is dry. To water plants properly, growers must understand this fact.

Capillary Rise

Water moves upward in the soil as surface layers dry, moving from areas of high potential to areas of low potential. This upward movement is called **capillary rise**. The subirrigation of Figure 7–9 depends on capillary rise to deliver water into the root zone of the tomato plants.

Because of capillary rise, soil water can evaporate from the soil surface. However, capillary rise does not continue until the entire soil column dries. When the surface dries, cohesive films become too thin for capillary flow, so upward migration almost

Courtesy of USDA Natural Resources Conservation Service

Figure 7–9 Subsurface irrigation in a California tomato field. Water trickles out of the device shown. Water moves by capillary action in all directions to moisten crop roots.

halts. This creates a sharp boundary between the dry surface and a moister soil below. The boundary protects against further rapid moisture loss.

Generally, capillary rise does not bring much water from deeper in a soil to plant root systems, because unsaturated flow works solely over a short distance. The plant still extends its roots into lower horizons to draw water. However, where there is a water table near the surface that is a source of saturated soil, capillary rise does carry moisture to plant roots. One method of irrigation makes use of capillary rise. Some greenhouse potted plants are even watered from below by placing pots on benches that can be flooded.

In dry climates, or in potted plants, as water rises to the surface it carries dissolved salts with it. These salts are left behind when water evaporates, so they build up in the root zone. Salt deposits on the surface of the soil in a potted plant is a consequence of this capillary rise. Salts may reach levels that injure the plant. The problem is countered by overwatering slightly during irrigation, washing excess salts deeper into the soil or out of the pot.

Effect of Soil Horizons

Figure 7–8 suggests that water flows differently in soils of different textures. Normal soil profiles contain horizons that may differ in texture. What happens when percolating water meets the boundary between two horizons of very different character?

In Figure 7–10, water percolating through a fine-textured horizon encounters a coarser soil layer. One might expect that percolation would speed up because of the larger pores of the coarse layer (greater hydraulic conductivity). The soil would become more droughty. In fact, percolation slows down. As the figure shows, water does not enter the coarser layer at first, but instead spreads out along the boundary. Why?

Recall that water is being pulled down by capillarity as well as being pushed down by gravity. The large, noncapillary-sized pores of the coarse layer exert much less "pull" on the advancing water than do the fine pores above the boundary, so the clay will not "let go" of the water. Or put differently, water tends to move from large pores into smaller pores because of matric forces. Small pores do not let go of water into large pores. Because water is more strongly attracted to clay than sand, the front spreads rather than being pulled across the boundary. When the topsoil is almost saturated, its potential is high enough that gravity can pull water downward into the sand.

Commonly, the A horizon is coarser than the B, so a sharp boundary exists between a coarser upper layer and a finer lower layer. As expected, the finer pores

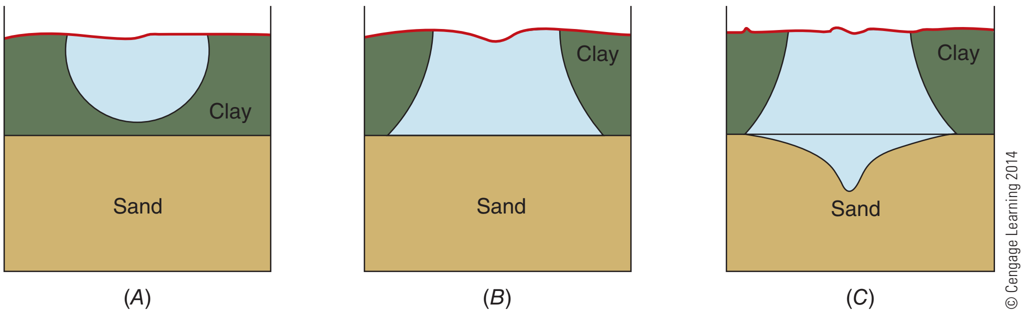

Figure 7–10

Effect of textural boundaries. (*A*) Water infiltrates clayey surface soil. (*B*) Wetting front strikes layer of sand and spreads out along boundary. (*C*) When the clay is saturated, water begins to be released into the sand.

pull the water down. However, because water naturally drains more slowly through fine soils with their lower hydraulic conductivity, water will still build up above the fine-textured layer.

Any sharp boundary between two layers of dissimilar texture retards drainage. This may be helpful because it can improve the water-holding capacity of a topsoil. In some situations, though, slowed drainage may keep the upper soil saturated long enough to injure roots. We sometimes call this *perching* the water. Landscapers encounter, and sometimes create, these interfaces between different textures. An example is topdressing a yard with "black dirt" before laying sod, which may be more damaging than helpful (see Chapter 17). The rule here is to mix the topdressing into the soil to avoid the sharp boundary.

Golf greens may be designed to hold moisture by creating conditions similar to those shown in Figure 7–10B. A 12-inch layer of special root-zone mix is laid atop a 2-inch layer of sand, over a 4-inch layer of pea gravel over drain tile. The design causes a wet zone to develop above the sand, so turf roots are watered from below by capillary action. If the root zone gets too wet, excess moisture drains into the pea gravel and is removed from the green.

All sorts of features that create discontinuities in the soil profile—sharp textural boundaries, soil pans, and so on—can cause water to hang up in the root zone rather than percolate out of the root zone. These are important features of many natural ecosystems because they affect the natural wetness of soil, and thus the plants that grow there.

Preferential Flow

Besides saturated and unsaturated flow, water can move through the soil by **preferential flow**. Under saturated soil conditions, as occurs during heavy rains, water may encounter biopores or other soil channels and quickly enter the channel and flow downward under the force of gravity deeper into the soil profile.

Water enters channels under two conditions. If the channel opens to the surface where water is ponding, as in a heavy rain, water simply flows in. If the channel does not open to the surface, matric forces prevent filling of the channel until the surrounding soil is saturated. Once pores are full of water, the matric potential goes to zero, and water can be released into the channel. Because tillage reduces the number of channels and erases their entry at the surface, preferential flow will be most important in undisturbed soils and under reduced tillage or mulches.

Preferential flow can greatly increase infiltration and percolation, reducing runoff and allowing deeper penetration of water. It can also mean deeper penetration of pollutants such as pesticides because the water bypasses the filtering action of the soil matrix. This can increase the chance of groundwater contamination.

HOW ROOTS GATHER WATER

Uptake of water by plant roots is also governed by soil-water potential. Each root cell has its own water potential: an osmotic potential from chemicals dissolved in cell water; a pressure potential like the pressure in a water balloon; and others. If water potential inside a root is lower than the surrounding soil-water potential, then water flows into the root across the cell membrane.

We could say that roots absorb water if:

$$\Psi_{soil} > \Psi_{plant}$$

The larger the difference between soil- and plant-water potential, the more easily and quickly roots will take up water because of a steeper gradient. The smaller the difference, the less steep the gradient, and the more slowly water is taken up. At field capacity, water films are at their thickest. Therefore, soil-moisture potential is high, and water moves easily into a root hair. A root hair pulls a bit of water from this thick film (Figure 7–11), so the film becomes thinner at that point and water potential decreases. This causes capillary flow toward that point from nearby thicker areas of the water film. Therefore, the root hair can continue to draw on the water around it until the water film becomes too thin. As water films around roots continue to thin, conductivity declines until water no longer moves toward the root adequately.

A plant can be compared to an unbroken column of water, beginning in the soil volume that supplies water to a root and ending in the air outside the leaves. Normally, the "driest" end of this column—the lowest water potential—is the air. The potential of water vapor depends on relative humidity, and is always at relatively low potential unless the relative humidity approaches 100 percent. The "wettest" end—highest potential—is the soil. There is, then, a moisture potential gradient with soil at the high end and air at the low end. Water moves into roots, up the stems, into the leaves, and out into the air, high to low potential.

Another way to visualize the gradient is to picture the atmosphere as drier (less humid) than air spaces in leaves, which are always of nearly 100 percent relative humidity. Water transpires out of the leaf into the drier air, making the leaf drier. That water is replaced by water from the stem, which becomes drier, and so on down the stem into the roots. Water in the roots is replaced from the soil.

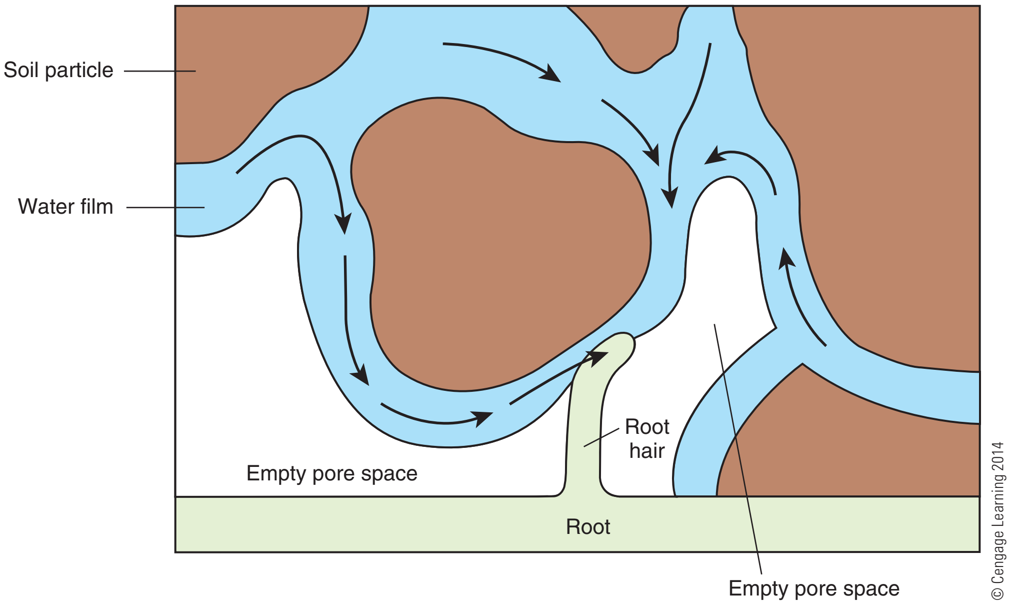

Figure 7–11
Water withdrawal by plants. As a root hair removes water from a pore, potential falls at that point, and water in nearby thicker films flows toward the low-potential site where the root is withdrawing water.

As soil dries, it becomes less moist compared to the air; the potential gradient becomes less steep so there is less pressure pulling water into the root. The remaining soil water is more tightly held, so more pressure is needed to remove it. The remaining water films become thinner as well, slowing capillary movement to the root. As the soil dries, then, it becomes increasingly difficult for plants to extract water from the soil. Eventually, the permanent wilting point is reached.

We could also say that as soil dries, soil-water potential approaches plant-water potential, the gradient becomes more shallow, and water flow slows. If the soil becomes dry enough, the two potentials become equal ($\Psi_{soil} = \Psi_{plant}$) and there is no driving force for water absorption. This is the permanent wilting point.

It is important to understand the implications of this. Earlier we defined "available water" as that water available to plants that lies between field capacity and the permanent wilting point. But that water is not all equally available. As soil dries, and potential gradient and hydraulic conductivity both decline, plants struggle to absorb water as fast as they need it. Water stress rises quickly as the soil dries much below field capacity, with loss of growth, productivity, and health.

In saline soils, matric potential is joined by the osmotic potential. In this case, both salt ions and particles hold soil water. As a result, even moist soil can be at quite a low potential, keeping water from entering roots. Thus, saline soils present special water management problems. If soil salts are concentrated enough—as could happen if one applies too much fertilizer—soil-water potential could even move lower than plant-water potential ($\Psi_{soil} < \Psi_{plant}$), and water would actually be drawn out of roots.

Pattern of Water Removal

Most plants get the bulk of their water from near the soil surface. Corn, a relatively deep-rooted plant, gets 40 percent of its water from the top foot, 30 percent from the next foot, and 20 percent from the 2- to 3-foot depth, when the soil is deep and there is no restriction to rooting depth. The depth being exploited by the plant also varies over time as the soil dries or is moistened by rain or irrigation.

As soil dries, capillary flow cannot readily supply all the water needs of a plant; it is important that roots spread easily to exploit a greater soil volume and find more moist soil. Roots grow best where oxygen is plentiful, and proliferate in damp soil zones where other zones are drier. This all means that where the surface soil, rich in oxygen, is damp, roots develop thickly there, and mainly draw on surface soil water to supply their needs.

As the surface soil dries, roots grow more densely into the moister soil below, stimulated by a shift of growth from top growth to root growth. The zone of main water absorption shifts downward (Figure 7–12). If the surface layer is rewetted, moisture absorption shifts back toward the surface.

The pattern of water absorption suggests how irrigation water should be applied. If surface soil is kept moist enough, then the plant is well supplied by near-surface water, top growth is favored over root growth, and plants will tend to have shallower, sparser root systems. The plant is unable to exploit lower soil levels quickly when the surface dries and is, therefore, vulnerable to drought. Proper irrigation wets most of the rooting depth of the crop and allows for some drying between waterings.

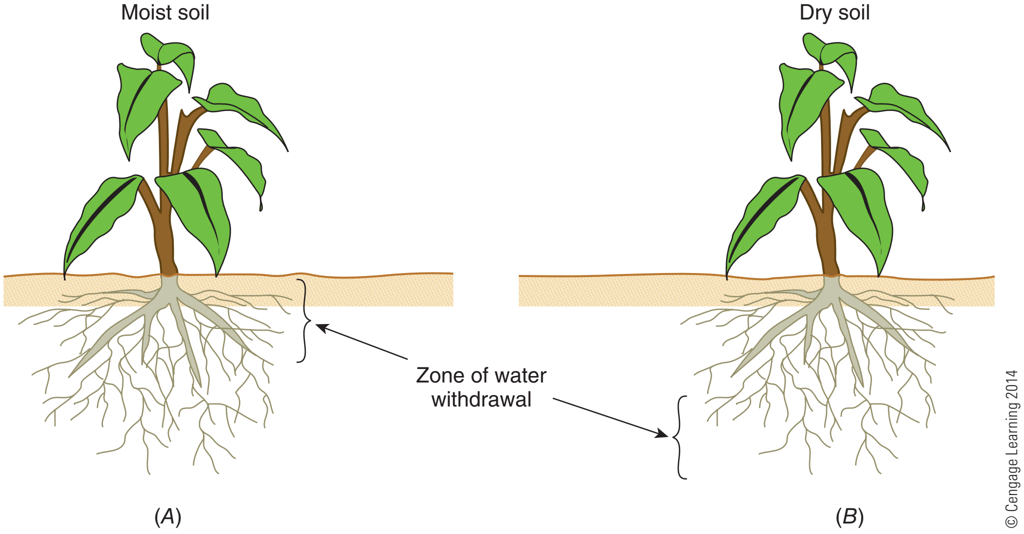

Figure 7–12
Water withdrawal from soil. (*A*) When the whole rooting zone is moist, the plant draws mainly from soil near the surface. (*B*) As the surface dries, the plants begins to draw more heavily from deeper soil.

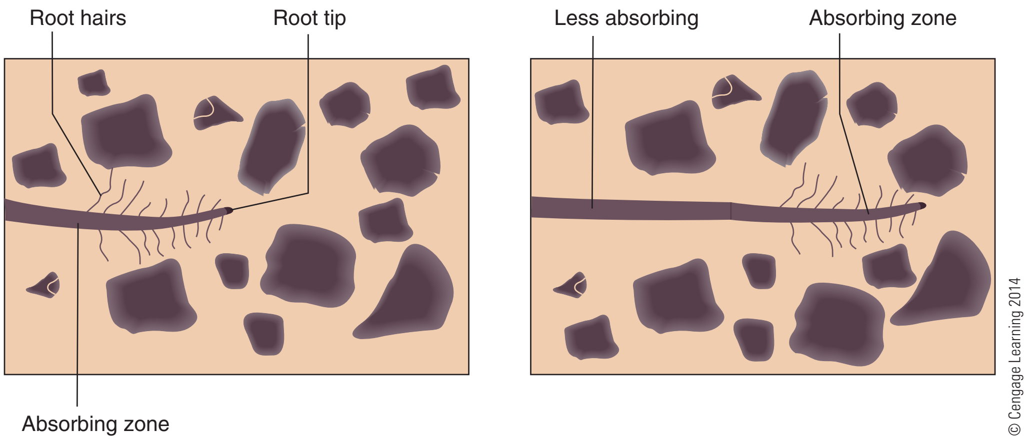

Figure 7–13
As roots grow at the tip, the most actively absorbing zone, including root hairs just behind the tip, also advances further into the soil. Older parts left behind lose their root hairs and absorb less readily. If older root tissue is not replaced by younger, uptake of water and nutrients become less efficient.

Another aspect of root growth also emphasizes the need for constant root development (Figure 7–13). Roots absorb water (and the nutrients dissolved in the water) most actively just behind the root tip, especially in the zone occupied by root hairs. This absorbing zone extends from about 10 mm behind the tip to about 100 mm farther back. But as the zone matures, within a few days, root hairs die and cells become less absorbing. At the same time, the root has elongated and the absorbent zone has been replaced farther ahead. Conditions that impair continual replacement of older root tissue with new growth inhibit water and nutrient uptake.

If soil dries too much, root growth declines, and some roots may even die. One use of irrigation can be to prevent this pruning of the root system. Interestingly, roots do have some defense. If some roots occupy soil more moist than another, perhaps moist deeper soil as the surface dries, water moves in the root system from the moist roots to dry roots. In a sense, the plant mines water in moist soil to support its other roots. This pattern, of course, follows a water potential gradient in the root system itself.

MEASURING SOIL WATER

People who design or use irrigation systems need to be able to measure the amount of water in a soil. They also need terms to name the amount of water present. Four methods are common: gravimetric measurements, potentiometers, resistance blocks, and other devices or procedures. At the base of all these are gravimetric measurements.

Gravimetric Measurements

Gravimetric methods directly measure soil **water content** by weight. This gravimetric water content can then be converted to other useful quantities.

Weight Basis

To measure water content of a soil sample by weight, the sample is weighed and the weight recorded. The sample is then oven-dried, and the dry weight noted. The difference between the two weights is the weight of water in the soil. Water content is the amount of moisture divided by the oven-dry weight:

$$\text{water content} = \frac{\text{moist weight} - \text{dry weight}}{\text{dry weight}}$$

Suppose one needs to measure water content of a soil at field capacity. A sample is taken two days after a heavy rain. If the sample weight were 150 grams when wet and 127 grams when dry, the moisture content would be

$$\text{water content} = \frac{150 \text{ grams} - 127 \text{ grams}}{127 \text{ grams}} = 0.18$$

The gravimetric water content can then be converted to percent water by weight simply by multiplying by 100, so

$$\text{Percent water by weight} = 0.18 \times 100 = 18\%$$

Volume Basis

It is often more useful to calculate water content on a volume basis. However, it is impractical to measure a volume of water in the soil. This problem can be solved by making a weight determination and converting it to **volumetric water content** using soil and water densities (density being mass per volume). The equation for the conversion is

$$\text{volumetric water content} = \text{gravimetric water content} \times \frac{\text{soil bulk density}}{\text{water density}}$$

The density of water is 1.0 gram per cubic centimeter. In the previous example, if the bulk density of the soil sample were 1.5 grams per cubic centimeter, water content by volume would be

$$\text{volumetric water content} = 0.18 \times \frac{1.5\ \text{gm/cc}}{1.0\ \text{gm/cc}} = 0.27$$

Thus, if one measures in the metric units of grams per cubic centimeter, the volumetric water content is simply the gravimetric content times the bulk density of the soil.

Soil Depth Basis

A meteorologist measures rain in inches of water; irrigation is measured in inches as well. Inches of water is a convenient, easily visualized unit that can also be used to measure the amount of water in a soil.

Let us say one could take 1 cubic foot of soil and squeeze all the water out of it into a 1-square-foot cake pan. How many inches of water would be in the pan? This can be calculated simply by the equation

$$\text{inches water per foot soil} = 12\ \text{inches} \times \text{volumetric water content}$$

In the previous sample, then

$$\text{inches water per foot} = 12\ \text{inches} \times 0.27 = 3.24$$

In the sample, each foot of soil depth contains 3.24 inches of water. If a soil profile were 3 feet deep, and each foot was the same, then the total of the entire profile would be 9.72 inches of total water.

Inches per foot is a common measurement used in irrigation. Irrigation also uses the acre-inch, the volume of water that would cover 1 acre of soil 1 inch deep. In the metric system, the measurement equivalent to an inch per foot is a centimeter of water per centimeter of soil.

In practice, it would be a bother to make gravimetric measurements to decide whether or not a soil needs watering. Several devices may be used to measure soil water for research purposes or for scheduling irrigation. Here we will discuss the two most common and least expensive devices, the potentiometer and resistance block.

Potentiometers

From the plant's point of view, the important thing is not how much water is in the soil, but the potential it is held at. A device called a **potentiometer**, or tensiometer, acts like an artificial root. It measures soil-moisture potential and so gives a "root's-eye view" of how much water is available.

A potentiometer is a plastic tube with a vacuum gauge at one end and a porous clay cup at the other end (Figure 7–14). The tightly closed tube is filled with water, then buried with the gauge sticking out. Dry soil outside the tube pulls water out through the clay cup, creating a partial vacuum inside the tube. The vacuum creates a force that opposes the pull of matric forces in the soil, and water ceases leaving the tube when the two are equal. At any given moment, the gauge reading the vacuum is then also reading the matric potential of soil water. Potentiometers work best in

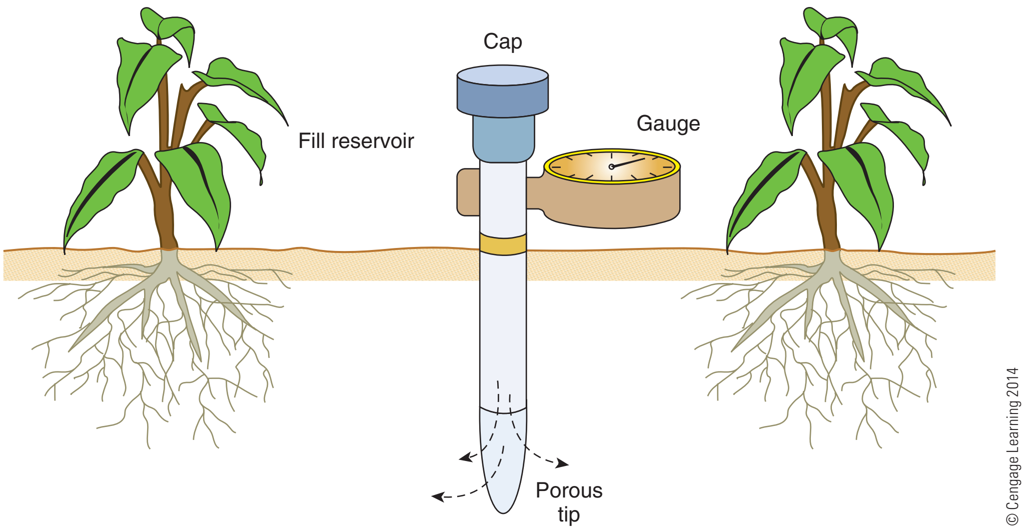

Figure 7–14
A potentiometer (tensiometer). As dry soil pulls water out of the porous tip, a partial vacuum is created inside the tube that is measured by the gauge. The vacuum pressure measures soil-water matric potential.

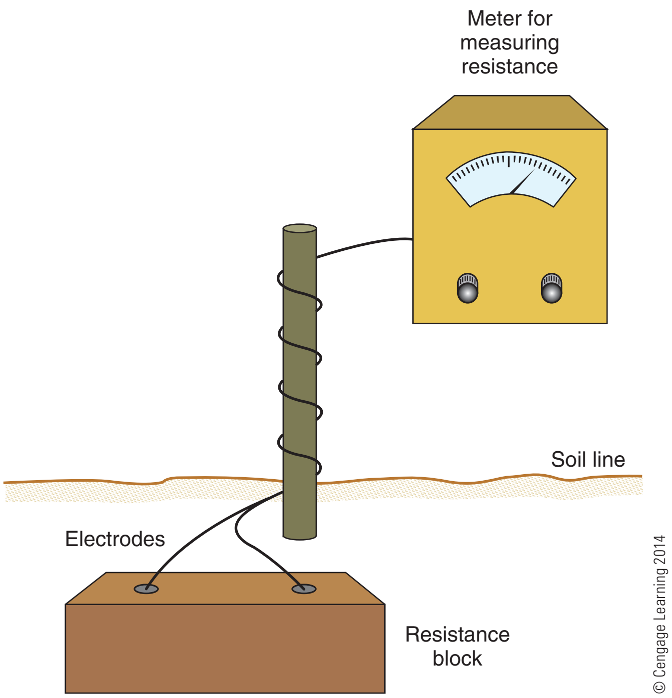

Figure 7–15
When using a resistance block, the meter reads resistance to electrical flow between two electrodes buried in the block. The drier the soil, the greater the resistance.

moist soil at potentials between 0 and −0.8 bar—a narrow range but an important one to plants.

Resistance Blocks

Another device for measuring soil moisture is the **resistance block** (Figure 7–15) or Bouyoucos block. Two electrodes are embedded in a block of gypsum, fiberglass, or other material. The gypsum block absorbs water from surrounding soil by capillarity through its own pores. The wetter the surrounding soil, the damper the block becomes. Moisture dissolves some of the gypsum, which is slightly water soluble. The block now contains a solution of water and dissolved gypsum, and this solution conducts electricity. (Pure water is a very poor conductor; it is ions dissolved in water that conduct electricity.) The drier the block, the greater the resistance to electrical current. Gypsum blocks work better in drier soil regimes than do tensiometers.

Gypsum blocks are embedded in the soil at the depths of interest, with wires leading to the surface. The irrigator simply applies a current to the wires, and reads the resistance on a device for measuring resistance. Blocks can be buried in several locations, and the device carried from block to block. Blocks do need to be replaced periodically as the gypsum dissolves.

Both gypsum blocks and tensiometers are permanently installed in a location for the growing season; one cannot simply poke them in the ground to get a reading at a moment's notice. Soil probes that measure electrical resistance of the soil solution itself answer the need for instant readings in any location, such as a landscape. Here a rod with two electrodes is pushed into the soil, and resistance is read on a dial. The readings of such probes reflect both moisture and salt content, so are not fully reliable measures of soil moisture. However, the better quality probes have been shown to be accurate enough for many purposes. Your author used to perform landscape inspections during the summer, and always carried a soil-moisture probe to get some idea what was going on below the surface. It was surprising how often new trees showing signs of stress had root balls that were bone dry or soaking wet.

A number of other, more expensive devices are also available for measuring soil moisture, such as neutron probes, time domain reflectometers (TDRs), and others. These more sophisticated devices are used much less commonly in commercial agriculture than tensiometers and gypsum blocks, so will not be detailed here. Interested students can search the Internet for more information.

WHERE DOES WATER GO?

So far this chapter has concentrated on water behavior *in* the soil. There it moves in response to differentials in gravitational, matric, and osmotic potential. However, water that lands on the soil but fails to enter the soil collects on the surface to form puddles—we call this "ponding." Matric and osmotic potential are negligible in this free water. It moves in response to gravitational potential only; that is, downslope. Anytime water ponds on the soil surface, it can move and carry with it soil and pollutants. When water moves, it leaves one place drier and goes to another place that becomes wetter, possibly too wet for good plant growth or even contributing to flooding.

The physics of it dictate that water will flow down the steepest gradient available to it. The steepest gradient is always perpendicular to elevation **contours,** imaginary lines across the landscape that remain at a constant elevation (Figure 7–16). The curving lines on topographical maps are elevation contours. Further, water flow concentrates where opposing contours meet, where gullies can form, as shown in

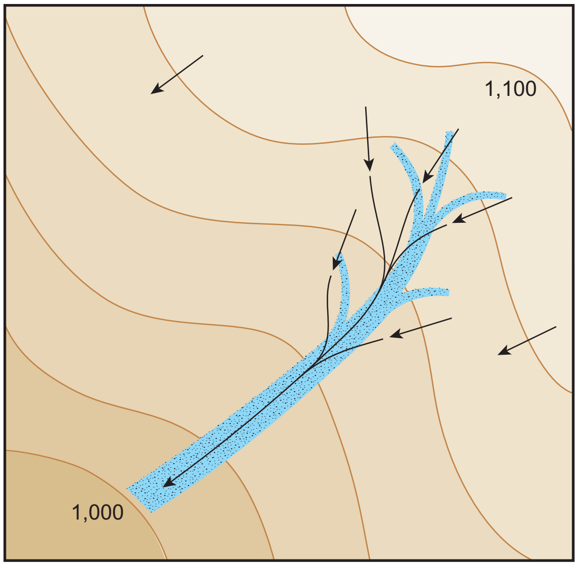

Figure 7–16
Water flow and contour lines on the landscape. The contour lines are imaginary lines that remain at constant elevation. This land generally slopes downhill from upper right to lower left. Water runs perpendicular to the lines, as shown by the arrows. Water flow concentrates where opposing contours meet.

Figure 7–16. A careful examination of Figure 18–24 illustrates this nicely—a grassed waterway protects the soil where water flow concentrates. Whether we are measuring tiny elevation differences in inches or larger ones of tens of feet, water follows these patterns.

Many soil conservation measures described in Chapter 18 are designed to inhibit water flow downslope, or force it into a less steep path so it will be less erosive, or to protect areas of concentrated flow. In construction sites, the land is often graded; essentially the contours are changed to direct water flow. Site surveys for new homes or developments show elevation contours; these help landscape architects or designers predict where water will flow on the site, a critical part of their work. The author has seen damaging mistakes in landscapes caused by a failure of the designer to understand where water will flow on the site, but has also seen landscapers solve such problems. Chapters 18 and 19 are very much concerned with water movement.

Under certain circumstances, water also flows downslope *in* the soil. Soil layers tend to follow the topography, so on a slope where the soil is wetter than field capacity, water will slowly flow through the soil in a downhill direction. This is particularly true when a subsoil layer perches water above it; the water will flow downhill just above the layer. It may come to the surface somewhere downslope as a seep.

Both these situations sometimes kill new landscape trees. Water may run off a roof, flow across the more compact soil of the yard, and then literally dive into the looser soil in a planting hole. Or the water seeps into the upper yard, then flows laterally down the yard through the soil, intercepting the planting hole and keeping it wet for long periods of time. Chapter 9 suggests a couple of practices that would alleviate the problem, but the proficient designer, again, needs to pay attention to where the water goes on a site.

SUMMARY

Soil-water potential dictates behavior of water in the soil. Total soil-water potential has three major components: the matric potential resulting from attraction of water to soil particles and to itself, gravitational potential, and osmotic potential derived from the amount of dissolved soil salts.

Based on their differing potentials, three types of soil water can be defined. Gravitational water drains away under the force of gravity. Capillary water is loosely held by cohesion and is mostly available to plants. Hygroscopic water is too tightly held by adhesion to be used by plants.

When all soil pores are occupied by water, soil is saturated. Most plants do not live well in saturated soils because of low soil oxygen. At field capacity, the last bit of excess water has drained away, and pores are occupied by air and water. Most plants grow best at field capacity. As soil dries further, plants must work harder to absorb moisture, so water stress increases until the permanent wilting point is reached. When the last water that can be removed by plants or evaporation is gone, the hygroscopic coefficient is reached.

Water moves through soil by both gravity and capillarity. Both forces contribute to downward movement, but only capillarity carries water upward or laterally. Water moves from locations in the soil of higher potential to locations of lower potential. Downward movement is most rapid in coarse soils, while lateral movement is most extensive in fine soils.

Water penetrates soil along a wetting front. Below the advancing front, soil remains dry. Whenever a wetting front meets a sharp boundary between soil layers of different texture, percolation slows. This may either improve the water-holding capacity of a soil or cause drainage problems.

Fine-textured soils have the highest water-holding capacity, but medium-textured soils retain the greatest available water.

Water is absorbed into plants because of root pressure and because transpiration causes low potential inside the plant. As the root draws from a water film, more water moves toward the root by unsaturated flow. Because such flow is slow, the extension of roots into moist soil is critical. The water is used by plants in photosynthesis, to transport materials within the plant, and to maintain plant tissue turgidity.

Soil moisture can be measured exactly by weighing the moisture in a soil sample. In practical applications, devices such as potentiometers and resistance blocks provide adequate information to make such decisions as the need for irrigation.

Water moves on the soil surface in response to gravitational potential in a downslope direction perpendicular to the countour. This fact can be used to predict water movement in farm fields or landscapes.

REVIEW

1. Of the three water potentials that make up total soil-water potential, which one would be most affected by compaction? Explain your reasoning.
2. Which soil texture would have to be watered more often, coarse or fine? Which would need more water each time? Explain your answers.
3. A 112-gram sample of soil, after drying in an oven, weighs 100 grams. Assume a soil bulk density of 1.4 grams per cubic centimeter. Calculate water content by weight, by volume, and by inches of water per foot.
4. The soil moisture of a soil was measured at several intervals after a heavy rain. Immediately after the rain, while still saturated, a sample weighed 132 grams. Two days later, just after drainage stopped, the sample weighed 116 grams. When plants wilted in the soil, the soil weighed 108 grams. Finally, the sample was oven-dried, for a weight of 100 grams. Assuming a bulk density of 1.4 grams per cubic centimeter, calculate the inches of available water per foot for this soil at field capacity.
5. In which soil is water most available to plants, one with a soil-water potential of −0.5 or −1.5 bars? What would happen to the water potential of either soil if fertilizer was mixed into it? What effect would that have on the plant? Should you fertilize plants suffering water stress?
6. Let us say that at point A in the soil, matric potential is −0.2 bar and in nearby point B, matric potential

is -0.4 bar. If all other components of water potential are the same, in which direction will water flow?

7. In plant propagation, rooting leafy cuttings requires reducing transpiration so the cutting does not wilt. One way to do this is to surround the cutting with a fog. Why would this work? Explain scientifically and in lay terms.
8. Some indoor foliage plants are potted in self-watering pots that water the soil mass from a reservoir of water in the bottom of the pot. How does this work? Might there be a problem if the soil was allowed to dry excessively before the reservoir was refilled?
9. Distinguish temporary wilting point from permanent wilting point. Which one is a trait of the soil only? Could a plant be taking up water and still wilt?
10. Describe some ways you might improve the available water-holding capacity of sandy soils. Explain your answer.
11. When planting trees in the landscape, the root ball might be of very different soil than the surrounding soil. How might this complicate proper watering?
12. In the author's home city, a sand sculpture contest is part of a summer festival. The sculptors continuously mist their work with water as they work; otherwise the sculpture would not hold together. Can you explain this?
13. Erosion thins the topsoil. Sometimes this can result in fine clay from the subsoil being mixed into the topsoil during field preparation. This can *reduce* available water for the crop. Can you explain why?
14. A case study: Ecologists have found that plants such as maple trees engage in "self-watering" when surface soils begin to dry. To explain: leaf stomata close at night, breaking the continuous column between soil water and atmospheric air described in this chapter. Little water is then lost through the leaves. Often, as surface layers of soil dry, deeper soil may still be moist. They have found that at night, deep roots absorb water, which rises to the shallow roots, where it is released into the soil. Ecologists call this hydraulic lift. Explain how this could happen in terms of water potentials. How might this be beneficial to the maple tree or other plants in the vicinity?

ENRICHMENT ACTIVITIES

1. Test the effects of cohesion and adhesion using two glass microscope slides. Hold the two slides flat against each other, then pull (not slide) them apart. Now put a drop of water between them, and repeat. Feel the difference.
2. Grow several tomato plants in pots until each has several leaves. Then divide the plants into three groups, watering each differently. Water one group so often that the soil stays wet. Water the second group when the soil surface dries. Water the third group only when the plants wilt. Observe the differences in growth.
3. A fellow Delmar author, Mark Coyne, suggests this exercise in his book on soil microbiology. It uses potato sticks to demonstrate osmotic potential and water absorption. Cut a potato into identical thin, long sticks. Place some into distilled water, others into a strong solution of table salt, and wrap some in cellophane and refrigerate; this last one is the control. After a couple of hours compare the length of the sticks. Those soaked in distilled water should be longest, those in a salt solution shortest. Can you explain the results in terms of osmotic potential of potato cells (caused by chemicals dissolved in the cell water) versus the solution they were soaking in? What would this say about water uptake in soils that are high in salts?
4. A nifty hydraulic properties calculator based on the soil texture triangle is at the following Soil Water Characteristics site which is developed and run by the USDA in cooperation with Washington State University: http://hydrolab.arsusda.gov/soilwater/Index.htm. This site requires registration and downloading, so perhaps should be installed in a classroom or lab computer. Use this triangle to compare the available water-holding capacity and hydraulic conductivities of a sand with 90 percent sand and 10 percent clay, a silt loam with 20 percent sand and 20 percent clay, and a clay with 45 percent sand and 55 percent clay. One can also estimate the effects or organic matter, salinity, or compaction here.
5. Practice the operation of a gypsum block or a tensiometer. Following the directions, set one up in the ground or in a potted plant. Observe readings as the soil dries, then rewet the soil and observe readings again.
6. Obtain a small, blown-up section of a topographical map or a housing site survey. Study how the contour lines work, then indicate how water will flow on the site.

CHAPTER 8

Water Conservation

TERMS TO KNOW

aeration (turf)
antitranspirant
aquifer
arid climate
buffer strip
conservation tillage
consumptive use
contour tillage
evapotranspiration
groundwater
humid climate
hydrologic cycle
hydrophilic gel polymer
mulch
nonpoint source
point source
precipitation
reclaimed water
runoff
semiarid climate
strip-cropping
stubble-mulching
subsoiling
surface water
syringing
terrace
water table
water-use efficiency

OBJECTIVES

After completing this chapter, you should be able to:

- explain the sources of our freshwater supplies
- explain the need for water conservation
- describe ways to make better use of water
- discuss water quality

Our world contains a lot of water, the vast majority residing in the oceans. We need freshwater to drink, cook, wash dishes, or irrigate; that is much more limiting. Freshwater resources of the world vary dramatically from place to place. Brazil enjoys an annual renewable freshwater supply of 8,200 cubic kilometers.[1] Assuming the author did not misplace a decimal point, this works out to about 9,700 million liters (a liter is about a quart) for every square kilometer (a bit less than a half square mile) of land surface, or 4,500 million liters per person. The much drier North African country of Morocco commands only 29 cubic kilometers of freshwater per year, about 65 million liters per square kilometer and less than a million liters per person.

And the United States and Canada? Both the United States and Canada can access a bit over 3,000 cubic kilometers, or about 335 million liters per square kilometer. This is about 10 million liters per person for the United States, while Canada's much smaller population enjoys 100 million liters per person.

These numbers sound like enormous quantities of water, but they are not. We share that water with industrial users, and yes, with nature. This

[1]Data calculated from the Pacific Institute's report *The World's Water 2006–2007,* and from The Economist, *Pocket World in Figures, 2007 Edition*.

chapter discusses water resources, mainly of the United States, and why and how they can be conserved in agricultural settings.

THE HYDROLOGIC CYCLE

Of the nine planets occupying our solar system, only Earth is known to contain large amounts of liquid water. Most of this water—97 percent—occupies the oceans.

The **hydrologic cycle** (Figure 8–1) is an engine, fueled by the sun's energy, that transports water from the ocean to land and back again. Air moistened by evaporation from the surface of the ocean passes over continents, where it is shifted upward by warm air rising from the land mass. When moist air has risen high enough, water vapor condenses into **precipitation** (rain, snow, and hail). Some rainwater runs into streams and lakes. Most of this water finds its way into rivers that finally flow into the ocean. Other water is absorbed into soil to later evaporate or be used by plants. Finally, some rainwater percolates into the **water table**, which is the upper surface of saturated underground material. Most of this, too, eventually returns to the sea.

It is worth pointing out that climate change is rapidly accelerating this water cycle. Higher temperatures means more energy; with more energy, more water can be transported more quickly through the cycle. It also means an increase in amplitude in precipitation variation; that is, more extremes between wet and dry cycles and more extreme events like 100-year rainstorms, exceptional snowfalls, or severe prolonged drought.

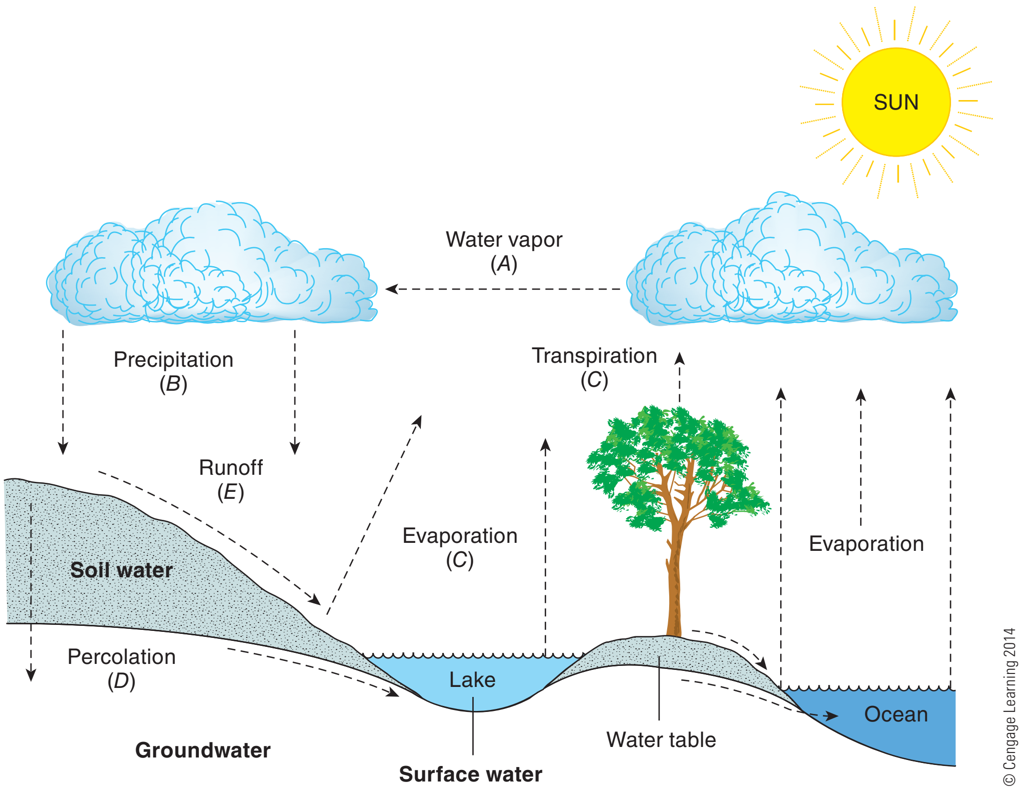

Figure 8–1
In the hydrologic cycle, water cycles between ocean and land, turning saline ocean water into freshwater available for our use. Letters labeling the cycle refer to the quantities listed in Figure 8–2.

Let us look more carefully at that point in the cycle when precipitation lands on the soil. Water proceeds in the cycle by one of four paths:

- Rainfall or snowmelt that cannot be absorbed into soil fast enough runs into low areas, streams, or lakes. This water is called **runoff**.
- Gravitational water percolates below the root zone of plants. Some may enter the water table.
- Some of the remaining water stored in the soil evaporates from the surface back into the atmosphere.
- Most water taken up from soil by plants is transpired into the atmosphere. The total water loss due to transpiration and evaporation is called **evapotranspiration**.

WATER RESOURCES IN THE UNITED STATES

Figure 8–2 shows where the United States' water resources are in reference to the hydrologic cycle. The reservoirs of water we draw on include water vapor in the atmosphere, surface water, and groundwater. Note that enormous amounts of water vapor float over the United States daily. Until we find practical ways to tap this supply without disturbing weather patterns elsewhere, we rely on natural precipitation to satisfy our water needs.

An average of 30 inches of precipitation falls each year over the continental United States, but the supply of water is unequally distributed. Average annual precipitation ranges from 9 inches in Nevada to 55 inches in Louisiana. Eastern states and the Pacific Northwest coastal areas tend to have higher rainfall, while most western states have a more arid climate and have to depend on irrigation to grow many crops.

More important than simple annual precipitation is the balance of precipitation and evapotranspiration. In the eastern half of the country and parts of the West Coast, more rain falls than is lost to evapotranspiration. In these **humid climates** water does not usually limit crop production, except on excessively well-drained soil or during occasional periods of dryness. In a **semiarid climate**, evapotranspiration

Yearly Amount	Inches/ Year	Billion Gallons/Day
(A) Water vapor	—	40,000
(B) Precipitation	30	4,200
(C) Evapotranspiration	21	2,900
(D) Percolation	3	411
(E) Runoff	6	822
Consumptive user	—	106

USDA Appraisal, Part I: Soil, Water, and Related Resources in the United States, 1980.

Figure 8–2
Each year in the United States tremendous amounts of water move through the water cycle.

Photo by Tim McCabe, USDA Natural Resources Conservation Service

Figure 8–3
Grazing land in Arizona. Raising animals on range is one way to use soil in drier climates.

slightly exceeds precipitation and moisture limits production. Special dryland farming systems (Figure 8–3) or irrigation overcome the problem.

In **arid c limates**, where evapotranspiration greatly exceeds precipitation, crop growth depends on irrigation. Despite the importance of irrigation nationally, natural rainfall remains the most important source of water. Seventy-five percent of our food and fiber is grown in "rain-fed" fields.

Climate change models predict significant changes in precipitation patterns that will influence agriculture. Rainfall in eastern states may increase; in fact, it has been mounting over the past decade or so. Rainfall in western states may decline, making a semiarid and arid zone even drier. Furthermore, if temperatures rise in western states, evapotranspiration rates will follow, as will the length of the growing season during which evapotranspiration occurs. The total effect will be to increase the moisture deficit in these states.

The remaining three sources of water, as shown in Figure 8–4, comprise stored water society draws on: saline ocean water, fresh surface water, and groundwater. As Figure 8–4 shows, saline ocean water supplies only a small percentage of the water used annually, and is very expensive both in cost and energy. Fresh surface water and groundwater are critical sources for irrigation and nonagricultural uses such as drinking water.

Surface water occupies lakes, rivers, and ponds and covers approximately 60 million acres of American land. The water is distributed unequally; most surface water is in the Great Lakes and a few other states, especially Alaska, Texas, Minnesota, Florida, and North Carolina. In many western states, surface water for irrigation and other uses depends on rivers fed by snowmelt in mountains; there the annual mountain snowpack is a matter of great concern, especially in this changing climate.

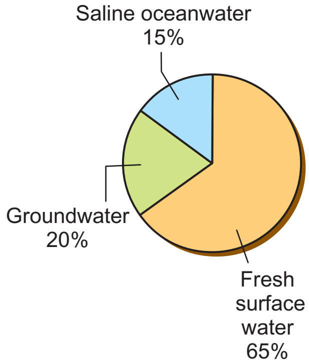

Figure 8–4

Water supply sources in the United States. We depend on fresh surface water and groundwater to meet our water needs.

Based on data from United States Geological Survey. Circular 1344. Estimated Water Use in the United States in 2005.

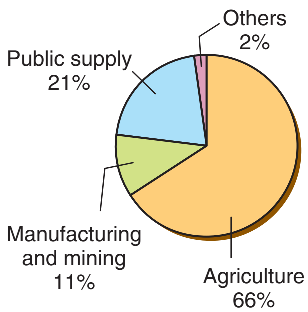

Figure 8–5

Agriculture, as in much of the world, is the largest consumer of water in the United States.

Based on data from United States Geological Survey. Circular 1344. Estimated Water Use in the United States in 2005.

Groundwater is stored in underground formations called **aquifers**. There is far more groundwater than surface water. Experts estimate that some 8,000 trillion to 10,000 trillion gallons of water are contained in mainland United States aquifers. However, this water renews very slowly, averaging about 3 inches per year (Figure 8–2). According to the United States Department of Agriculture (USDA), about 25 percent of the nation's groundwater supplies are being "mined," withdrawn more rapidly than renewed. This occurs mostly in the southern plains and the Southwest, where the water loss per day (in an average year) is 15 billion gallons of groundwater.

Reasons for Conservation

Agriculture consumes almost 70 percent of the water used annually in this country (Figure 8–5), mostly for irrigation. With expanding competition for water with growing urban populations and calls for increased streamflows to maintain natural habitats, the percentage of water dedicated to agriculture is likely to decline. Schemes to persuade growers to sell irrigation water to expanding municipalities have already begun to be implemented in western states. Even worldwide, water use is reaching some limit. Between 1940 and 1990, worldwide withdrawal of freshwater for human use quadrupled, mostly going to irrigation. This rapid expansion of irrigation was one of the factors responsible for a significant reduction in hunger is some parts of the world. Unfortunately, the supply of freshwater is limited by dynamics of the water cycle.

Interestingly, total water usage in the United States, according to the U.S. Geological Survey, peaked in 1980, including for irrigation. Public supply—water provided to people for nonindustrial use—has continued to grow, but less rapidly than population growth.

The nation and its growers benefit from agricultural conservation efforts in three ways: preservation of water resources, increased yields, and fewer water-quality problems from runoff.

Preservation of Water Resources

It takes 40 gallons of water to produce 1 egg, 150 gallons for 1 loaf of bread, and 2,500 gallons for 1 pound of beef. If forecasts are correct, growers will increasingly compete with other users for the nation's water to produce such agricultural products.

As the largest user, agriculture has a special responsibility to conserve, both for national well-being and in its own self-interest.

Increased Yields

Water conservation methods result in improved soil moisture and better yields. Semiarid areas respond especially well to conservation efforts. For example, about 4 inches of water is needed to mature a wheat crop. Reports from USDA research indicate that each additional inch of available moisture stored in the soil can raise production from 2.5 to 6 bushels per acre.

Reduced Runoff

Some of the strategies for conserving water involve reducing runoff from farm fields.

Methods for reducing runoff do more than improve soil moisture. They have other beneficial effects, such as:

- Reduced erosion and topsoil loss
- Reduced downstream flooding because less water runs into rivers
- Reduced water pollution from soil particles, fertilizers, pesticides, and human pathogens carried off farm fields by runoff

Water-Use Efficiency

Water-use efficiency is a good place to begin a discussion of water conservation. Of the water that lands on a field, little actually becomes part of the dry matter of crop plants. Most is lost to runoff, percolation, or evapotranspiration. The total amount of water needed to produce a unit of dry plant matter, such as a bushel of oats or a nursery tree, is one measure of **water-use efficiency**.

There are three primary means of improving water-use efficiency. One is to capture more of the water from precipitation in the root zone of crop plants. This means improving the infiltration rate and reducing percolation. Having captured more water, the second step is to reduce consumptive use. **Consumptive use** is the sum of the water lost by evapotranspiration and the amount contained in plant tissues. About 1 percent to 10 percent of total consumptive use actually becomes part of the plant; 90 percent to 99 percent of the total is evapotranspiration. The third way to improve water-use efficiency is by improving irrigation systems (Chapter 9).

CAPTURING WATER IN SOIL

To capture into the root zone more of the water landing on a field, a grower can improve infiltration or reduce deep percolation. Of the two options, improving infiltration is easier. Infiltration rates are, of course, a function of soil texture, structure, organic matter content, degree of compaction, or presence of barriers such as hardpans and plowpans. Slope also increases runoff and decreases infiltration.

Structure of the entire soil profile is important, but structure at the soil surface is most critical to infiltration. As noted earlier, the soil surface is sealed by the shattering of surface aggregates by raindrops or puddling. As a result, a crust may be formed that significantly reduces infiltration.

In both urban and rural areas, managing soil to encourage infiltration instead of runoff is a major tool of water conservation that also reduces soil erosion. The list of factors influencing infiltration suggests two problems that lower the amount of infiltration. One problem is low water-intake rates and the other is runoff due to slope. Let us look at methods for dealing with slope first.

Capturing Runoff

Terraces have long been used to capture runoff water. Terraces consist of a series of low ridges and shallow channels running across the slope, or on the contour, as

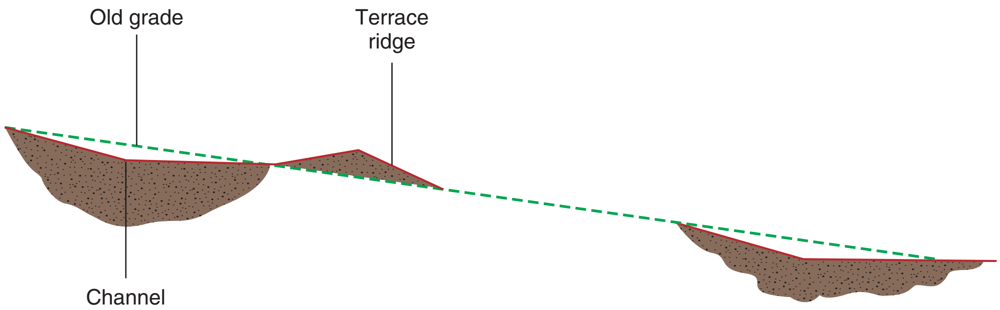

Image based on the Natural Resources Conservation Service Conservation Practice Standard for Terrace, NE-T.G. Notice 274, Section IV, NRCS, April 1998.

Figure 8–6

Cross section of flat-channel terrace designed for water-use conservation.

shown in Figure 8–6. When water begins running down the slope, it runs into the terraces, where it gathers while it seeps in.

All terraces are built to control runoff. However, in humid areas, the main concern is to control erosion. In drier areas, the primary purpose of terracing is to increase moisture in the soil. To save moisture, terraces are designed to cause ponding of water on the terrace, giving water time to infiltrate. Figure 8–6 shows the cross section of a flat-channel terrace built for this purpose.

Container nurseries and golf courses often alter their topography to capture rainfall and excess irrigation water and direct it into holding ponds for reuse. While a major reason for such a design is to retain pollutants such as pesticides and fertilizers on-site, it also conserves water.

Contour tillage is practiced by operating all equipment across the slope of the field, on the contour. This practice makes many tiny ridges across the slope. Water ponds behind these ridges, giving it time to infiltrate the soil. In contrast, tilling up and down hills creates actual channels for water flow, contributing to runoff and erosion.

Strip-cropping slows runoff water by alternating bands of different crops across the slope. One band may be a row crop that leaves most of the soil bare, such as corn or soybeans. The next band would be a close-growing crop (small grains), or a crop that completely covers the soil, such as hay. The close-growing strips slow water, keeping it from achieving the speed it would on a continuous slope of corn.

These practices are detailed in Chapter 18 (Soil Conservation) and images of them can be examined there.

Improving Water Intake Rate

A second way to decrease runoff is to improve the rate at which soil absorbs moisture. The soil's physical properties of texture, structure, and permeability set the infiltration rate. Chapter 4 lists ways to improve soil permeability and structure in the section on tilth. Because compacted soil tends to shed water, growers should be particularly careful to avoid severe compaction. The following practices also help soil absorb moisture.

Subsoiling, or deep plowing, shatters plowpans resulting from years of tillage, letting water seep deeper into the soil. At the same time, it allows roots access to deeper soil levels. Power requirements for subsoiling equipment make this method expensive, especially if it must be repeated later.

Crop Residue (tons/acre)	Runoff (percent)	Infiltration (percent)
0	45	54
1/4	40	60
1/2	25	74
1	0.5	99
2	0.1	99
4	0	100

Table created based on data from Purdue University

Figure 8–7
Effect of crop residue on water runoff and infiltration on a 5 percent slope.

Aeration is a term applied by turf managers to the process of punching or coring holes every few inches in turfgrass to break through surface compaction. Improving infiltration is one of several benefits (Chapter 16).

Mulch, such as a layer of straw or wood chips on the soil, strikingly improves infiltration by eliminating crusting and improving surface soil structure. Mulch protects the soil surface from the impact of raindrops. Studies show that mulched soil absorbs water two to four times better than bare soil. Gardeners or growers of high-value crops may mulch with straw, leaves, or grass clippings. Landscapers use gravel, wood chips, shredded barks, or other materials. In farm fields, **conservation tillage** leaves a mulch of crop residues on the soil surface (Figure 6–5 in Chapter 6). Figure 8–7 demonstrates improvements in infiltration rates and reductions in runoff due to conservation tillage.

Capturing Snowfall

In northern areas, capturing winter snowfall is an important way to retain natural precipitation. The key is to keep snow from blowing away from fields. Some growers leave strips of a tall crop standing at right angles to the prevailing winter wind. These **buffer strips**, which act as snow fences, should be about 50 feet apart. Some strawberry growers in cold climates plant such strips between strawberry rows to capture snow for cold protection.

Crop stubble left standing over winter also captures some snow. Because the stubble also lowers runoff, more of the snowmelt water is then able to soak into the ground. This practice is called **stubble-mulching**.

Reducing Percolation

Water drains very quickly through coarse soils, causing high percolation losses, which are difficult to reduce. The most practical way to reduce percolation losses is to improve the water-holding capacity by maintaining the organic matter level. Because topsoil is usually the most moisture-retentive soil layer, reducing erosion is also important. In fact, the USDA estimates that the loss of moisture-holding capacity due to excess erosion costs American growers $2 billion annually.

The water-holding capacity of soil, especially of sandy soil, may also be improved by incorporating crystals of **hydrophilic gel polymers**. These new materials absorb many times their weight in water, swelling dramatically. Because these gels release water at low potential, moisture is retained until the soil dries enough for plants to need access to the water. Gels have been most often used in greenhouses to increase water retention in potted plants, but they have also been used in sand-based sports turf and to improve survival in transplanted tree seedlings. However, when they are buried, pressure from surrounding soil inhibits their swelling, and thus their ability to take up water. High soil salt levels also reduce their effectiveness, so gels may not help in all situations.

REDUCING CONSUMPTIVE USE

Consumptive use is the total water "used" to produce a crop—including evaporation, transpiration, and water that becomes part of the plant. Consumptive use varies dramatically from place to place and crop to crop. Warm temperatures, wind, and low relative humidity all increase evapotranspiration.

Reducing Evaporation

The factors that affect evapotranspiration are largely beyond the grower's control. However, there are some methods that can help reduce evaporation. Growers can lower evaporation from soil by covering the soil surface with either vegetation or mulch, shading the soil, and reducing wind velocity at the soil surface. To shade the ground with crops means to grow them so the crop canopy quickly covers the soil.

Mulches have the additional benefit of acting as a barrier to moisture movement. Loose, organic mulches such as straw form only a partial barrier, and reduce but do not eliminate evaporation. Many growers of high-value crops, such as berries, nursery stock, or vegetables, mulch not only to preserve moisture but also for weed control and other purposes (see Chapter 6). For other growers, conservation tillage leaves residues as a mulch on the soil surface.

Reducing the number of tillage operations helps control evaporative losses. Each time the soil is worked, moist soil is dragged to the surface where it can dry out. Conservation tillage, use of herbicides for weed control, and combining tillage operations are ways to reduce tillage.

Reducing Transpiration

It is difficult to control transpiration in plants. Three weather conditions cause high transpiration: high temperature, low humidity, and wind. Frequent light sprinkling of plants with water improves conditions by wetting the leaves and raising humidity. This practice is called "crop cooling." Golf course and turf managers may lightly sprinkle turf to reduce heat stress during temperature extremes, a practice they call **syringing**. However, this method can hardly be called a moisture conservation measure because it uses moisture.

Transpiration may be reduced directly by coating leaves with a material that reduces water loss through stomata and leaf surfaces. These **antitranspirants** may be used on golf greens, to reduce transplant stress to landscape plants during planting, and in other special situations. However, while reducing water loss through stomata, antitranspirants also reduce movement of carbon dioxide into the leaf, inhibiting photosynthesis. It seems unlikely that antitranspirants would be useful in reducing water loss when active photosynthesis and growth are desired.

Another method of reducing transpiration is to plant windbreaks to cut the wind (Figure 8–8). Orchardists often plant tree windbreaks. A few growers protect low-growing crops by planting rows of taller plants across the field. For example, a truck farmer may plant a few rows of sweet corn every 50 feet at right angles to the prevailing summer wind. Between these rows are planted cucumbers or another low-growing crop. The tall sweet corn rows create areas of less wind and so protect the cucumbers from the effects of wind.

Weeds also transpire moisture, so weed control is a basic moisture control measure. Weed control is a central part of summer fallow, a grain-farming technique in semiarid areas of the Great Plains. This will be covered in detail in Chapter 16, but it involves leaving the soil bare every other year to store moisture for the following season. Weeds are controlled by cultivation or chemicals so they do not pull moisture out of the soil.

Improving Plant-Use Efficiency

This chapter has focused on how to increase the amount of water available for plants in the soil. Another way to conserve moisture is to help plants make better use of soil water. This allows greater production with the same amount of water.

The efficiency of plant water use can be measured by the transpiration ratio. This ratio is the amount of water transpired divided by the amount of dry matter produced. The ratio is affected by climate, the specific plant, and the soil conditions. The higher the ratio, the greater is the amount of water needed to produce a pound of dry matter. There is great variation between plants. For example, alfalfa (885) needs three times as much water to produce a pound of material as sorghum (271).

Photo by Erwin C. Cole, USDA Natural Resources Conservation Service

Figure 8–8

These windbreaks in Indiana, by reducing wind velocity over the field, reduce evapotranspiration water losses.

One does wonder, as water scarcity increases, if irrigating alfalfa in dry climates is a sustainable practice.

How can growers improve transpiration efficiency? Windbreaks and crop cooling can help by lowering transpiration. One important method suitable for all growers is to improve the rooting zone of plants. Compaction and plowpans limit the soil volume that a plant can exploit, leading to an increase in the transpiration ratio. Therefore, practices listed in Chapter 4 for improving structure and controlling compaction are important techniques.

Good soil fertility also improves water use by plants. Adequate levels of nitrogen and phosphorus increase the size and depth of root systems and lower the transpiration ratio. For example, work in Texas showed that unfertilized (nitrogen) sorghum produced a 190-pound yield per inch of water used, while sorghum fertilized with 240 pounds per acre of nitrogen produced a 348-pound yield per inch of water used.

Some plants are well adapted for growing under dry conditions, and the use of such plants can improve water use. Selecting crops in dry areas with a low transpiration ratio, such as sorghum, reduces the need for irrigation. New crops can be an answer, but breeders also search for more drought-tolerant varieties of established crops like corn. Breeders now can also use modern genetic techniques to engineer low-water-using and drought-resistant varieties.

Water Conservation in Urban Areas and the Landscape

This text discusses techniques that conserve water in urban and landscaped areas in Chapters 17 and 19, but we will discuss a few here. As before, improving infiltration should be a primary goal, but most lawns shed water because of poor soil correction and preparation after the damage done during construction (Figure 4–14). Impervious surfaces like roofs and roadways also cover much of the ground.

The yard in Figure 4–14 should be leveled, then ripped (subsoiled) with a deep tillage tool to break up compaction, then tilled with the incorporation of large quantities of an appropriate organic amendment (like that of Review Question 11, Chapter 6). More likely, in practice it will just be leveled, perhaps tilled lightly, and a thin layer of topsoil spread over the surface. Heavy equipment can induce its own compaction, so should be avoided.

Water can be captured from hard surfaces by making them able to absorb water with *pervious paving* (also known as permeable or porous paving), by capturing runoff in rain gardens or retention ponds, or even collecting roof runoff with rain barrels or cisterns. Such techniques are becoming more popular and are discussed in more detail later in the text.

Urban dwellers can also replace humid climate grasses, shrubs, trees, and flowers with dryland-adapted species. This technique, xeriscaping, is growing rapidly in cities of the American Southwest where landscape irrigation strains water resources (Chapter 17). Some communities require xeriscaping in new construction.

LEED points are awarded (see Chapter 1) for implementing these practices, as well as the use of reclaimed water, and so are increasingly being employed in landscape settings. The new Minnesota Twins baseball stadium, Target Field, achieved LEED certification partially based on its system for reclaiming rain and irrigation water for irrigation and cleaning the stands.

USING RECLAIMED WATER

A final approach to conserving water is to apply water that had been used for some other purpose. This **reclaimed water** might be effluent of a sewage-treatment plant, or *greywater*, water used in the home kitchen or laundry. Use of such water has been investigated, and is finding increasing application in many locations, such as golf courses or even fruit groves. Some reclaimed waters contain contaminants that require special care, including higher salt levels, detergents, disease organisms, or heavy metals. Such water needs to be tested, filtered, and purified by various procedures. Even so, much reclaimed water can be applied successfully to a variety of horticultural and agricultural situations.

WATER QUALITY

Water quality is as important as water quantity. Like conserving water, agriculture has a special role in the preservation of our nation's water supplies. Fish kills in trout streams of the author's home state, caused by runoff from insecticide-treated corn fields, are an example.

Agricultural sources of water pollution are difficult to pin down, compared to a pipe coming out of a factory or sewage plant. Such **point sources** of pollution are relatively easy to identify, and government regulations have allowed the nation to make good progress in bringing industrial and urban point sources under control. Most agriculture is a **nonpoint source**, such as farm fields. An exception is large manure storage facilities and feedlots, which can be identified and are considered point sources. A number of studies have indicated that agriculture now accounts for the bulk of water-quality problems across the nation.

Current agricultural issues include seepage of nutrients such as nitrates (Figure 8–9) and pesticides into groundwater, and pollution of surface waters. Contaminants of the latter include soil particles, pesticides and fertilizers, organic debris, and disease-causing organisms. Manure applications can discharge nutrients into both groundwater and surface water, and can be a source of human pathogens. Some of these problems are discussed in Chapter 15, after fertilizers have been presented.

It has been assumed that the soil matrix filters chemicals from percolating water. Too often, the assumption has turned out to be false: preferential flow can bypass the soil matrix and move pollutants deeper into the soil quickly. Another case is that of very coarse soils with a high water table, especially if irrigated. Examples are wells of such areas as central Wisconsin and Long Island, New York, that have been contaminated by the toxic pesticide aldicarb used on potatoes. Aldicarb's use has been largely discontinued. It has even been found that contaminants can move in the soil attached to clay particles filtering through the soil with moving water.

Parts of the United States with limestone bedrock may exhibit Karst topography, or land in which solution of limestone bedrock by water creates caves, sinkholes,

Figure 8–9
Measuring nitrates in runoff using a monitoring well along a river in the Pacific Northwest.

and other channels from the surface. Agricultural chemicals traveling in runoff can flow directly into aquifers through these channels.

While agriculture leads all the contributors to water pollution, urban areas contribute lesser amounts. Most storm drains (Figure 8–10) conduct contaminated runoff into rivers or other receiving bodies of water. For that reason, the author's home state bans most uses of phosphorus in lawn fertilizers. Any action that prevents water reaching the storm sewer system thus improves water quality, such as improved soil preparation, green roofs, rain gardens, and others discussed in this text.

Climate change is likely to compound water-quality problems in some parts of the world. Climate change models predict a greater frequency of high-intensity rainfalls, leading to greater runoff into streams and rivers. The storm sewer systems in many cities are already undersized for the more frequent heavy rainfalls, causing bursts of polluted water to enter surface waters. Many of these cities are working on "green" solutions like rain gardens to avoid expensive upgrades of stormwater and sewage systems.

Ways to avoid water pollution are largely covered in various sections of this text. Here is a brief summary:

- Reduce runoff that can carry contaminants (earlier in this chapter).
- Reduce erosion that can carry contaminated soil (Chapter 18).
- Reduce fertilizer losses in percolating water (Chapter 15).

Courtesy of USDA Natural Resources Conservation Service

Figure 8–10
Storm drains lead to some body of water, so urban runoff reduces water quality. Keeping the water on the land reduces the runoff.

Photo by Lynn Betts, USDA Natural Resources Conservation Service

Figure 8–11
Tillage to the edge of the drainage ditch permits water to run off the field into the water without being filtered of sediment, fertilizer elements, pesticides, and other pollutants.

Figure 8–12
This vegetative buffer protects the stream by filtering sediment and pollutants out of runoff before it enters the stream.

- Apply and store manures properly (Chapter 15).
- Retain and restore wetlands that can filter pollutants from runoff (Chapter 9).
- Practice drainage management in artificially drained fields (Chapter 9).
- Install conservation buffers along streams and other bodies of water, as in Figures 8–11 and 8–12, to slow and filter runoff (Chapter 18).
- Follow LEED standards (see Chapter 1) in construction of new buildings, which incorporate the practices described here.

SUMMARY

Water conservation is important because usable freshwater is not an unlimited resource. Our major water supplies are rainfall, fresh surface water, and groundwater. In many areas of the nation, rainfall is inadequate and stored water is being depleted. As the major user of water, agriculture has an obligation to make more efficient use of water and to conserve water supplies.

Each grower has an interest in conserving water as well. Making the best use of water increases yields and controls erosion. Many techniques for improving

water-use efficiency have been outlined in this chapter.

One technique is to capture more of the water that lands on a field or yard. This can be done by terracing and contour tillage. Improving the soil-infiltration rate by means of preserving soil structure, mulches, conservation tillage, subsoiling, and proper soil preparation after building construction also helps. In some areas, it is helpful to trap snow in the fields.

Consumptive use can be reduced by lowering the amount of evapotranspiration. Methods include reduced tillage, windbreaks, and weed control. A large, healthy root system, possible in soils of good physical condition and adequate fertility, helps the plant use more of the soil moisture and reduces the transpiration ratio. The use of dryland-adapted plants in agriculture and landscape can greatly reduce water use. Reclaimed water may also be available in some locations for some uses.

Growers and other soil users need to pay attention to their contributions to polluted water. Fertilizers, pesticides, eroded soil, and organic debris can harm the environment and health.

REVIEW

1. Describe what paths water can follow after it falls to earth in precipitation.
2. Distinguish point and nonpoint sources of water pollution. What might be pollutants contributed by agriculture? Is agriculture usually a point or nonpoint source?
3. How does improving the infiltration rate improve water use? What are some methods for doing so? Why is this often particularly important in urban and suburban yards?
4. Plant-available water can be lost from the soil in ways that do not improve crop productivity. Describe these ways and how they might be reduced.
5. What benefits for growers, society, and the environment result from retaining more water on fields and reducing runoff?
6. Using information from Chapter 7, explain why we cannot use the vast amount of oceanwater directly for irrigation purposes.

ENRICHMENT ACTIVITIES

1. Observe the effect of mulching by filling two deep jars with soil to within 3 inches of the top. Carefully moisten the soil in each jar with the same amount of water. Mulch the top of one jar, leave the other bare, and compare the drying. Weighing each jar before and after a period of drying may also provide interesting results.
2. The Environmental Protection Agency has fact sheets on managing nonpoint sources at http://www.epa.gov/owow/nps/facts. You will find sheets there on both agricultural and urban sources.
3. For a broader view of water use in the United States, go to the U.S. Geological Survey main Web site on water use at http://water.usgs.gov.
4. A biennial report on the world's water resources is available at http://www.worldwater.org. The latest edition at the time of this manuscript preparation was *The World's Water 2011–2012*. A variety of data such as maps, tables, and charts are available on the site, and the full report can be ordered. This chapter opened with information off the Web site.

CHAPTER 9

Drainage and Irrigation

TERMS TO KNOW

- border-strip irrigation
- capillary fringe
- center-pivot irrigation
- drainage
- drip irrigation
- evaporation pan
- furrow irrigation
- hand-move irrigation
- hydric
- hydric soil
- leaching requirement
- mesic
- microirrigation
- microspray irrigation
- moisture regime
- perched water table
- saline (soil)
- seep
- solid-set irrigation
- soluble salt
- subirrigation
- subsurface drainage
- surface drainage
- surface irrigation
- traveling-gun irrigation
- wetland
- wetland hydrology
- wheel-move irrigation
- xeric

OBJECTIVES

After completing this chapter, you should be able to:

- define drainage and explain its importance
- explain the difference between wetlands and wet soils
- identify methods of artificial drainage
- identify methods of irrigation
- decide when and how much to irrigate
- name water-quality problems for irrigation
- explain natural soil moisture regimes

Many acres of American land suffer from one of two moisture problems—either the soil is too wet or the soil is too dry. With proper treatment, however, some of these acres become productive cropland, popular golf courses, and even attractive wetlands. These important moisture management tools—artificial drainage and irrigation—have made some lands highly productive. On the other hand, they have also been the root of some ecological problems. This chapter describes artificial drainage and irrigation, with some of its attendant problems. This chapter also says a few words about natural soil moisture regimes and their influence on ecosystems.

THE IMPORTANCE OF DRAINAGE

Drainage refers to how rapidly excess water leaves soil by runoff or draining through the soil. The term also describes a condition of the soil—how much of the time soil is free of saturation.

In a well-drained soil, excess water leaves the root zone quickly enough that roots do not suffer lack of oxygen. Poorly drained, or "wet," soils remain waterlogged long enough to interfere with plant growth. Three conditions contribute to soil wetness. First, soils may be wet because they are naturally impermeable, like a compacted clay soil. Second, soil may be inundated by flooding or runoff from higher elevations.

The third and most common cause of soil wetness is a high water table—the upper surface of a zone of saturation in the soil. Commonly there are major regional water tables at some depth. There may also be shallower local water tables that form above an impermeable soil layer that restricts deeper percolation. These are called **perched water tables** because they are perched above the regional water table (Figure 9–1).

Extending above the water table is a wet, nearly saturated zone created by capillary rise called the **capillary fringe**. The height of the fringe varies from about 6 inches in sand to about 18 inches in fine-textured soil.

Most drainage problems occur in depressions or large level areas that water cannot quickly exit by runoff. Parts of slopes may be wet where a groundwater layer intersects the land surface. Water leaks out into the soil at these locations, called **seeps**.

Effects of Poor Drainage

Where the water table or capillary fringe intrudes into the root zone, soil wetness can create anaerobic conditions that deprive roots of oxygen, as described in Chapter 7. For most plants, rapidly growing points such as root tips and root hairs are quickly

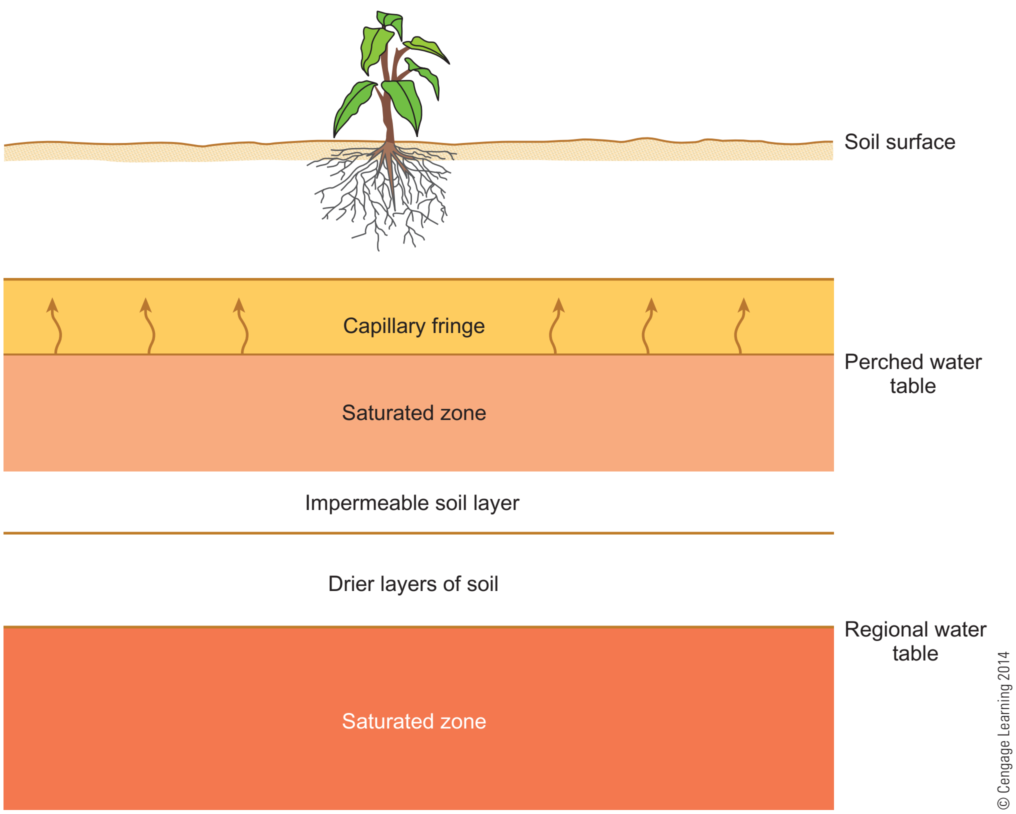

Figure 9–1
Water tables in the soil. Regional water tables can be at any depth. Sometimes an impermeable layer prevents deeper percolation, creating a perched water table. Above the water table lies a zone of wetness called the capillary fringe.

Figure 9–2
Heavy rains left standing water in these Iowa fields.

damaged, and root-rotting organisms attack the roots. Water and nutrient absorption suffers, and toxic materials build up in the soil. Rooting will be limited to the aerated zone above the fringe. Thus, soil wetness limits the growth of upland crops such as corn and apple trees, and most common landscape plants.

Poor drainage interferes with tillage and other growing operations like harvesting nursery stock. Poorly drained soil tends to stay wet later into the spring, delaying planting operations. Slow drying on poorly drained soils also keeps growers out of fields or nurseries after a rain (Figure 9–2). Because wet soils warm slowly, they stay cold later into the season and delay planting and seed emergence. Draining these soils lengthens the effective growing season. In arid and semiarid areas, poor drainage can cause accumulation of salts in the root zone, leading to crop damage and increased susceptibility to erosion. Poor drainage also frequently interferes with success in managed landscape settings.

WETLANDS AND WET SOILS

This text draws an important distinction between wet soils and wetlands. The latter are sufficiently valuable to the nation in the ecological services they deliver that their drainage is a questionable practice. Here we will describe differences between the two.

Wetlands

As a consequence of their importance, federal and state programs offer protection to wetlands (Chapter 20) (although Supreme Court decisions have diluted those protections), and losses have slowed over the past decades. Nevertheless, the 1997 National

Resource Inventory (NRI) estimates a current average annual loss of almost 33,000 wetland acres, about half to development and a quarter to agriculture. The 2003 NRI estimated that wetland acres had actually grown in the prior few years, but critics pointed out that many counted sites could not be considered true functional wetlands. Aerial surveys in 2006–2007 in Minnesota revealed continued wetland destruction, more than had been expected.

While the definition of a wetland and the procedures for determining what a wetland is (called *wetland delineation*) are based on a solid scientific foundation, rules concerning wetlands are also based on legal and political factors. **Wetlands** are defined as areas that are flooded or saturated by surface or groundwater often enough and long enough during the growing season to support vegetation adapted for life in saturated soils. This condition is currently indicated by three criteria:

- Wetlands possess **hydric soils**, defined as soils that are saturated, flooded, or ponded long enough during the growing season to develop anaerobic conditions in the upper part. More simply, the water table of a hydric soil is shallow enough that the capillary fringe extends to the surface, or is even wetter, for several weeks during the growing season. Gleying, mottling, and other indicative features in the upper part of the soil are indicators of a hydric soil.
- Wetlands exhibit **wetland hydrology**. That is, the amount and behavior of water in the soil is such that the surface soil is saturated enough during the growing season to warrant the designation of wetland, determined by actual measurement. Long periods of standing water are neither required to meet the definition nor to offer the benefits of wetland functions.
- Wetlands host identifiable wetland vegetation. National lists of these plants are maintained for purposes of applying these criteria.

Soils meeting these criteria are legal wetlands, and gain certain protections. Details of applying these criteria are beyond the scope of this text and continue to change and develop. However, we should discuss some of the values and functions of wetlands.

Water Control

Wetlands play an important role in water cycles of the United States. Many wetlands are sites for the recharge of groundwater. Wetlands also store water during snowmelt or heavy rains, reducing the amount of flooding by buffering rivers from an immediate influx of water. When wetlands are replaced by drained fields or suburban streets, large amounts of water enter rivers quickly, rather than being held in wetland reservoirs. Both large, permanent wetlands and small, seasonal wetlands contribute to flood reduction.

Water Quality

Wetlands play a role in improving water quality by trapping and filtering nutrients, sediments, and pollutants. Marsh plants absorb nutrients and even toxic chemicals. Peat on the marsh floor also absorbs pollutants, and high bacterial populations denitrify and remove nitrogen contamination. Thus, wetlands help reduce nutrient and chemical runoff from farms and nurseries. Restored or wholly created wetlands are

Figure 9–3
This small woodland pond in Minnesota is a natural wetland. Such wetlands have important ecological functions. These woodland ponds, for example, are important to woodland amphibians like tree frogs and wood ducks.

increasingly being used to cleanse runoff from farm fields, stormwater discharge into urban lakes, or even as an alternative to septic systems.

Wildlife Habitat

Wetlands function as wildlife habitat (Figure 9–3). Even small, seasonal, temporary wetlands are important to many species of waterfowl during spring migration. Hundreds of other nongame animals depend on wetlands for food, protective cover, or sites to raise young. More than 50 percent of threatened or endangered species are associated in some way with wetlands. In addition, wetlands provide spawning areas for many fish and shellfish, particularly coastal marshes that host commercially important species.

Recreation and Education

Wetlands also provide recreational and educational opportunities. Much hunting and fishing depends on wetland habitat, either directly or as nursery habitat for game or gamefish. Science classes often visit wetlands for study. Pollen embedded in peat layers on the marsh floor is studied to re-create past climatic and vegetative conditions.

Although society benefits from wetland preservation, landowners bear the cost without directly realizing all its benefits. This makes it common to drain or fill wetlands for cropping or development. In many areas of the country, few of the original wetlands remain. Iowa has lost 95 percent, California and Nebraska 90 percent, and the lower Mississippi Valley 80 percent.

Wet Soils

Wet soils have fewer ecological functions compared with wetlands. Nearly 25 percent of all farmland would be too wet to support full production if it were not drained.

The most apparent sign of poor drainage is the presence of standing water several days after a rain. Water-loving plants are often found growing on wet soil. A percolation test serves to infer drainage. In the test, holes are dug and filled with water to wet the soil around the hole. After emptying, the holes are refilled with water, and the time it takes for drainage is noted.

Soils are divided into the seven drainage classes listed in Figure 4–19. These classes range from the driest, *excessively drained*, from which water is removed very rapidly, to the wettest, *very poorly drained*, in which water leaves the soil so slowly that surface soil is wet during long periods of the growing season. Soil colors, as shown in Figure 4–19, can be good indicators. In general, soils of uniform color of high value and chroma are well drained, while mottling and low-value and low-chroma colors indicate poor drainage.

Soils classified as very poorly drained, and many of those that are poorly drained, meet the criteria for legal wetland and are best preserved as wetlands. Poorly drained soil must be treated for most crops, and even somewhat poorly drained soils often require treatment for best results. Those soils at the dry end, on the other hand, benefit from irrigation, discussed later in this chapter.

ARTIFICIAL DRAINAGE

Soils that stay saturated can be artificially drained. Artificially drained soils can be remarkably productive, as they are in much of the Corn Belt. Two types of drainage are available: surface and subsurface drainage.

Surface Drainage

Surface drainage systems collect and remove excess water from the soil surface. Surface drainage is best suited to three situations:

- Collecting excess surface water on impermeable soil that cannot absorb it readily
- Channeling away water flooding fields from higher elevations
- Collecting irrigation water applied in excess of the soil's ability to absorb it (although such application is itself a poor practice)

Surface systems are inexpensive to install because they are simply ditches dug through the field (Figure 9–4). Water flows off the land into the ditch and is discharged off the field. Random ditches may be dug to drain a few depressions. In large, uniformly wet fields, a series of parallel ditches collects water from the whole area. Some grading may be done to improve the slope of the field to ensure that the water runs into the ditches.

The primary function of surface systems is to remove surface water. However, they can also lower the water table in permeable soil if the ditches are dug deep enough to enter the water table. Water leaks into the drainage ditch from the soil. In most situations, however, a subsurface system is needed to remove subsurface water. The tile lines of a subsurface system often discharge into drainage ditches.

Surface drainage may also be improved by land grading. For example, playing fields are often crowned—elevated in the center, gently sloping to the edges—to

Photo by Lynn Betts, USDA Natural Resources Conservation Service

Figure 9–4
A drainage ditch drains these fields in Iowa.

move water more quickly off the field. Similarly, landscapes are also graded to avoid water problems around the building foundation, and drainage swales—essentially shallow vegetative drainage ditches—carry water out of housing developments.

Subsurface Drainage

Subsurface drainage collects water that has seeped into the soil and discharges it into surface ditches. A subsurface system consists of buried "pipes" into which water seeps and then flows to an outlet.

Water will not be released into a drain unless the surrounding soil is saturated, when matric potential goes to zero. Drains are therefore installed below the water table in the zone of saturated material. By removal of excess water, drains lower the water table, leaving a deeper surface layer of drained soil (Figure 9–5).

Subsurface drains are made of several materials. Common materials in the past were short drain tiles made of fired clay or concrete. The tiles are hollow cylinders 1 or 2 feet long. The contractor digs a trench and lays the tiles end-to-end. The tiles are not sealed together, so water seeps into the line through the joints.

Today, perforated plastic pipe largely replaces tiles in subsurface drainage systems. A long, continuous flexible plastic tube with holes (perforations) spaced along its length can be installed much more quickly than tiles. Plastic is less expensive to install than tile and is especially useful in soils that may break up tile lines by shifting.

The design of subsurface drainage systems depends on the situation. Small, poorly drained areas can be drained with a targeted system, while large areas will be served by a definite pattern (Figure 9–6). Soil texture determines depth and spacing; coarser-textured soils with better hydraulic conductivity allow wider spacings and deeper placement (Figure 9–7). A gentle grade in the tile line allows water to flow toward a collection main and on to an outlet (Figure 9–8), usually in a drainage ditch. From there the water flows toward some body of surface water, often a river, and is carried on to the sea. Where a grade is not feasible, water will be pumped for removal.

Tile lines are also installed around foundations to avoid moisture problems in basements. Some of the most advanced playing fields also include tile lines to return

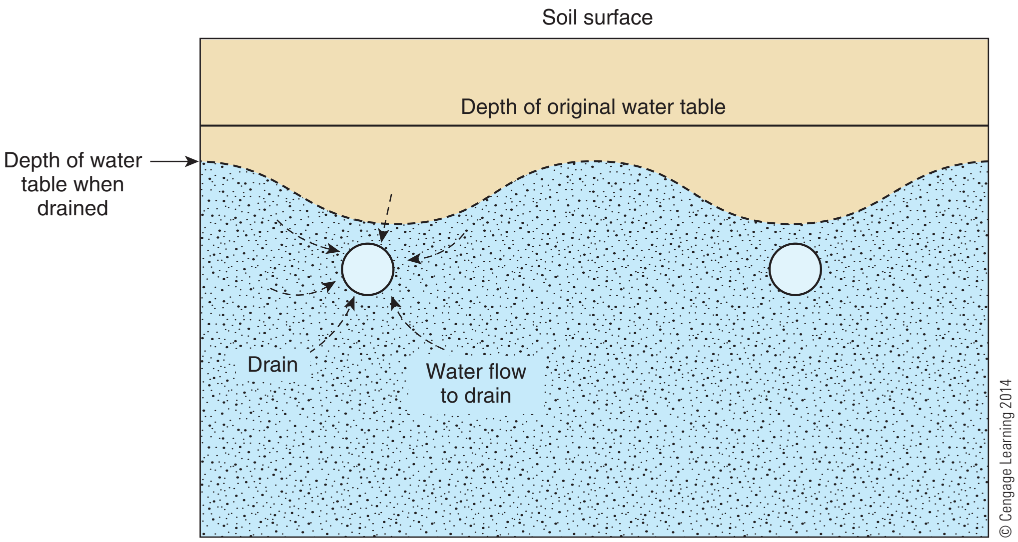

Figure 9–5
Buried drains lower the water table, especially the soil over the drains. Excess water flows toward the drains, and is carried out of the field.

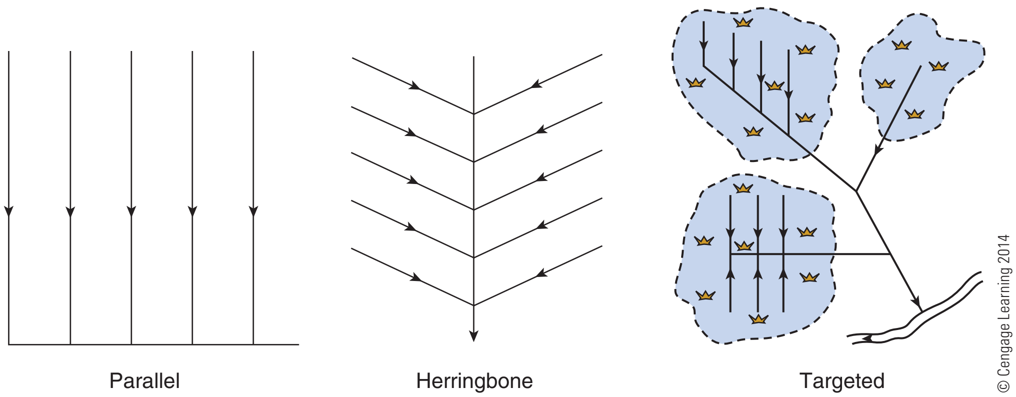

Figure 9–6
Different patterns can drain entire fields or isolated patches in a field.

Soil Texture	Depth (ft)	Spacing (ft)
Coarse	4.5	300
Medium	4.0	100
Fine	3.0	70
Organic	4.5	300

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Figure 9–7
Guide to maximum depth and spacing for tile lines.

fields to playability quickly after a rainfall, and residential landscapes with drainage problems may also be drained.

Drainage Management

While drainage systems enable us to farm some of our most productive soils, the accelerated water cycling on land creates environmental problems. It can, for instance, contribute to increased flooding by moving water rapidly off fields into rivers, causing a rapid increase in streamflow. Frequent flooding of the Red River of Minnesota and North Dakota is partially attributed to widespread artificial drainage of the surrounding flat land.

Artificial drainage degrades water quality by transporting contaminants through ditch systems and into rivers. In places, like some areas of the western United States, salt-laden drainage raises the salinity of water downstream. In many areas, drainage water carries nitrates from fertilization and manure application—no doubt, the tile outlet of Figure 9–8 is dumping not only water but also nitrates and some phosphorus into the ditch. Contaminants end up downstream where they cause water-quality and environmental problems. For instance, a large dead zone in the Gulf of Mexico has been attributed partially to drainage systems in the Mississippi River basin (Chapter 15).

Nitrate loading is most severe when drainage is most intense; that is, tile lines are deep (creating a deeper aerated zone), spaced close together, and run all the time. Nitrate loading can be minimized by installing or altering systems to drain less intensely. *Agriculture Drainage Management Systems*, or controlled drainage, reduce drainage intensity while allowing successful cropping. Controlled drainage systems shut down or adjust the outflow of drainage water during times of the year when the water table can be allowed to rise. Also, they can reduce overdrainage, or lowering the water table too much during dry spells.

Controlled drainage reduces the pollutant load because less total water is conducted out of the field in a year, and when soil is wetter, bacteria denitrify more nitrates to nitrogen gas before they leave the field. Allowing the water table to rise at times also allows water to be stored for crops, and can be used to slow subsidence

Photo by Lynn Betts, USDA Natural Resources Conservation Service

Figure 9–8

A tile outlet into a drainage ditch in Iowa. This excess soil water, and whatever contaminants it contains, enters local river systems and eventually the Gulf of Mexico.

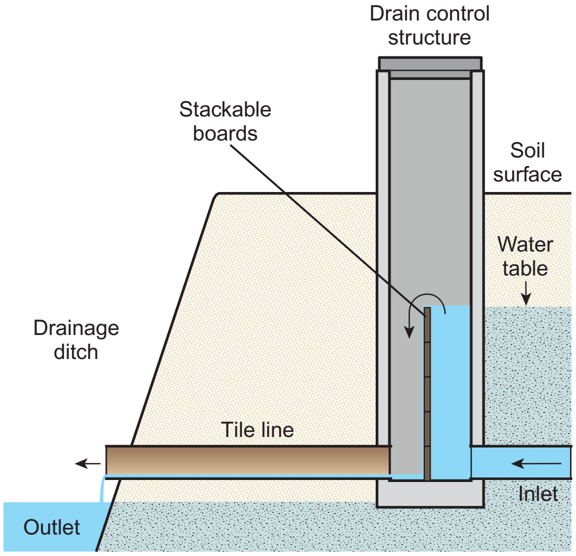

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Figure 9–9
A control structure for a drainage line. The water table will rise to the top of the stack of control boards, and so can be adjusted as needed.

of organic soils by reducing oxidation. Generally, controlled drainage involves gates that control outflow (Figure 9–9). By controlling outflow, the water table can be adjusted and allowed to rise during noncropping periods or even as a form of subirrigation (described shortly) during dry periods. In practice, the pollution load can be reduced an average of 30 percent with no loss (or even a gain) of productivity. The actual design of controlled drainage systems and their use varies from region to region depending on climate and topography

Landscape Drainage

Drainage problems can also haunt urban landscapes, compounded by the actions of developers and contractors, overirrigation, compaction, and other soil problems common to urban settings (see Chapter 19). We are speaking here of dealing with wet soils, not the engineering issue of removing stormwater out of yards. Anybody landscaping a yard may confront these problems, and we can suggest a few solutions.

Often the easiest solution is the selection of plant materials suitable to the drainage (see Appendix 5 for examples). However, even wet-tolerant plant species are usually raised in nurseries with well-drained soils, and commercially available specimens may not have developed the adaptations they would have if grown in the wild in wet soils.

Typically yards are graded to move water off the yard, and especially graded away from foundations to avoid moisture problems in the basement. Landscapers are often required to adjust this form of surface drainage. One of the most dependable, attractive, and inexpensive surface drainage options is the *landscape berm*, a gentle mound raised by piling good soil atop the existing grade in an artistic fashion. Plants are installed on this berm, which raises roots above the drainage problem and which sheds water enough to maintain good aeration in the root zone. Berms should never be placed on the root systems of existing trees. On a smaller scale, individual trees are often planted on their own slight mound to improve drainage around the root ball.

A simple surface/subsurface system common to landscape settings is the *French drain*, a narrow ditch filled with gravel, with or without drainage tubing in it. They are particularly useful for intercepting runoff or seepage from higher elevations, as described in Chapter 7. The trench must drop about 6–12 inches per hundred feet to an outlet, perhaps a rain garden (see glossary). More can be learned about French drains on the Internet.

In large-scale landscape settings, drainage problems may require the help of a drainage expert, being beyond the scope of many of us.

In the confined settings of urban areas, one must be very cautious about adjusting drainage lest the neighbors receive unwanted water. Your author has repeatedly seen changes in one yard lead to water problems in the neighbors' yards.

IRRIGATION SYSTEMS

Irrigation has a long history in world agriculture. We know irrigation has been practiced for at least 4,000 years. The success of civilizations along rivers such as the Nile in Egypt and the Ganges in India has been partially attributed to irrigation. In the United States, traces of 1,000-year-old irrigation canals can be found along the Gila River in Arizona.

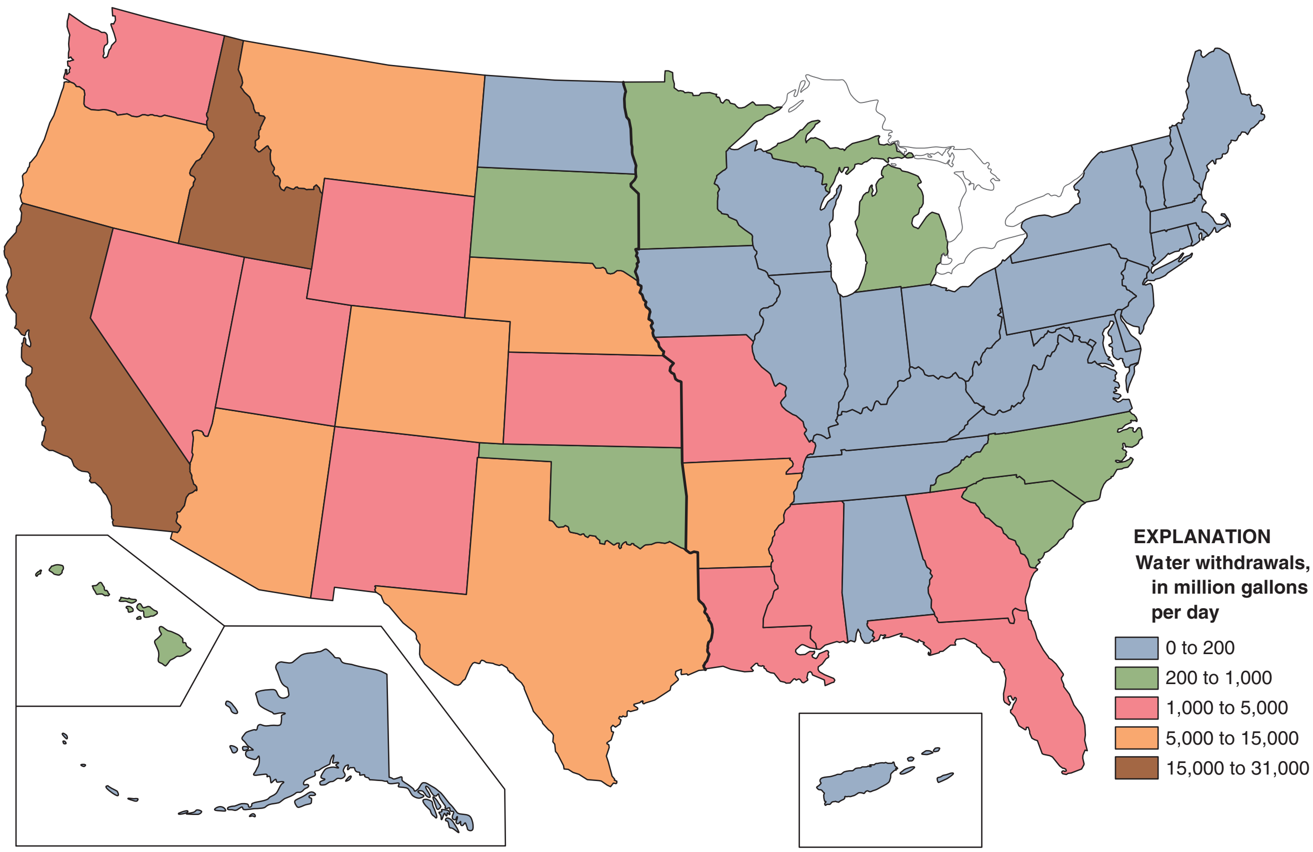
Today, 11 percent, more than 500 million acres, of the world's cropland is irrigated, especially in India, China, the United States, Mexico, and the Middle Eastern nations. Indeed, irrigation is partially responsible for a large reduction in world hunger since the 1950s in places such as India and China as part of the Green Revolution of the late twentieth century.

About 16 percent of American cropland is irrigated, concentrated especially in certain states (Figure 9–10). In dry parts of the country, irrigation is essential to cropping the land. Even in less arid regions, irrigation supplements natural rainfall, waters droughty soils, or relieves moisture shortages during dry spells.

Irrigation water can be applied in a number of ways that can be divided into four categories: subsurface, surface, sprinkler, and microirrigation.

Death of an Inland Sea

One of the world's largest lakes is—or was—Lake Aral in the former USSR, now in Kazakhstan and Uzbekistan. Soviet planners, in support of cotton growing, created vast irrigation systems that diverted water from the lake's tributaries. These drained the lake to such a degree that it is now a quarter of its former size and split into two smaller lakes, with the remaining water becoming quite saline. Dust blowing off the exposed lake bed and salt pans has contaminated surrounding regions, and regional climate has been altered. This ecological disaster is only the most extreme example of the damage that careless irrigation can do.



United States Geological Survey, Circular 1968. Estimated Water Use in the United States in 2000

Figure 9–10
Irrigation withdrawals in 2000 for the United States.

Subsurface Irrigation

Subirrigation is watering from below, using capillary rise from a deeper zone of saturated soil. The zone must be high enough that water can rise into the root zone, but not so high as to saturate it. In some places, subirrigation occurs naturally; in other areas, subirrigation is simply an extension of controlled drainage. Subirrigation on cropland is useful only in special situations. It is, however, increasingly common as a way to water potted plants in greenhouses using what we call flood benches or even flood floors. The specially designed bench is flooded, the pots are watered by capillary rise, and then the bench is drained and the water recycled. Forms of subsurface irrigation are also common to athletic turf management.

Surface Irrigation

Surface irrigation involves flooding the soil surface with water released from canals or piping systems. Surface irrigation is most suitable to level or slightly sloping land of moderate permeability. This is so because surface irrigation depends on ponding of water on the surface, and so can be used only where ponding does not lead to runoff and erosion.

Figure 9–11
Part of a canal system, a concrete lateral that services orchards in New Mexico. Such water conveyance systems are a typical part of surface irrigation systems.

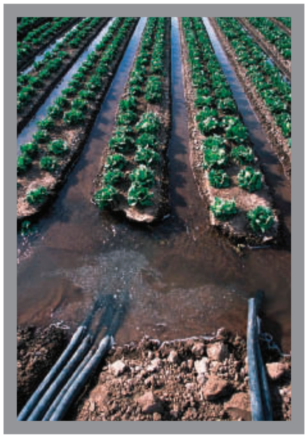


Figure 9–12
Water is siphoned out of the canal serving this lettuce field in Arizona for furrow irrigation. Note the dark soil on the sides of the ridges, evidence of capillary movement of water.

In preparing land for surface irrigation, fields are carefully leveled to a slight slope. A system of canals (Figure 9–11) uses gravity to carry water to the farm and among the fields. Surface irrigation is especially suited to areas where region-wide canal systems can be built, as in parts of the American West. After the water has reached the fields, it is distributed mainly by one of two ways—border strips or furrows. **Furrow irrigation** distributes water to the field in furrows, with the crop planted on the ridges between (Figure 9–12), while **border-strip irrigation** floods whole sections of field separated by dikes.

Surface irrigation is the least water efficient means of irrigation, with efficiencies ranging from 20 percent to 50 percent. This means only 20 percent to 50 percent of the water applied to a field is taken up by plants. The rest is lost to evaporation, deep percolation, or running off the end of the field. Soil erosion can also be a problem, as it always can be when water ponds on the soil surface.

Sprinkler Irrigation

Sprinkler systems pump water-under pressure through pipes to sprinklers that spray water out in a circular pattern (Figure 9–13). Sprinkler irrigation can be used where it is not possible to surface irrigate. For example, soil that is too permeable or too impermeable for surface irrigation can be sprinkled. Ground that is not level can be sprinkled without leveling. Uniform application of water over a large area, such as turf or pasture, is best accomplished by sprinkler systems. However, wind can disrupt the sprinkling pattern, so irrigation in windy weather may not be uniform; water evaporation also reduces efficiency.

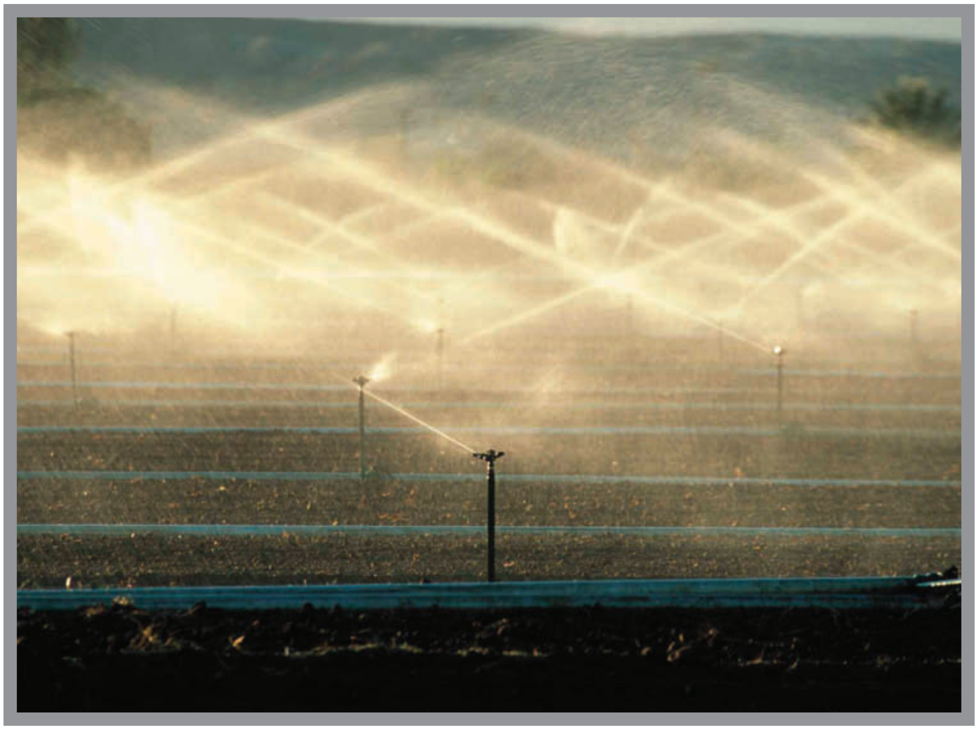


Figure 9–13
Solid-set sprinkler system in Arizona. Sprinkler irrigation is particularly useful for uniform wetting of larger areas, and is usually more water efficient than surface systems.

Sprinkler irrigation equipment can be used for other purposes in addition to watering crops. Some growers apply agricultural chemicals by sprinklers, a technique termed *chemigation*, or *fertigation* for fertilizers. Sprinklers can also substitute for rainfall to activate herbicides. One sprinkler system can be used for frost control.

Growers such as farmers or nurseries employ a number of sprinkler systems. **Solid-set irrigation** (Figure 9–13) involves laying out a pattern of aluminum pipes on the ground with sprinkler heads on short risers. The layout is designed for proper overlap of the circles. Solid-set systems work well for frost control on high-value crops. **Hand-move** systems use only a single line of pipe, moved manually from one setting to the next. Hand-move is much less expensive to install, but much more labor intensive.

Traveling-gun irrigation employs a single, very large sprinkler that covers several acres at a time. It travels the length of a field under its own power. It requires very high pressure to operate. A line of sprinklers mounted on wheels that rolls from one end of a field is a **wheel-move** system, as visible in the background of the image that heads this chapter.

The most common of all sprinkler systems is the **center-pivot** (Figure 9–14). The watering line is elevated above the crop by towers mounted on wheels. As the system operates, the line slowly turns around the pivot point. By the time the circle is complete, as many as 160 acres have been watered. Center-pivot irrigation has the lowest labor requirement of any irrigation method and is the best suited for large-scale irrigation.

Sprinkler irrigation has a moderate efficiency of 60 percent to 70 percent. Properly designed and executed sprinkler systems reduce sediment loss from fields, compared

Figure 9–14

A center-pivot system in Colorado. It will irrigate a large circle many acres in size as it pivots around its central point, not visible in this photograph.

to surface irrigation, as long as water is applied more slowly than the infiltration rate (Figure 9–15).

Microirrigation

Microirrigation includes two irrigation technologies designed to make more efficient use of water, improve productivity, and reduce environmental problems associated with standard irrigation methods. Unlike other methods, microirrigation delivers water to small, localized zones where the bulk of the roots are. The two techniques, drip (or trickle) and microspray, deliver water at slow rates right at the plant's root zone with little evaporation or runoff and without watering surrounding soil.

Drip irrigation was pioneered in Israel, where water conservation is critical. A trickle system is made of flexible plastic tubing running down a crop row, or buried under the row, with special "emitters" spaced along the pipe (Figure 9–16). Water drips out at a single point and wets a soil volume by capillary movement. Therefore, the wetting pattern and volume wetted depend on soil texture, and so must the spacing of the tricklers. On coarse, sandy soils, tricklers must be spaced very close together. Figure 9–17 shows how trickle irrigation can be designed to wet only the part of the soil occupied by roots.

Drip tape is an alternative to drip systems with emitters. Here a very lightweight plastic tube oozes water out its entire length, wetting a continuous band. These may

Photo by Tim McCabe, USDA Natural Resources Conservation Service

Figure 9–15

Surface ponding under a center-pivot system. Water is being applied faster than the soil's infiltration rate, and when water ponds on the soil surface, it can move and cause runoff and erosion.

Photo by Jeff Vanuga, USDA Natural Resources Conservation Service

Figure 9–16

Drip irrigation in a vineyard in New Mexico. More commonly, the tubing that carries water to the drippers lies on the ground. It may also be buried under the crop. Drip irrigation is the most water efficient of all systems.

be left on the surface or buried a few inches underground. Common to agriculture in drier places, they wet a crop row for good seed germination and plant growth.

Trickle irrigation is designed to *prevent* rather than *correct* water stress, unlike sprinkler and surface systems. Therefore, it generally takes less water to produce a better yield than the alternative systems. It also leaves much of the soil dry, reducing weed growth and interference with growing operations like tillage.

Drip irrigation is also widely used by greenhouse and nursery growers of potted plants. In this application, the emitter is on the end of a long "spaghetti" tube lodged in the pot.

In **microspray irrigation**, small spray heads replace tricklers (Figure 9–18). Like regular sprinklers, water is delivered through the air, but these are located near the ground in spray patterns only a few feet across. Like drippers, they wet only localized areas where roots are most concentrated, and so save water. Because they wet a larger area, microsprays are particularly useful for irrigating large trees, as in orchards, beds in landscape areas, or in coarse, sandy soils.

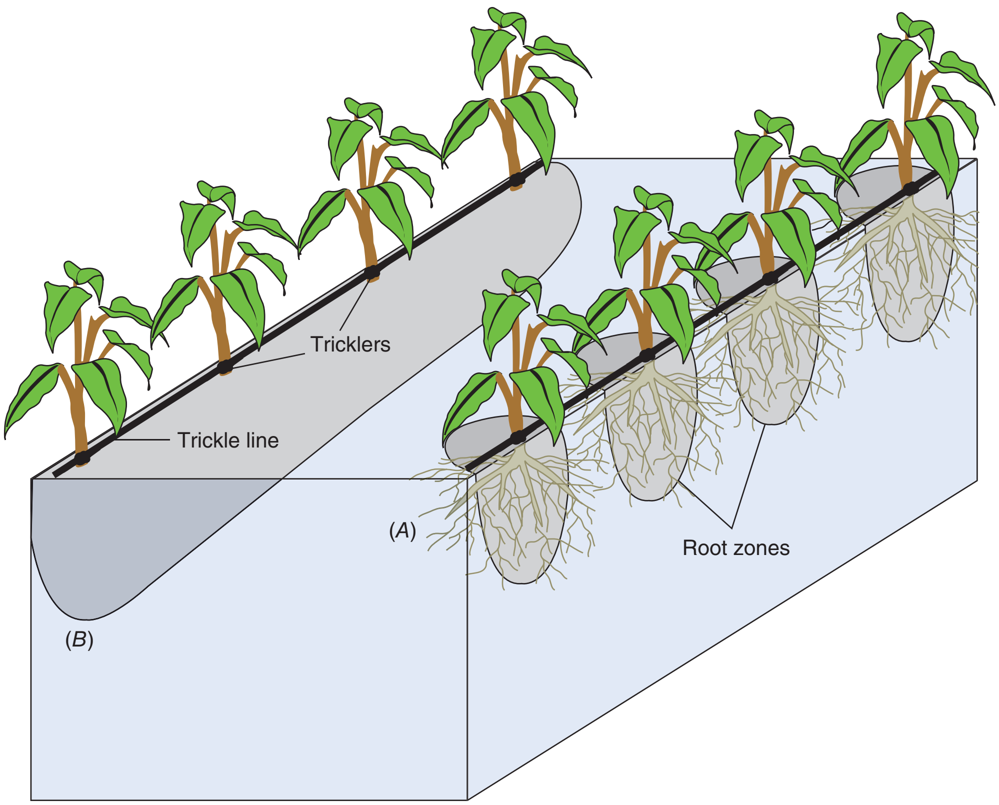


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Figure 9–17
Emitters can be spaced to water individual plants *(A)*, or spaced more closely to water a solid strip *(B)*. Nearly ideal moisture is maintained in part of the root zone, while nearby soil remains unwetted.

Photo by Lynn Betts, USDA Natural Resources Conservation Service

Figure 9–18
Microspray irrigation watering a landscape tree in Nevada. While watering only the root zone, it covers a wider area than drippers.

Much greenhouse irrigation uses microspray. Benches of plants can be watered with microsprinklers mounted on computer-controlled traveling booms that traverse the length of the bench, or from stationary microsprinklers mounted on stakes or even hanging above the bench.

The best water efficiencies are obtained by microirrigation, ranging from 80 percent to 90 percent. Trickle systems are the most efficient of all.

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Figure 9–19
A pop-up sprinkler in a lawn. In turf areas, sprinklers are attached to buried lines and pop up above the turf when in use. When not in use, they should be flush with the ground and below the level of mowing. They must be monitored for proper functioning and proper depth.

Landscape Irrigation

Just a few words about irrigation in the landscape. Landscape irrigation usually employs some combination of sprinklers and microirrigation. Irrigation design can be complex compared to agricultural systems because of numerous small, oddly shaped zones; because of the combination of different types of irrigation; because of high soil variability over small areas; and due to different types of vegetation. Nor should water land on hard surfaces like driveways, or hit the side of the house or other structures.

Landscape sprinklers are most often pop-up sprinklers attached to buried lines (Figure 9–19). The top of the sprinkler should be flush with the soil and pop up higher under hydraulic pressure when turned on. Often these fail to function properly, so landscape systems must be carefully monitored and maintained. Drip lines can be laid in parallel rows for beds of flowers and shrubs or snaked around to each plant.

Landscapes are often overwatered, which is wasteful of water and frowned on by municipalities. And high water application rates to turf can be damaging to flowers, trees, and shrubs. Thus, design and installation is best left to trained and certified professionals. The next section contains some bits of advice applicable to efficient lawn systems, such as the use of rain sensors, replacing time clocks with better sensors, and the like. Chapter 17 discusses xeriscaping, a style of landscaping designed to greatly reduce the need for irrigation, which is usually needed only during the first year for establishment.

LEED certification offers credits for systems that greatly reduce the use of potable (drinkable) water for irrigation. Listed examples include landscapes that reduce irrigation need by plant selection and other practices, high-efficiency irrigation, and the use of captured precipitation or recycled water. LEED-certified systems strongly promote the use of drip irrigation.

USING IRRIGATION

The ideal irrigation brings just the soil in the root zone to field capacity. Irrigation engineers—and growers who use the systems they design—decide how much water must be added to reach that moisture level. They must also decide how dry the soil should be before irrigating.

Irrigation practices vary in different parts of the country. In general, irrigation begins when 50 percent to 60 percent of the available water has been used by plants. An exception to this general rule is drip irrigation, which is designed to maintain field capacity.

Deciding When to Irrigate

Decisions about when to irrigate can be made based on three approaches: simple scheduling, measuring soil moisture, or determining evapotranspirative (ET) loss since the last irrigation or rainfall.

Simple scheduling is based on average crop needs and weather in a given region. Using local recommendations, one might read that corn requires a certain amount of water during the month of July, and irrigation is scheduled accordingly. Lawn sprinkler systems are often simply set on time clocks, which is easy for the owner but often does not reflect actual turf needs. Such systems may underwater during dry periods and, more commonly, overwater during periods when little irrigation is needed. We do not want to see sprinklers going during a heavy rainstorm, and time clock systems in landscapes should at least carry a rain sensor that shuts off the system during rainfall.

Soil moisture can be judged using a feel test similar to ribbon testing (Figure 9–20). A soil sample is taken from several inches below the surface. The feel of the soil is then compared with the chart in Figure 9–21. Irrigation should begin when the soil reaches the "fair" moisture level. While experience helps, feel tests are less reliable than measuring devices.

Photo by Jeff Vanuga, USDA Natural Resources Conservation Service

Figure 9–20
Efficient use of irrigation water requires proper scheduling with devices like potentiometers, evaporation pans, or manual evaluation using the wet ball method shown here.

Degree of Moisture	Feel	Amount of Available Moisture
Dry	Powdery dry	0%
Low	Crumbly, will not hold together	<25%
Fair	Somewhat crumbly, will hold together	25–50%
Good	Forms ball, sticks together slightly with pressure	50–75%
Excellent	Forms pliable ball	75–100%
Too wet	Can squeeze out water	Over field capacity

Figure 9–21
Guide to interpreting the manual soil moisture test of Figure 9–20. Begin irrigation when soil moisture is at the "fair" level. The third column lists the remaining percentage of available water at each soil moisture condition.

Potentiometers (tensiometers) and resistance blocks render more reliable readings of soil moisture, and so work very well for deciding when to irrigate. Resistance blocks work over the widest moisture range, but potentiometers are more accurate within a narrower range. Generally, potentiometers or gypsum block sensors are placed in pairs, one at a shallower depth and one deeper. An irrigation system can be automated by adding a controller to the potentiometer that triggers irrigation when the soil is too dry.

An alternative approach is to measure losses due to evapotranspiration. When those losses reach some level, the lost moisture is replaced by irrigation. A traditional way to do this is the **evaporation pan**, a large pan of prescribed dimensions set out where it will experience the same conditions as the crop. The rate of evaporation depends on temperature, light, humidity, and wind: the same factors that affect evapotranspiration (ET). Evaporation from the pan can be measured, compared to charts, and correlated with water needs. New, sophisticated irrigation controllers based on ET are now available that are like small weather stations, either sensing local conditions directly or obtaining real-time data from the local weather service. Such controllers, becoming more common in landscape applications, turn on or off irrigation automatically and allow precise control.

How Much to Water

It is important to add the right amount of water when irrigating. Too much water causes excess percolation and runoff, resulting in leaching of nutrients, wasted water, possible pollution, and even erosion. Too little water fails to bring soil to the best moisture level. Two factors affect the amount of water to be applied during irrigation: soil texture and rooting depth.

Figure 9–22 is a simplified table showing how much available water soils of different textures hold at field capacity; Figure 9–23 gives examples of the average rooting depth of several crops. As a simplified example of how to calculate the amount of water to be applied in one irrigation, let us consider soybeans in a sandy loam soil.

1. A medium-coarse soil holds 1.2 inches per foot of available water.
2. Soybeans root to a 2-foot depth.

Soil Texture	Available Water per Foot of Soil
Coarse	0.3–1.1 inches
Medium coarse	1.1–1.8 inches
Medium	2.0–2.9 inches
Medium fine	1.8–2.6 inches
Fine	1.2–2.0 inches

Figure 9–22
Available water held in soils of different textures at field capacity. This information is used to design irrigation systems and to calculate how much water to apply during irrigation.

Average Rooting Depth (ft)			
1	2	3	4
Beans	Beets	Alfalfa	Nuts
Cabbage	Cane berries	Cotton	Tree fruits
Carrots	Corn	Grapes	Shade trees
Cucumbers	Grains		
Onions	Melons		
Peanuts	Peas		
Strawberries	Potatoes		
Tomatoes	Sweet potato		
Turfgrass	Soy beans		

Figure 9–23
Average rooting depths for a variety of crops.

3. Total water available to soybeans = 1.2 inches/foot × 2 feet = 2.4 inches water.
4. Irrigation is turned on when 50 percent of the available water is gone. Thus, 50 percent of the water is to be replaced. Total added = 2.4 inches × 0.5 = 1.2 inches per irrigation.

This calculation tells a grower that if watering is started when the water is 50 percent gone, 1.2 inches of water will bring the root zone of soybeans in medium-coarse soil to field capacity. If the rooting zone contains more than one soil layer, each should be calculated separately. Precise information on any given soil is available in soil surveys (Chapter 3).

Application Rate

Water application rate is an essential component of irrigation design. In surface irrigation systems, with water ponded, the intake rate depends entirely on the infiltration of the soil. Water should be applied so the entire furrow or basin is flooded without large excesses leaving at the end.

For sprinkler systems, as long as we apply water more slowly than the infiltration rate, intake depends on the system's application rate. Water should not be applied faster than the soil's ability to absorb it to eliminate ponding and runoff

(Figure 9–15). The system's application rate is largely a matter of the engineering of the system; interested students should take additional coursework in irrigation design.

Saving Water

Saving water is an increasingly important task for the grower. In irrigation systems using a pump, saving water also means saving energy. It also helps avoid water pollution from unused irrigation water flowing into streams or seeping underground. The following points are ways irrigation water can be saved:

- Use the most water-efficient system that is practical. Where feasible, trickle irrigation uses the least amount of water.
- Make sure all systems are designed correctly to fit the crops, soil, and terrain. Maintain all systems for efficiency.
- Use the amount of irrigation water that gives the best return. Using less than the ideal amount may cause some slight yield loss, but it results in a savings in water. Researchers are developing models for determining the most efficient amounts of irrigation water to be applied.
- Schedule irrigation on actual plant needs, as noted previously, not on a time schedule.
- Use computers to automate irrigation systems and to make decisions about what crops need to be irrigated when.

WATER QUALITY

Both groundwater and fresh surface water are used for irrigation. The choice depends on the type of irrigation system used and on the water source that is most practical locally. When obtaining water, the first consideration is its legal availability. Most states have laws controlling access to water, such as water-use permits. Growers using water from federal water projects must also meet federal regulations. The second consideration is the quality of the irrigation water. Water may be contaminated by suspended solids, boron, or soluble salts.

Suspended Solids

Suspended solids are small bits of solid material floating in the water. Groundwater may contain grains of sand or silt. Surface water often has bits of organic matter or small aquatic organisms such as algae. Most irrigation systems are not bothered by small amounts of solids, but drip systems can be clogged. All drip systems should include filters to remove suspended solids.

Boron

Tiny amounts of boron are needed for plant growth, but slightly larger amounts can be toxic to plants. Some irrigation water has an excessively high boron level, especially for sensitive plants. Most fruits and nuts are sensitive to boron levels, while some crops, such as alfalfa and sugar beets, are relatively tolerant.

Soluble Salts

The most widespread water-quality problem is the presence of **soluble salts**. Soluble salts are compounds of sodium, calcium, and magnesium that dissolve in water. These compounds are found in various levels in soil and water. The problems of soluble salts will be examined in detail in Chapter 11, but their effect on irrigation will be surveyed briefly here.

When irrigation water evaporates from the soil surface or is removed by plants, salts will be left in the soil. Over time, irrigated fields may accumulate high levels of salts and become **saline**. Over human history, salinization of irrigated land has been one of our most persistent problems.

In the United States, salinity is most common in the western states. In the East, because of high amounts of natural rainfall, enough water percolates through the soil to leach salts out of the root zone. Soluble salt problems are especially acute for growers of potted plants because of the large amount of watering.

Soluble salts cause three problems. First, salts strengthen the osmotic potential of the soil, causing the plant to work harder to absorb water. Second, one of the cations, sodium, tends to break down soil aggregates. As a result, the soil surface is sealed and crusts form. Third, certain soluble salts raise soil pH, a particular problem in some greenhouses. Relatively salt-tolerant crops include barley, sugar beets, and cotton. Most vegetables, fruits, and alfalfa do not tolerate a saline soil.

Salinity is most severe where land is heavily irrigated with water containing fairly high salt levels. Irrigation water can be classified by salt and sodium hazard levels, as shown in Figures 9–24 and 9–25. The units in the table are explained in Chapter 11. One answer to the problem of salt buildup from irrigation is to use water low in salts. Container growers, in fact, must use water lower in salinity than that shown as acceptable in Figure 9–24.

However, as demand for water increases, irrigators may be forced to use increasingly salty water. Thus, growers must learn how to manage salty water.

The key to using salty water is to overirrigate so excess water leaches salts below the root zone. However, if the soil is impermeable or there is a high water table, salts

Class	Salinity Hazard	Conductivity (Micromhos/cm)	Description
I	Low	100–250	Suitable for most crops, little leaching needed
II	Medium	250–750	Moderate salt-tolerant crops or moderate leaching needed
III	High	750–2,250	Plants with good salt tolerance on drained soil with salinity control
IV	Very High	>2,250	Not suitable for irrigation except for occasional use under high salinity control

USDA Agriculture Handbook 60, 1954

Figure 9–24

Irrigation water salinity classes. This is for field irrigation; water for plants in containers should be much less salty.

Class	Sodium Hazard	Sodium Adsorption Ratio	Description
I	Low	0–10	Suitable for irrigation except for crops very sensitive to sodium
II	Medium	10–18	Suitable for coarse-textured or organic soils with good drainage
III	High	18–26	Soil will need treatment for sodium, or water must be treated to remove sodium
IV	Very High	>26	Generally not suitable for irrigation

USDA Agriculture Handbook 60, 1954

Figure 9–25
Irrigation water classes for sodium hazard.

return to the root zone by capillary rise. Drain tiles may be needed to carry salty water off the field. Of course, moving the salty water out of the field through a drainage system tends to move the problem downstream.

In irrigating saline land, one must balance the salt coming into the field with the salt going out to avoid a buildup. The saltier the irrigation water, the more excess water must be applied. This excess is called the **leaching requirement**. It is the amount of water to be applied in excess of that needed to wet the root zone of the plant. Leaching is also a common practice of folks who grow plants in pots, by letting excess water run out the bottom of the pot. Here the leaching fraction is commonly 10 percent to 15 percent of the water applied.

NATURAL MOISTURE REGIMES

So far, this chapter has stressed moisture management in agricultural or horticultural settings. Drainage classes discussed here, for instance, reflect a grower's understanding of soil moisture. But soil moisture also strongly influences natural habitats, and people who work with natural ecosystems need some way to classify soil moisture as well.

Ecologists tend to think of **moisture regimes**, soil moisture conditions during the growing season. The term can be confusing because the *Soil Taxonomy* (Chapter 3) also uses the term in classifying soils (not discussed in this text), but we are looking at a different system here, and terms may be used differently.

Xeric moisture regimes are dry. The soil is moist for very short periods after precipitation. These may occur on upper slopes, which are mostly shedding water, steep slopes, thin or coarse soils, soils with many coarse fragments, and where no layers in the soil retard drainage. Habitats under xeric moisture regimes will feature plants well adapted to dry conditions. Xeric regimes may also simply be called *dry*.

Mesic moisture regimes are of average moisture. The soil is moist for significant periods after precipitation. These may occur on midslopes, which are both shedding and receiving water from above, moderate to fine soil textures, reasonably deep soil profiles, or where some feature in the soil profile retards drainage slightly. Habitats under mesic moisture regimes host plants favoring adequate moisture, but intolerant of soil saturation.

Hydric moisture regimes are wet. The water table remains near the soil surface for significant periods during the growing season. These may occur in depressions or where some soil feature perches a water table. Habitats under hydric moisture regimes feature wetland plants, tolerant of soil saturation. Hydric moisture regimes may also simply be called *wet*.

Such schemes have intermediate conditions, such as dry–mesic or wet–mesic.

Individuals working with natural ecosystems are not, of course, interested in managing soil moisture by drainage or irrigation, but in better understanding and classifying natural habitats. But people who restore habitats, such as prairie restoration experts, need this information to guide their efforts. Even homeowners who want to use native plants will find that native plant catalogs use such a system.

SUMMARY

Artificial drainage allows a grower to make a productive field out of soil that is too wet to grow crops. In addition, drainage effectively prolongs the growing season by allowing earlier planting and better growth. While naturally wet soils are candidates for drainage, wetlands carry some legal protection as an important natural resource. Benefits of wetlands include improvement of water quality, reduction of flooding, and retention of wildlife habitat.

Poorly drained soil is deficient in oxygen, indicated by the presence of standing water or subsoil color. Surface drainage carries excess surface water off the field by means of ditches. Subsurface drainage moves excess underground water from the soil through buried drainage lines.

Drainage systems do have negative consequences, including losing wetlands, speeding the flow of water into swollen rivers, and transporting pollutants into rivers and other bodies of water. Controlled drainage systems reduce pollutant transport and water loads to surface waters.

Irrigation is primarily used to supply some or all of the water needs of crop or landscape plants. Subsurface irrigation uses capillary rise from a natural or artificial water table to water plants. Surface irrigation floods a field through border strips or furrows. Sprinkler irrigation sprays water over the soil surface through systems such as center pivots and solid set. Microirrigation drips water on the soil near plants or uses small sprinklers. It is the most efficient system in terms of water use.

A goal of irrigation is to avoid water stress on the plant. The need for irrigation can be judged by feeling the soil, by using potentiometers or resistance blocks to measure soil moisture levels, or by more exacting ET-budgeting methods. By knowing the soil type and rooting depth, growers can calculate how much water is required.

Water quality is a concern to all irrigators. Some water contains too much boron or suspended solids. Soluble salts are the more common problem, especially in the western United States. Growers can manage salinity by making sure drainage is adequate and by overirrigating to leach salts out of the root zone.

As water supplies dwindle, growers are becoming more concerned about their water use. Over time, irrigation must continue to become more efficient. In addition, more efficient and cost-effective ways must be developed to solve salinity problems.

REVIEW

1. Assume we wish to irrigate turf to a depth of 8 inches when 60 percent of available water is gone. Assume also that the root depth is a uniform silt loam texture with an available water-holding capacity of 2.5 inches per foot. How much water will we add each time?
2. Assume that the soil in question 1 has an infiltration rate of 2 inches per hour. What would be the shortest acceptable run time that could be designed into a sprinkler irrigation system? What would happen if the soil were later severely compacted and one maintained the same application rate?
3. Describe the benefits and drawbacks of artificial drainage.
4. How might topography affect the choice of irrigation systems?
5. Explain why poor drainage harms most plants.
6. Why might landowners decide to restore wetlands on their property?
7. Why might an irrigated field need to also have a subsurface drainage system? For which part of the United States might this be most likely?
8. What is a water table and a capillary fringe? How close would a water table have to be to the soil surface to meet the criteria for a wetland?
9. Some garden writers suggest loosening heavy clay soils with organic matter to relieve drainage problems. Under what situations might this help, and when would it not?
10. On citrus groves in sandy Florida soils, drip irrigation does not relieve moisture stress during dry spells as well as microsprinklers. Explain why.
11. When planting some trees in a landscape with impaired drainage, a landscaper digs some deep holes and fills the lower part with gravel to improve drainage. Would this be successful? Explain your answer.

ENRICHMENT ACTIVITIES

1. Observe the effects of salinity by watering previously established potted tomato plants with saline solutions. Use common table salt in water to create solutions of varying concentrations. Grow some control plants with untreated water, and compare differences in growth over time.
2. Obtain and use potentiometers or resistance blocks.
3. For an interesting historical perspective on wetland drainage, read "The Problem: Drained Areas and Wildlife Habitats" by F. Kenney and W. M'Atee in the *1938 Yearbook of Agriculture: Soils and Men*.
4. There is a wealth of information about wetlands and wetland protection at this Environmental Protection Agency site: http://www.epa.gov/owow/wetlands/vital/toc.html.
5. The University of Minnesota maintains a drainage site on the Internet that links to various other sites at http://www.drainageoutlet.umn.edu/education/default.html. It also has a drainage fact sheet at http://www.extension.umn.edu/distribution/cropsystems/M1292.html.
6. For photos and descriptions of drippers, microspray heads, or many other components of irrigation systems, numerous commercial sites may be found on the Internet.
7. The Environmental Protection Agency operates a program for promoting sensible water use in residential areas, including landscape irrigation, called WaterSense. The program is widely followed in the landscape industry. For the WaterSense page on landscape irrigation, see http://www.epa.gov/WaterSense/outdoor/landscaping.html.

CHAPTER 10

Soil Fertility

TERMS TO KNOW

adsorption
anion exchange
base saturation
beneficial element
cation exchange
cation exchange capacity (CEC)
colloid
diffusion
dissolution
essential elements
exchangeable base
expanding clay
isomorphous substitution
luxury consumption
macronutrient
mass action
mass flow
micelle
micronutrient
nonexchangeable ion
oxide clay
precipitate
primary macronutrient
root interception
secondary macronutrient
sesquioxide
silicate clay
soil fertility
soil solution
trace element

OBJECTIVES

After completing this chapter, you should be able to:

- name and classify the essential elements
- list four sources of nutrients in the soil
- describe soil colloids
- define *cation exchange capacity* and related terms
- describe how plants absorb nutrients
- explain other soil fertility factors

Soil fertility is the ability of soil to supply nutrients for plant growth. The soil is a storehouse of plant nutrients, stored in many forms, some very available to plants, some less so. The concept of soil fertility includes not only the quantity of nutrients a soil contains but also how well they are protected from leaching, how available they are, and how easily roots function. A beginning point for discussing soil fertility is to define the term *plant nutrient.*

PLANT NUTRIENTS

Plant nutrients are the **essential elements** needed for plant growth. Plants absorb at least 90 different elements, but only a few are needed for plant growth. Some are not needed by plants, but are needed by animals that eat them, and that makes those elements important for human and animal nutrition. Many elements are needed by neither plants nor animals, and others, like lead, are even toxic. Thus, plants contain many elements not needed for growth.

Which elements are essential? The most commonly accepted rules for determining whether an element is essential are as follows:

1. A lack of the element stops a plant from completing growth or reproduction.
2. The element is directly involved in plant nutrition, not merely "taking up space" in plant tissues.
3. A shortage of the element can be corrected only by supplying that element.

Based on these rules, 17 essential elements are identified by most scientists (Figure 10–1). Several others play a role in the nutrition of some plants but cannot yet be considered true essential elements for all plants. Some of these **beneficial elements** are also identified in Figure 10–1. The definition of an essential element is not as clear-cut as it might seem, and some scientists might include some or all the beneficial elements as essential (see sidebar).

A live plant is mostly water, some 90 percent by weight. Of the remaining mass, or dry weight, most is carbon, oxygen, and hydrogen in the form of organic compounds. Plants obtain these 3 from air and water during the process of photosynthesis. The remaining 14 elements are obtained from the soil, and we might call these *mineral nutrients*. It is these 14 elements that are discussed in this chapter.

Plants use 6 of the 14 mineral elements in large amounts. These 6 **macronutrients** are nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur. In the following relationship, the 6 nutrients are listed in decreasing order from the greatest amount used by most plants (nitrogen) to the smallest amount (sulfur).

$$N \geq K > Ca > Mg \geq P > S$$

Soils are less likely to be deficient in calcium, magnesium, and sulfur than the other 3 nutrients, and since most soils supply enough calcium, magnesium, and sulfur, soil scientists call them **secondary macronutrients**, or simply, secondary nutrients. The **primary macronutrients**, sometimes called fertilizer elements, are often not available in large enough amounts for best growth. The 3 primary nutrients—nitrogen, phosphorus, and potassium—are most often added to soil by fertilization. Note that the division into primary and secondary macronutrients is not based on the relative amounts used by plants but on their importance as fertilizers.

Defining Essentiality

The three criteria listed here were proposed in a seminal article by Arnon and Stout in the journal *Plant Physiology* in 1939, available on the Internet. Other authorities have proposed other criteria, and accordingly, between 16 and 20 elements may be considered essential. In practice, a fourth criterion is followed by many—that the element must be necessary for a wide range of plants, not just a few.

Name	Symbol	Ionic Form	Ion Name
Carbon	C	—	—
Hydrogen	H	H^+—(not used by plants in this form)	
Oxygen	O	—	—
Primary Macronutrients			
Nitrogen	N	NO_3^-, NH_4^+	Nitrate, ammonium
Phosphorus	P	HPO_4^{-2}, $H_2PO_4^-$	Orthophosphates
Potassium	K	K^+	—
Secondary Macronutrients			
Calcium	Ca	Ca^{+2}	—
Magnesium	Mg	Mg^{+2}	—
Sulfur	S	SO_4^{-2}	Sulfate
Micronutrients			
Boron	B	$B(OH)_3$, $B(OH_4)^-$	Boric acid, borate
Copper	Cu	Cu^{+2}	Cuprous
Chlorine	Cl	Cl^-	Chloride
Iron	Fe	Fe^{+2}, Fe^{+3}	Ferrous, ferric
Manganese	Mn	Mn^{+2}	Manganous
Molybdenum	Mo	MoO_4^{-2}	Molybdate
Nickel	Ni	Ni^{+2}	
Zinc	Zn	Zn^{+2}	
Beneficial Elements			
Sodium	Na	Na^+	
Silicon	Si	SiO_3^{-2}	
Cobalt	Co	Co^{+2}	

Figure 10–1

Essential elements and their ionic forms. Sodium, silicon, and cobalt are nonessential but beneficial elements.

The 6 macronutrients, except for potassium, are part of the materials that make up the bulk of the plant. Protein, for instance, includes both nitrogen and sulfur. Living tissue also contains very small amounts of certain important chemicals that control life processes, such as enzymes. The other 8 essential elements form part of these key materials in plants.

The other 8 nutrients, listed in Figure 10–1, are labeled **micronutrients** or **trace elements** because they are used in small amounts. Iron, for example, plays a role in the process that forms chlorophyll. Only a small amount of iron is needed, but too little iron means that chlorophyll fails to form (Figure 10–2). The term *micronutrient* does not, however, mean the elements are unimportant. Plants will not grow normally without enough of these trace elements; micronutrients are as important as macronutrients for plant growth.

Figure 10–1 also lists three examples of beneficial elements. These are elements that may not meet the strict requirements for being essential for most plants but that are helpful, or even important, for growth, or are needed by some plants. For instance, few plants require silicon to complete growth and reproduction, but its presence strengthens cell walls and reduces insect and disease problems, and nitrogen-fixing plants need cobalt.

The 14 "micro" and "macro" elements are furnished by soil. Plants absorb these elements in a specific way—as the ions listed in Figure 10–1.

Figure 10–2

The healthy pin oak *(Quercus palustris)* leaf is darker green than those exhibiting a lack of iron, a condition called *iron chlorosis*. Iron is a trace element involved in chlorophyll formation. In the chlorotic leaves in the background, little of the dark green chlorophyll has formed.

Nutrient Ions

Ions, as explained in Appendix 1, are charged atoms or molecules. The charge, either positive (a cation) or negative (an anion), results when there is a difference between the number of electrons and protons. One way ions form in soil is when compounds dissolve in water. For example, when the soluble fertilizer potassium nitrate dissolves, the molecule breaks into two ions:

$$KNO_3 \xrightarrow{\text{solution}} K^+ + NO_3^-$$

The potassium and nitrate ions now in solution can be absorbed by plant roots.

The concept of nutrients as ions is important. Plant roots *absorb* nutrient ions; soil particles *adsorb* them. Absorb means to take in something, like a sponge absorbing water. Adsorb means to attract a thin layer of molecules to a surface, where they stick. Figure 10–1 lists each nutrient in the ionic form(s) most commonly absorbed by plants. Any special name for the ion is also listed.

SOURCES OF ELEMENTS IN SOIL

Nutrient elements are present in the soil in four forms, as shown in Figure 10–3. We could consider these four pools of plant nutrients. Together, these four pools perform two functions: to store nutrients and to make them available to plants. The pools vary in their function: One pool is immediately available, but, like cash in the pocket, is easily spent or lost. Another pool becomes available very slowly, but, like long-term financial bonds, is preserved for future use. The four pools are as follows:

1. Soil Minerals. Minerals are the major source of all soil-supplied nutrients except nitrogen. Soil minerals are the longest-term storage. Weathering frees the elements slowly over time, dissolving the minerals into ions. Figure 2–5 lists the nutrients contained in several rocks. As minerals, we include here products of reactions of soil ions that remove them from the soil solution by precipitation. (see Enrichment Activity 4 and following discussion).

2. Organic Matter. This stores large amounts of several elements like nitrogen and the nutrient anions listed in Figure 10–1. Organic matter is an intermediate to long-term form of storage, since elements are freed for plant use by decay. Some nutrients in fresh organic matter are released fairly quickly, while those in humus are released more slowly.

3. Adsorbed Nutrients. These nutrients are held in the soil attracted to clay and humus particles. **Adsorption** occurs because clay and humus particles are negatively charged. Many plant nutrients are positively charged and so stick to the soil particles. Adsorbed nutrients are held fairly tightly by particles, but most become readily available to plants.

4. Dissolved Ions. Nutrient ions dissolved in soil water are the most readily available form of nutrients. The mixture of ions and soil water is termed the **soil solution**. Plants absorb ions directly from the soil solution. However, these nutrients may be rapidly consumed or leached away by percolating water.

As shown in Figure 10–3, nutrients can change form. As plants withdraw nutrients from the soil solution, elements held in reserve can become available to plants. While nutrients are held in reserve, they are protected from leaching or other losses.

The functioning of these four major pools creates a complex web of interactions that set storage and availability of plant nutrients. We tend to think of fertilization as "feeding" plants, from the grower's hand to the soil to plants, but in truth, the elements we add by fertilization simply enter this complex web. Only some are quickly taken up by plants.

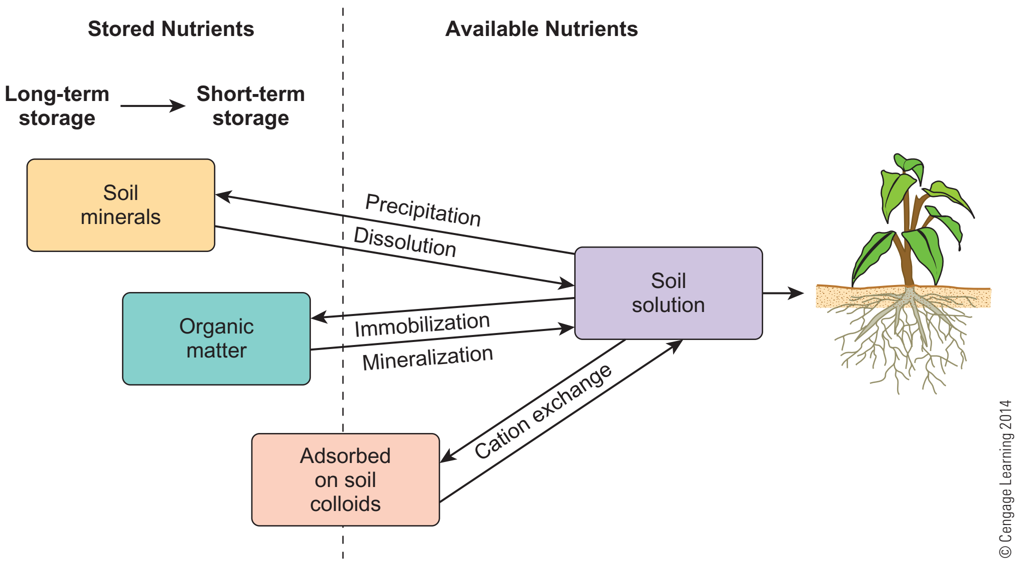


Figure 10–3

There are four primary pools of nutrients in the soil. Sources least available are shown on the left, most available on the right. Elements can change pools, and when they are removed by plants from the soil solution, stored ones become available.

SOIL MINERALS

We discussed the organic pool of Figure 10–3, and the processes of mineralization and immobilization in Chapter 6, and need not discuss it further here. However, it is worthwhile adding a few words about the soil mineral pool, before we proceed to soil colloids.

The mineral pool partially consists of *primary* soil minerals like feldspar in the process of weathering. As the process proceeds, elements are released into the soil solution, a process called **dissolution**. Dissolution may proceed very slowly in the case of weathering-resistant rocks like granite or more quickly in other rocks like limestone.

However, the process is not entirely one-way. Ions of nutrient elements can react with other ions in solution to form new, less soluble compounds. These new compounds **precipitate** out as solid particles of new, or *secondary*, minerals that form in the soil. An Enrichment Activity at the end of the chapter demonstrates the process. Such ions leave the soil solution and reenter the mineral pool. These reactions strongly reduce availability of some nutrients in many soils.

Removal by precipitation need not be permanent. The products of precipitation are themselves subject to dissolution and may later reenter the soil solution. Dissolution and precipitation of soil minerals strongly relates to soil pH, which will be discussed in the next chapter.

SOIL COLLOIDS

As shown in Figure 10–3, adsorption serves as a source of stored nutrients when plants take nutrients out of the soil solution. Nutrients are adsorbed on soil **colloids**, tiny clay and humus particles that carry a slight electrical charge. This charge is important because it attracts nutrient ions. The soil contains three types of colloids: silicate clays, oxide clays, and humus.

Silicate Clays

Clay minerals are not simply pieces of silt or sand broken into tinier particles. A clay particle is a tiny crystal of mineral formed in the soil from the weathered products of minerals like feldspar or mica. Feldspar and many others are primary minerals of the earth's crust, while the clay minerals that form from the products of their weathering

Colloids are tiny particles in the range of 0.005–1.0 µm (micrometer, or 0.000001 meter), which can remain suspended in a liquid medium for long periods of time. In the soil, clay and humus particles have the size and exhibit the behavior of colloids. These traits explain the large specific surface area they impart to soil and why they can move in soil, suspended in water.

are called secondary silicate minerals. The formation of these secondary minerals could be shown as:

$$\text{primary mineral} \xrightarrow[\text{dissoluion}]{\text{weathering}} \text{Ions in soil}$$

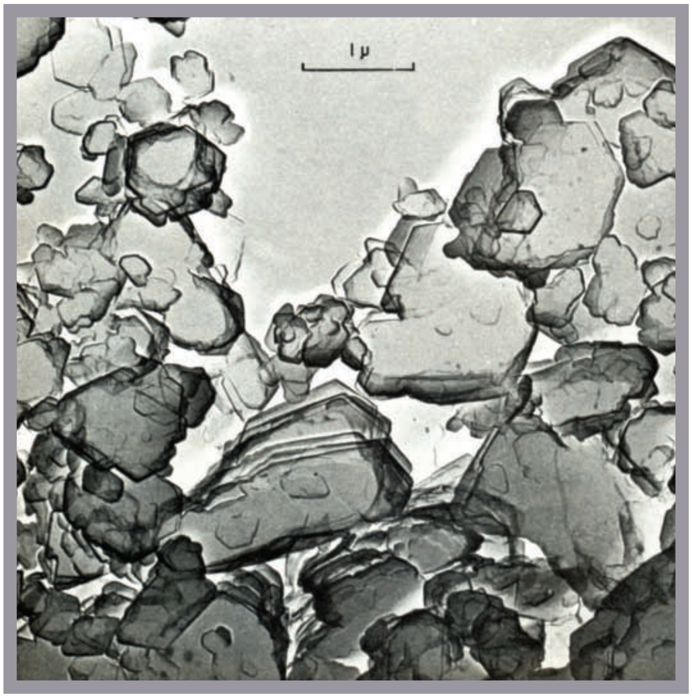
$$\xrightarrow{\text{crytalllzation}} \text{clay mineral (secondary mineral)}$$

A particle of **silicate clay**, called a **micelle**, is a flat, platelike crystal made of many layers (Figure 10–4). Each layer, in turn, is made of two or three sheets. The sheets are mainly composed of three elements: silicon (Si), oxygen (O), and aluminum (Al). These three elements combine to form several kinds of sheets, which can combine to form several kinds of clays.

In the soil, silicon combines with oxygen to form the silica sheet. The basic unit of the silica sheet is the silica tetrahedron: a silicon atom surrounded by four oxygen atoms. This forms the shape of a four-sided pyramid or tetrahedron (Figure 10–5A). Many tetrahedra join together by sharing oxygen atoms to form the silica sheet.

The second important sheet in silicate clays is the alumina sheet. The basic unit of the alumina sheet is the alumina octahedron (Figure 10–5B). Here, an aluminum atom is surrounded by six hydroxyl groups (OH^-) to form an octahedron or eight-sided figure. Octahedra join through the hydroxyl groups to form the alumina sheet.

These sheets can stack atop one another in several ways to form a complete clay crystal. The simplest stacking joins a single alumina sheet to one silica sheet, forming what is called a 1:1 layer (Figure 10–6). The alumina sheet sheds some of its hydroxyl groups by sharing oxygens at the "tips" of the attached silica sheet. Note the clear order of the 1:1 layer: hydroxyl groups at the top and oxygen atoms at the



Courtesy of Terrence Boerboom, from the Minnesota Geological Survey publication Clay Mineralogy and Geology of Minnesota's Keolin Clays, Walter Parham, 1970.

Figure 10–4

A photomicrograph of clay crystals from ancient kaolinite deposits in Minnesota. Notice the sheetlike crystals.

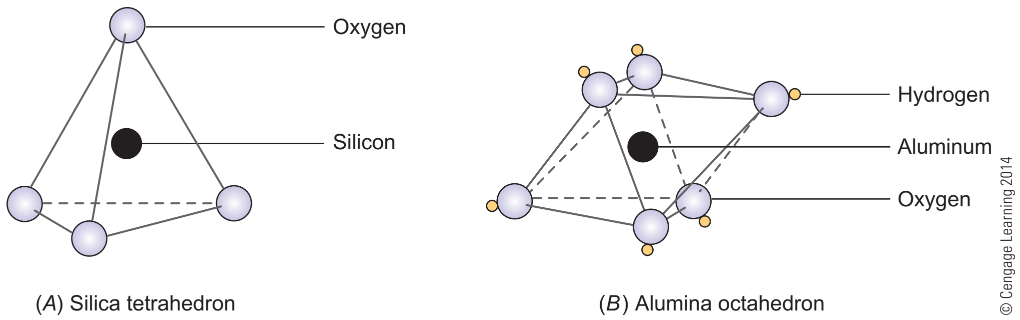


Figure 10–5

(A) In the silica tetrahedron, each silicon atom is located in the center of four oxygen atoms. *(B)* For the alumina octahedron, each aluminum atom is centered among six hydroxyl (OH^-) groups.

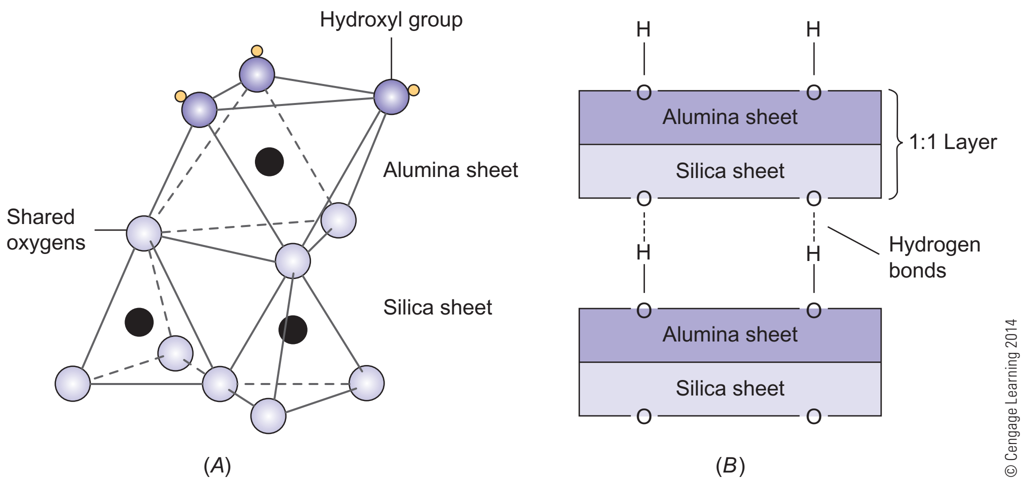


Figure 10–6

The 1:1 layer is one way of stacking sheets to form a clay crystal. *(A)* Alumina sheets bond to silica sheets by sharing oxygen atoms at the tip of each silicon tetrahedron. *(B)* Hydrogen bonding between layers permits several layers to bond together to form a complete micelle.

bottom. Two layers can now join by hydrogen bonding—the hydroxyl groups of one layer bond to the oxygen atoms of another. Hydrogen bonds hold the layers in the clay crystal together tightly. One clay mineral composed of bonded 1:1 layers is kaolinite (Figure 10–4).

A second way to stack sheets is to sandwich an alumina sheet between two silica sheets (Figure 10–7). Here the alumina octahedra replace all but two of their hydroxyl groups by sharing oxygen atoms with the silica sheets. This is a 2:1 structure. No hydroxyl groups are exposed at the surface, so layers are not cemented by hydrogen bonds. The bonds that hold the layers together are much looser than hydrogen bonds, so most 2:1 clays can "open up."

Types of Silicate Clay

Several types of clays result from the ways in which 1:1 or 2:1 layers bond together.

Some clays are highly charged and hold cations well; others are not. Some clays are sticky, some are plastic, and some swell when wet. These traits are the soil consistence factors listed in Chapter 4.

Two important traits of silicate clays depend on how easily the layers can be separated. If they loosen easily, then water can enter the micelle between the layers, and the particle will swell when wetted and shrink when dried (Figure 10–8). Such

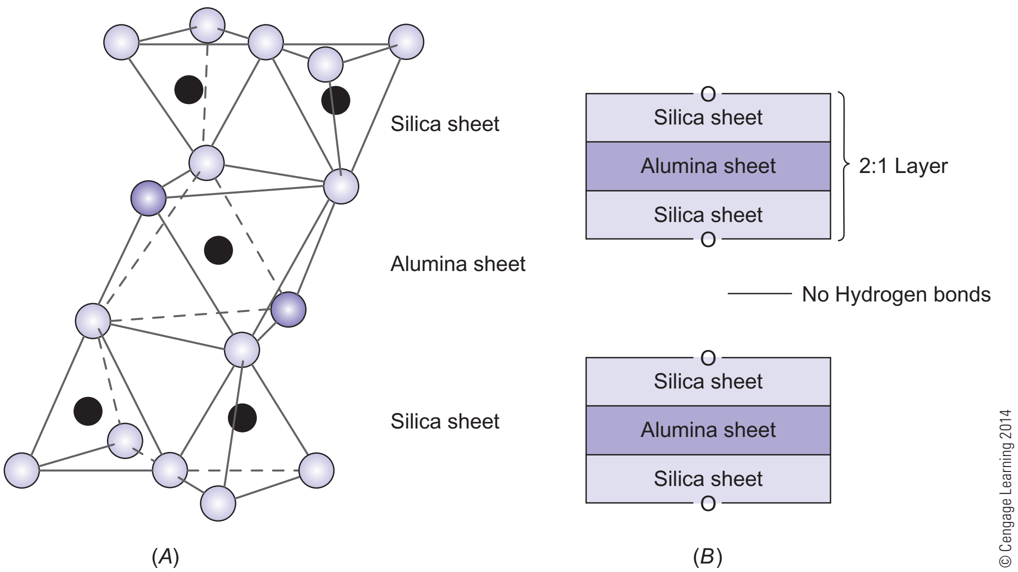


Figure 10–7

Another way of stacking sheets is the 2:1 layer. *(A)* Sheets are bonded by shared oxygen atoms. *(B)* Hydroxyl groups are not exposed, so layers are not joined by hydrogen bonds. They are joined by a weaker type of bond, allowing them to open up to permit entry of water and other ions.

Figure 10–8

Mud cracks in expanding clay. This Vertisol swells as it wets and shrinks as it dries, forming these deep, wide cracks.

clays are called **expanding clays**. If layers separate, more surface area is exposed for adsorption of cations. Thus, clays with loosely bound layers usually hold more nutrients. Figure 10–9 sketches the structure of several types of clays, while Figure 10–10 summarizes some characteristics of these clays.

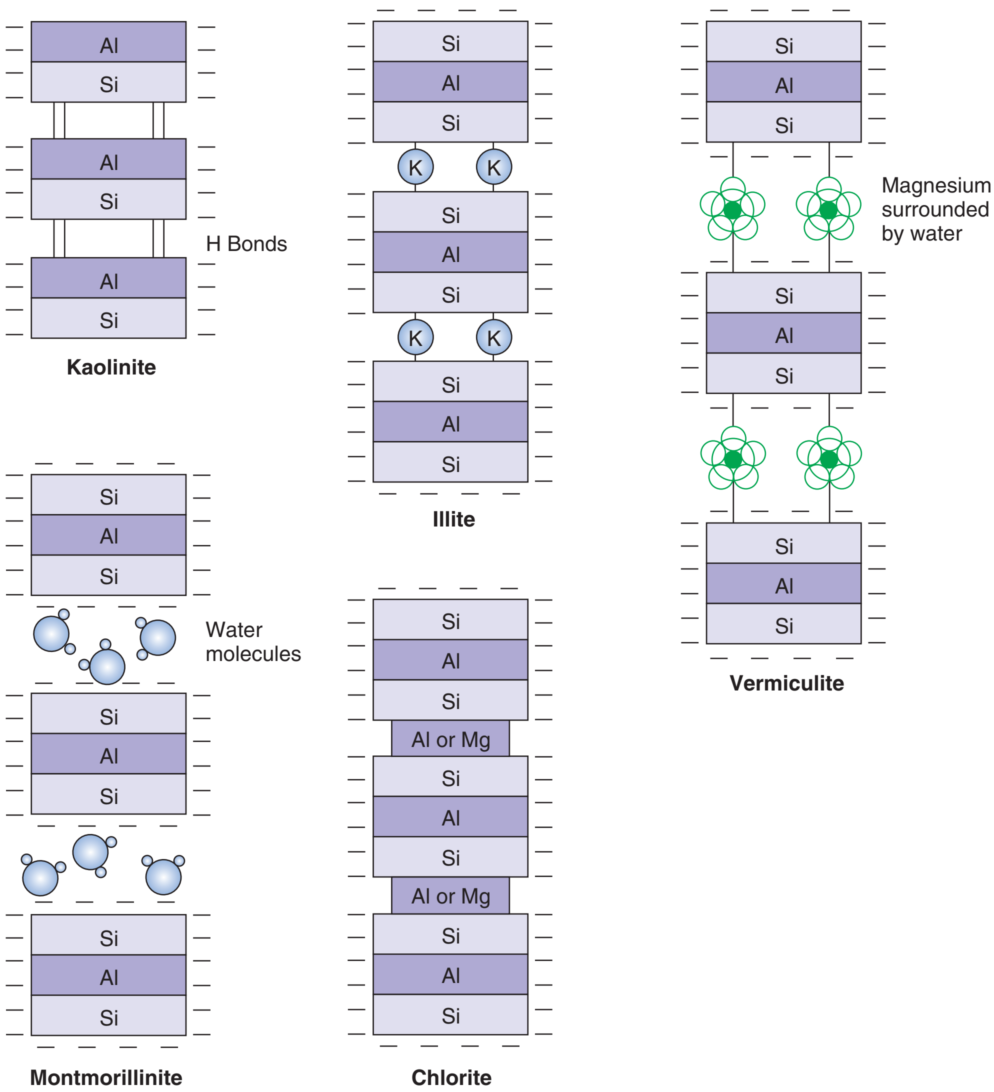


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Figure 10–9
Each drawing illustrates the structure of different types of silicate clay. Dashes indicate where negative charge is exposed.

Clay	Wet Consistency	Relative Swelling When Wetted	Interlayer Bonding
Smectites (2:1)	Very sticky	High	Very weak
Vermiculite (2:1)	Sticky	High	Moderate
Illite (2:1)	Slightly sticky	Low	Strong, by K ions
Chlorite (2:1:1)	Nonsticky	None	Strong, by fourth sheet
Kaolinite (1:1)	Plastic, slightly sticky	Very low	Strong H bonds
Sesquioxides	Nonsticky	None	—

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Figure 10–10
Characteristics of important soil clays.

Mica Clays

Mica clays are 2:1 clays resulting from the weathering of mica minerals. The layers of one mica clay, *illite,* are firmly bound by bridges of potassium ions. If some potassium leaches away, then the layers can open up slightly, so illite is slightly expanding. If all the potassium is lost, a new clay called *vermiculite* forms. Vermiculite layers are loosely bound by magnesium ions surrounded by six water molecules. Vermiculite expands greatly when wetted.

Smectite Clays

Smectites result either from weathering of feldspar or from advanced weathering of vermiculite. They are 2:1 clays, sticky and highly expanding (Figure 10–8). Water fills the space between the layers, so the layers are very loosely held. The bonding force is too slight to hold a large particle together. This means that smectite clays are formed of very small particles. The best known smectite is *montmorillinite.*

Chlorite Clays

Chlorite layers are tightly bound by a fourth clay sheet. Chlorite is often termed a 2:1:1 clay. The fourth sheet is either another alumina sheet or a sheet of magnesium–oxygen octahedra. This sheet binds the 2:1 layers together fairly tightly.

Kaolinite Clays

These are 1:1 clays. Hydrogen bonds bind the layers tightly, so water cannot get between the layers. Thus, kaolinites swell least of all the clays. They present the smallest surface area for adsorption of soil cations. Strong bonds allow particle sizes as large as silt. Kaolinite is highly plastic and is used for making pottery.

Oxide Clays

Oxide clays, called **sesquioxides**, are tiny particles of iron (Fe_2O_3) and aluminum oxides ($Al(OH)_3$). Oxides are common to old soils in humid tropical climates. Long periods of weathering leach out silica and some alumina, leaving behind the oxides. Oxide clays tend to aggregate into strong, coated, sand-sized peds that behave much like sand. Oxide clays can form stacked sheets but do not form the crystalline structure of silicate clays. Oxide clays do not swell, are not sticky, and have limited power to hold nutrients. Oxide clays are typical of Oxisol soils, and the red color often found in Oxisols reflects the reddish hue of iron oxides.

Humus

Humus particles are the residues of organic matter decay. They are not crystalline and form irregular, round shapes. They have none of the physical properties of clays, like stickiness or plasticity. However, they have more power to adsorb nutrients than clays. Humus is not stable; it decays over time to carbon dioxide.

CATION EXCHANGE

The importance of soil colloids lies in their chemical and electrostatic reactivity. Their electrically charged surfaces are able to attract and adsorb a wide range of ions and molecules in the soil—most important here, plant nutrients, but also materials like pesticides and a variety of other organic molecules. These activities profoundly influence soils and how we manage them.

Charged Colloids

Soil colloids usually carry a negative charge that attracts cations from the soil solution.

Clay particles gain a negative charge in two ways. First, some hydroxyl groups on the broken end of a clay micelle lose their hydrogen ion (Figure 10–11). The hydrogen ion is simply a proton, so this leaves a charge imbalance. The remaining oxygen, therefore, has a negative charge, and a negative electrical charge is acquired by the surface.

The second process is **isomorphous substitution**. One cation can replace another cation of similar size in a clay sheet. For instance, aluminum (Al^{+3}) can replace a silicon atom (Si^{+4}) in a silica layer. While the cation fits, it has a smaller positive charge. This leaves a "spot" in the crystal that is short of positive charges. These spots acquire a negative charge.

Because a clay crystal contains many of these negative spots, the entire particle maintains a negative charge. The minus charge creates an electrostatic attraction for positively charged cations, so the micelle is surrounded by a swarm of cations adsorbed to the surface of the clay particle. The minus and plus charges balance, for a net zero charge.

In actuality, the two pools of adsorbed ions and those in the bulk soil solution, as pictured in Figure 10–3, are not so distinctly different. Near the clay or humus particle, the cloud of ions is dominated by positively charged ones, of a number that balances the charge of the colloid. These are adsorbed. As the distance from the colloid increases, the number of anions climbs and the number of cations falls, until a distance is reached where cations and anions balance each other, and that is the bulk soil solution of Figure 10–3. Ions can move through this distance, and an equilibrium exists that tries to maintain a constant level of a given cation in the soil solution.

Clays differ in the number of sites for negative charges, so their ability to retain cations also differs:

- Kaolinite has a small negative charge because little isomorphic substitution occurs. The only exchange sites are from hydroxyl groups on the broken ends of a clay micelle.
- Smectites have many negative sites because magnesium ions (Mg^{+2}) substitute for some aluminum (Al^{+3}) in the alumina sheets. In addition, cations can adsorb on sites between the 2:1 layers.

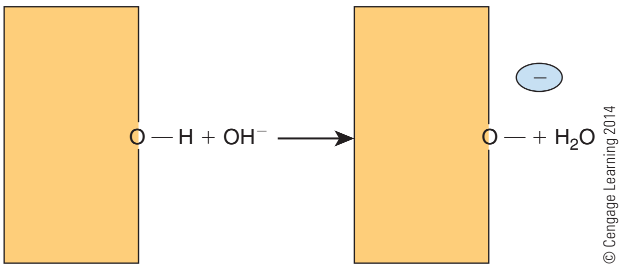

Figure 10–11
Loss of a hydrogen ion (proton) from a hydroxyl group on the surface of a clay micelle leaves the oxygen with a negative charge that can attract cations from the soil solution.

- Vermiculite has an even greater negative charge because about one in four silicon atoms is replaced by aluminum. Being a swelling clay, some cations can be retained between the 2:1 layers.
- Illite has the same substitutions as vermiculite. However, because the layers are held together by potassium, few cations can be held between the layers. Thus, illite holds fewer cations than vermiculite.
- Sesquioxides have very little negative charge, except for a few hydroxyl groups on the surface.
- Humus has numerous sites. Many organic compounds found in humus have hydroxyl groups as part of their structure. These groups can lose a hydrogen to form negative spots over much of the humus particle surface.

Cation Exchange

The negatively charged surface of soil colloids plays a key role in the way nutrients behave in soil. Because the tiny particle bears a negative charge, it attracts positively charged ions as a swarm of cations near its surface. The attraction is strong enough to prevent cations from leaching in downward-moving water but not so strong as to prevent their use by plants.

Figure 10–12 shows that cations can move on and off the particles, generally maintaining an equilibrium between adsorbed ions and those in the bulk soil solution. When one ion leaves, it is replaced by some other cation. We call replacement of one ion for another **cation exchange**. Cations that can be replaced on exchange sites are said to be *exchangeable*, such as exchangeable potassium.

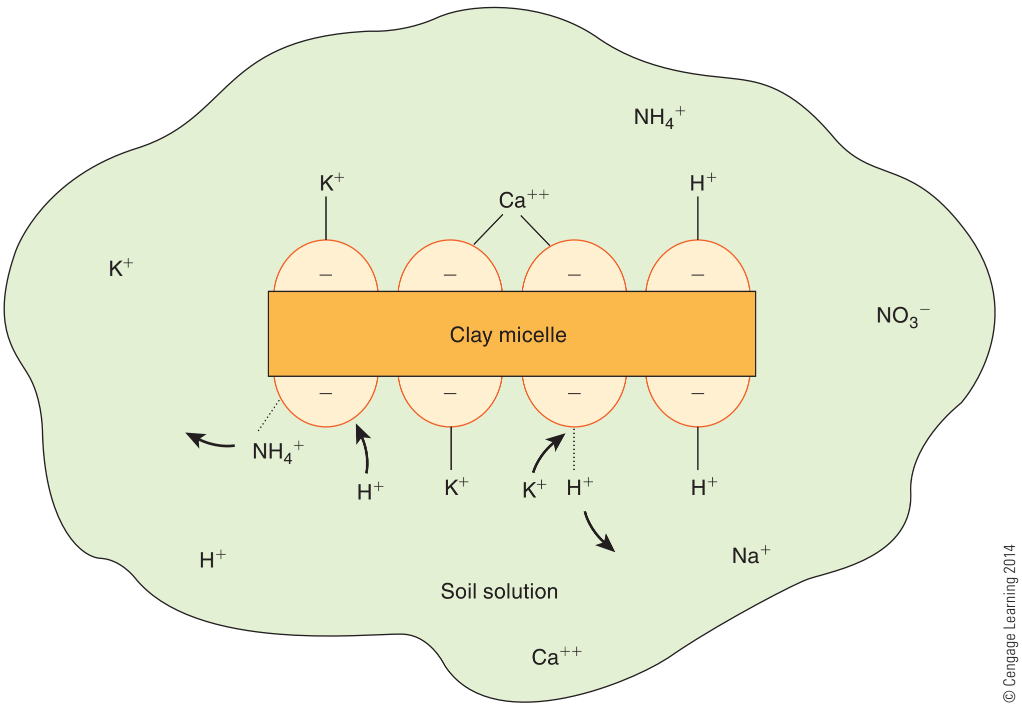

Figure 10–12
The colloid surface is negatively charged, so it adsorbs cations. Cations are exchangeable in that if one leaves, another takes its place. (*Note:* The semicircles used to represent exchange sites are for illustration only.)

The ability of a soil to hold nutrients relates to the number of cations it can attract to soil colloids. This value, determined by the amount of clay, the type of clay, and the amount of humus, is measured by **cation exchange capacity (CEC)** measured in centimoles of charge per kilogram of dry soil (cmol/kg). It may also be expressed as milligram equivalents per 100 grams of soil (me/100g). The numbers are the same in both systems.

Figure 10–13 lists CEC values for several clays, humus, and soil textures. Note that humus has a much higher CEC than clay. However, clay usually adds more CEC to a soil than does humus because there is so much more clay than humus in most soils. Organic soils, which are mostly organic matter, are an exception. Sandy soils, low in clay, may also gain a large portion of their exchange capacity from humus, which largely explains why the addition of organic matter is so beneficial to sandy soils.

CEC of colloids whose negative charge depends largely on surface hydroxyl (OH^-) groups—oxide clays and humus—is said to be pH dependent.

Soil pH is discussed fully in Chapter 11; simply stated, the higher the soil pH, the greater the concentration of hydroxyl ions in the soil solution. Examine Figure 10–11. If the concentration of hydroxyl ions in the soil is high, then the reaction pictured in that figure is driven to the right (see the discussion of chemical reactions in Appendix 1 if necessary), and the number of cation exchange sites increases. Therefore, the higher the pH, the larger the pH-dependent CEC.

Cation Behavior at the Exchange Sites

Cations cluster most densely near the micelle surface, neutralizing negative charge. Cations can move on the micelle and trade places or exchange with cations in solution. Several factors control the selection of cations that leave the micelle or become adsorbed. Two important factors are (1) relative bonding strength of each cation and (2) number of each type of cation.

Colloid	Cation Exchange Capacity (mEq/100 g soil)
Humus	100–300
Vermiculite	80–150
Montmorillinite	60–100
Illite	25–40
Kaolinite	3–15
Sesquioxides	3–9
Soil Texture *(Temperate Climate Soils)*	
Clay loam	30
Silt loam	27
Loam	24
Sandy loam	17
Loamy Sand	9

Figure 10–13
Sample CEC of several colloids and soils. An individual soil will vary from these values.

If two cations are present in the soil in equal numbers, then the one that bonds most tightly to exchange sites will tend to be found on the micelle. The most strongly adsorbed cation is aluminum, followed in decreasing order by:

$$Al^{+3} > H^{+} > Ca^{+2} > Mg^{+2} > K^{+} = NH^{4+} > Na^{+}$$

Assume that a soil has equal numbers of calcium and sodium (Na) ions. Calcium tends to dominate exchange sites because it adsorbs more strongly on the micelle. Sodium tends to leach out of the soil solution.

The second controlling factor is **mass action**. Mass action means that the greater the number of an ion in the soil, the more exchange sites it will occupy. As an example, in high-lime (calcium carbonate) soils, most exchange sites are occupied by calcium. Mass action is a function of chemical equilibrium. Study the description of equilibrium in Appendix 1 for further explanation.

Consider treatment of high-sodium soils with gypsum (calcium sulfate). In a high-sodium soil, many exchange sites are taken up by sodium (more than 15 percent). When gypsum is added, calcium displaces sodium on the exchange sites. Displaced sodium enters the soil solution and is leached away by heavy watering. Calcium replaces sodium on the exchange sites by means of mass action (there are many calcium ions in solution) and because calcium is adsorbed more strongly than sodium.

Cations that are weakly held, in direct contact with the soil solution, are exchanged fairly easily. These are termed exchangeable cations. Some are held very tightly against the colloid or may be trapped between layers of a clay micelle. These do not normally pass into solution easily and are said to be **nonexchangeable ions**. Even these may be given up slowly if the surrounding solution becomes very low in those ions.

Anion Storage

Several nutrients are available to plants as negatively charged ions, or anions (refer to Figure 10–1). The negative charge means that an anion is repelled from a cation exchange site. While these elements, like sulfur, are to a large degree stored as organic forms in humus, an **anion exchange** process stores small amounts of some anions.

Anion exchange sites are the opposite of the cation exchange sites, where hydrogen is lost from a hydroxyl group. At an anion exchange site, an extra hydrogen joins the hydroxyl group to produce a net positive charge (Figure 10–14). The positive charge can then attract anions. For most soils, anion exchange capacities are quite low. Typical values are a few tenths of a milliequivalent per 100 grams of soil. Anion exchange is greatest in acid soils high in oxide clays.

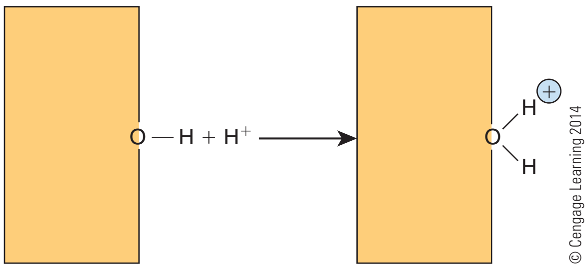

Figure 10–14
At anion exchange sites, a hydroxyl group on the surface picks up an extra hydrogen ion (proton). The site now has a net positive charge that can attract anions. This is most likely in acidic soils where the soil solution contains many hydrogen ions.

Applications of the CEC

How growers use soil is strongly influenced by CEC. High-CEC soils, measuring between 11 and 50 units, usually contain a lot of clay. Low-CEC soils, measuring below 11 units, usually have a high sand content. Sticky soils are high in the types of clay having the highest CEC. Thus, CEC is reflected in physical properties of soil, such as texture and consistence.

CEC is one of the factors that determines how much herbicide should be spread on the soil. Colloids adsorb pesticides as well as nutrients; therefore, clay and humus tend to tie up many chemicals. As a result, we often have to apply higher chemical rates to high-CEC, clayey soils than to low-CEC, sandy soils, and on sandy soils, one must be more cautious to apply a pesticide at a lower rate to avoid toxicities.

The amount of lime needed to raise soil pH or sulfur to lower pH is also a function of the CEC. In the process of liming soil, calcium displaces hydrogen on cation exchange sites. The more exchange sites in the soil, the more lime is needed. Therefore, growers apply much more lime to correct the acidity of fine-textured soils than they do to correct coarse-textured soils. The next chapter explains this thoroughly.

CEC influences fertilization practices. High-CEC soils have greater potential to hold cationic nutrients than low-CEC media. Smaller amounts of fertilizer, applied more often, are needed in low-CEC soils to prevent leaching losses, while larger amounts may be applied less frequently in high-CEC soils. Golf course managers with all-sand greens fertilize lightly often. Greenhouse growers using soilless mixes with low CEC may fertilize lightly with every watering.

The concept of cation exchange suggests that it is easier to improve the CEC of a sandy soil by improving the organic matter content than by adding clay. In temperate humid climates, most clays are kaolinite (CEC = 3–15 cmol/kg) and illite (CEC = 25–40 cmol/kg). In a soil composed of these clays, each percentage of clay in the soil adds between 0.03 and 0.5 cmol per kilogram to the CEC of the soil. In contrast, each percentage of humus adds between 1 and 3 full cmol per kilogram. Far less organic matter is required, compared to clay, to raise the exchange capacity of the soil.

Percent Base Saturation

Soil fertility is influenced not only by CEC (how many cations it can store) but also by how much of the CEC is actually filled with plant nutrients. Exchange sites may be filled by members of two groups of cations. One group consists of hydrogen and aluminum, which are not plant nutrients at all. Their primary contribution is to acidify the soil. The other cations are called **exchangeable bases** and include elements such as calcium, magnesium, potassium, and sodium. Except for sodium, the bases are plant nutrients.

The percentage of the cation exchange sites filled with exchangeable bases is called the **base saturation**. It expresses how much of the soil's "potential fertility," the CEC, holds exchangeable bases. For example, if the total CEC of a soil is 10 cmol per kilogram and bases occupy 6 of the 10, then the base saturation percentage is 60 percent. Most crops grow best at a base saturation of 80 percent or more. These plants require a good supply of nutrients. Some trees that grow on infertile soils do well at a base saturation of around 50 percent.

NUTRIENT UPTAKE

This chapter has already noted two factors that affect soil fertility: (1) the amount of storage capacity of a soil (CEC), and (2) how much of that storage actually contains nutrients (percent base saturation). A third fertility factor is how easily roots take up nutrients. How do plants take up nutrients from the soil?

Plants absorb nutrients mainly as the ions listed in Figure 10–1. Nutrient absorption means that nutrient ions cross cell membranes of root cells and eventually move to the root's vascular system to be delivered to the rest of the plant. In some situations, some nutrients may be passively absorbed with water entering roots, but otherwise a more active process is required. In fact, roots may have a concentration of some nutrients hundreds of times that of the soil solution. For nutrients to passively "soak in" against such a gradient would be like water running uphill. Roots actively transport nutrient ions through root cell membranes, an active process that uses energy. Because roots produce energy by respiration, conditions that limit root cell respiration, like a waterlogged soil, also limit nutrient uptake. In addition, the active transport of ions across a cell membrane allows some selection—the root can take up some elements more than others.

The soil solution surrounds roots growing through soil pores. Root hairs get ions directly from the soil solution through their own form of cation and anion exchange. If a cation is removed from solution, the root gives up a hydrogen ion (H^+) to replace it in the soil solution (Figure 10–15). If an anion is absorbed from solution, the root gives up an anion to replace it. The exchange maintains electrical balance in the root and in the soil.

Plants take exchangeable bases from solution and replace them with hydrogen ions. Because hydrogen forms stronger bonds on the exchange sites, they replace

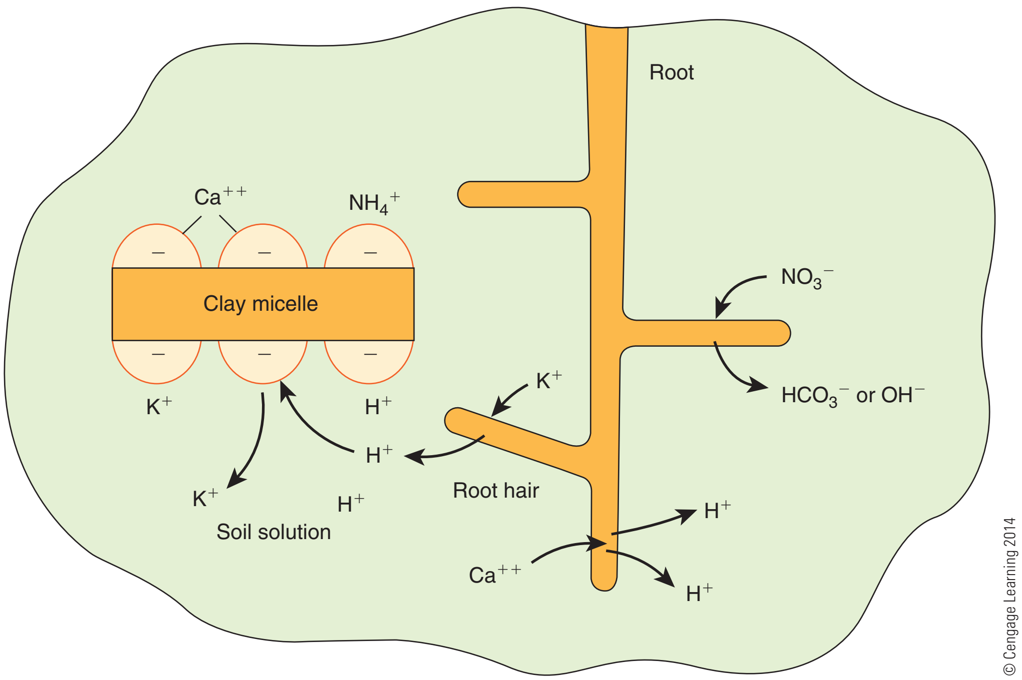

Figure 10–15
Roots absorb nutrient ions from the soil solution. To maintain electrical balance, roots release a different ion of the same charge into the rhizosphere. For cations, a hydrogen ion is released. A loss of bases in the soil solution and a buildup of hydrogen ions cause hydrogen–base exchange on soil colloids and acidity in the rhizosphere.

other cations on the exchange sites (Figure 10–15). This exchange renews nutrient cations in solution, allowing plants to continue to draw nutrients from the soil. Over time, however, the exchange increases the number of hydrogen ions bonded to exchange sites and lowers percent base saturation.

When growers fertilize and lime soil, they are reversing the loss of nutrient cations. If, for example, potassium fertilizer is supplied in the form of potassium chloride, potassium replaces some other cations, including hydrogen, by mass action (Figure 10–16).

Figure 10–15 raises a question about nutrient uptake. Near roots nutrients should be depleted. How does the root continue to obtain nutrients? Remember, plant roots absorb only nutrients that are in solution at the root surface. Roots continue to grow through the soil mass to find new supplies of nutrients. This growth is especially important because roots most effectively take up nutrients near root tips, where the root hairs are, while older root tissue forms barriers to absorption. New root tips must be constantly formed for efficient nutrient uptake. These absorbing roots access nutrients by means of root interception, mass flow, and diffusion.

Root interception results directly from the extension of root systems. As new roots grow, they displace a volume of soil that contains nutrients; those nutrients are at the root surface and are readily absorbed. However, roots closely contact very little soil, so other means of obtaining nutrients are needed.

Mass flow carries nutrient ions to roots from nearby soil in water flowing toward roots by capillary action. The driving force for nutrient transport here is simply a water potential gradient. Review Figure 7–11, if necessary, to understand how this works. Mass flow obviously depends on water usage by the plant, and it supplies nutrients most effectively when plants are taking up water rapidly and the soil is moist. In a sense, mass flow is driven by transpiration.

Diffusion also moves ions toward the root from the surrounding soil, but the ions are diffusing *through* soil water rather than being carried *with* it. The driving force is a nutrient concentration gradient in the soil near roots.

Consider calcium as an example. Near the root there is less calcium because the root has been removing it. In response, calcium ions move toward the root through

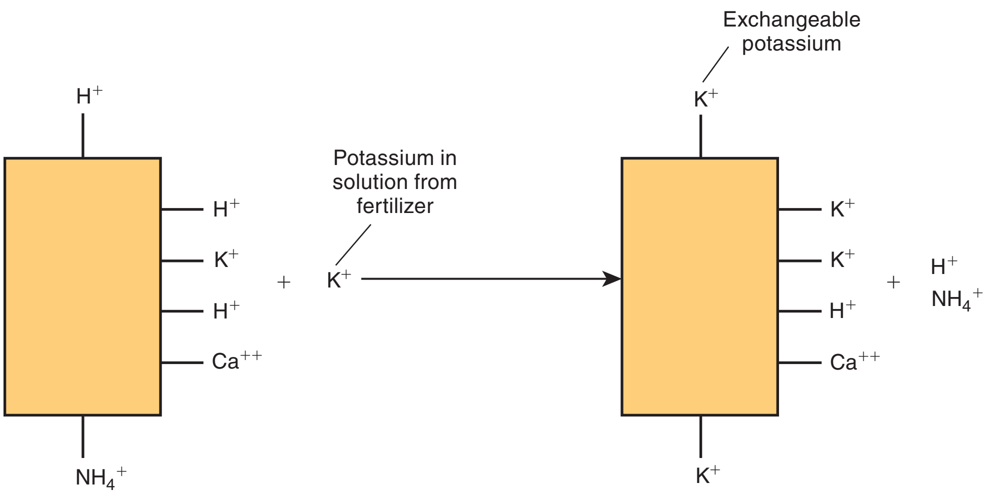

Figure 10–16
When a grower limes or fertilizes the soil with a nutrient base, the base cation replaces other cations on exchange sites due to the effect of mass action.

soil water (not along with it) to make a new balance. The movement of ions is from areas of greater concentration to areas of lesser concentration, a slower process than that of mass flow.

Since nutrients diffuse through water films, diffusion is particularly sensitive to soil moisture and declines greatly in dry soil.

While all three mechanisms operate at the same time, the relative importance of root interception, mass flow, and diffusion depends on plant species, specific nutrient, soil texture, moisture content, and other factors. In general, diffusion is the most important mechanism. However, a plant's ability to obtain a nutrient depends not only on that nutrient but also on its mobility in the soil. Those nutrients that move primarily by diffusion, like phosphorus, tend to be much less mobile than those nutrients than can move by mass flow, like nitrogen. This fact contributes to the difficulties of obtaining sufficient phosphorus.

Factors Affecting Uptake

Several factors affect how well plants take up nutrients. Plant use of nutrients is affected by soil features such as oxygen supply, water supply, and soil temperature. Root distribution in the soil is another factor.

Active uptake consumes energy produced in the roots by respiration; the food to fuel root respiration is produced in leaves during photosynthesis and delivered to the roots by the plant's vascular system. Anything that interferes with any step of this process also reduces nutrient uptake. For instance, plants growing under low light make less sugar to send to the roots and so take up fewer nutrients. Whether it be turf under a tree or a houseplant indoors, one should reduce fertilization compared to plants growing in the sun.

More important, since respiration uses oxygen, conditions that limit oxygen supply also limit nutrient uptake. Both poor drainage and soil compaction slow the movement of oxygen into the soil. As a result, these conditions also limit the ability of plants to absorb nutrients. This is another reason for draining wet soils and for avoiding compaction.

Dry soils lower nutrient uptake because lack of water impedes nutrient flow toward the root hairs by mass flow and diffusion. Phosphorus, for example, moves in soil largely by diffusion, so phosphorus uptake is sharply reduced in dry soil.

Soil temperature also affects nutrient uptake. The rates of all chemical reactions, including those in soil and plants, depend on temperature. Respiration rates go down in cold soil, so the plant has less energy to take up nutrients. Root growth is also slowed in cold soil, limiting root interception of nutrients. Mineralization of organic matter declines as well, so fewer organic nutrients are made available. Diffusion itself slows in colder soils, since the diffusion rate depends on temperature. For these reasons, cold soil hinders nutrient uptake. Phosphorus and iron deficiencies are common, for example, in spring when soils are cold and wet. Farmers often place an extra amount of phosphorus fertilizer beside planted seeds to overcome early-season deficiencies.

Greenhouse growers must be aware of the effect of cold soil, because irrigation water may be cold enough during the winter to induce nutrient shortages. For example, cold irrigation water can induce phosphorus deficiency in potted geraniums. Early fall is a preferred time for fertilizing turf in many parts of the country. Air temperature is cool and shoot growth is active but slowed, while roots remain active in the still warm soil. Fertilizer will be taken up easily at this time and stored in the roots for the coming season, avoiding problems with cold early spring soils.

Warmer soil temperatures improve uptake up to around 85°F, partially by speeding diffusion, but beyond that uptake declines. Thus, both cold and hot soil inhibit uptake.

An increase in the amount of nutrient ions in the soil improves absorption. This factor is obviously one reason growers fertilize their crops. When some elements, like potassium, are present in very high amounts, plants even take up more than they can use. This condition is called **luxury consumption**. However, because the excess is stored in plant cells, it may be used later if something happens to slow uptake by the roots. Excess uptake of some other nutrients, like boron, harms plants.

Uptake is most rapid, of course, where roots are most numerous. We know roots grow best where air, water, and nutrients are in good supply. Drainage, compaction, and fertilization influence how well roots grow, as do soil or root depth. Plants with deeply growing roots need less fertilization than plants with shallow root systems. Soils that have restricted zones—those with high water tables, plow pans, or bedrock—can cause shallow root systems.

Organisms in the rhizosphere, and their interactions with plant roots, obviously influence nutrient uptake as well. Soil-borne pathogens like nematodes or root-rotting fungi damage the ability of roots to take up nutrients, while mycorrhizal infections improve nutrient uptake. Some rhizosphere microbes can make nutrients more available. Insects, on the other hand, may feed on plant roots.

Figure 10–17 summarizes the factors affecting soil fertility and nutrient uptake.

Raises Fertility	Lowers Fertility
High clay content	High sand content
High humus content	Loss of organic matter
Good structure	Compaction
Warm soil	Cold or hot soil
Deep soil	Shallow soil
Moist soil	Dry or wet soil
Good drainage	Excess irrigation or drainage
Fertilization	Erosion
Desirable microbes	Root-damaging pests
Near neutral pH	pH too acid or alkaline

Figure 10–17
Factors affecting a soil's ability to supply plant nutrients.

SUMMARY

For normal growth, most plants require 17 essential elements. Carbon, oxygen, and hydrogen come from air and water, while the other 14 elements are absorbed by plants from the soil. Plants take up primary and secondary nutrients in large amounts; trace elements are needed in small amounts.

Four pools of nutrients work together to both store and release nutrients to plants. These are soil minerals, organic matter, soil solution, and adsorption by clay and humus. The ability of colloids to adsorb nutrients is based on their large surface area and on a negative surface charge. This ability is measured by CEC. Percent base saturation is the percentage of the exchange capacity filled with exchangeable bases.

Plants absorb nutrients by transporting ions into root cells. Uptake uses energy. To find new nutrient supplies, roots grow through the soil. In addition, nutrients flow either with (mass flow) or through (diffusion) soil water toward roots. Extreme soil conditions, including soil that is too dry, too wet, too cold, or badly compacted, impair the ability of roots to absorb nutrients.

Nutrient uptake is aided by a deep, well-drained soil. Several practices can improve soil fertility. Artificial drainage helps if a soil is poorly drained. Avoiding compaction or subsoiling already-compacted soils is useful. Organic matter additions improve CEC and provide nutrients, and also keep soil loose to enable sufficient oxygen to be supplied to roots. Proper fertilization improves soil fertility as well.

REVIEW

1. What do you think would be the effect on nutrient uptake of removing all the leaves from a plant?
2. Name four soil conditions that inhibit nutrient uptake and describe why they do so.
3. Discuss how we classify the 17 essential elements and the reasons behind each class.
4. Discuss the four primary pools of essential elements in the soil. Pick one of them and describe possible consequences if that pool were to suddenly disappear.
5. Why might two soils with identical percentages of clay have different cation exchange capacities? Explain your answer.
6. At any given moment, where in the soil (in what pool) are the nutrients a plant is actively taking up? How about the nutrients it will take up a in few hours from the present? How about some time in the more distant future?
7. What sorts of nutrients, in their ionic form, will be nearest to soil colloid particles? What sorts farther away?
8. A mathematical challenge: The CEC of a soil is simply the sum of its components. Assume we have a loamy sand soil that is 5 percent montmorillinite clay, with a CEC of 80 cmol per kilogram, and is 3 percent organic matter with a CEC of 200 cmol per kilogram. The rest is silt, sand, and coarse fragments. What is the CEC contribution of each component, and what is the total CEC of this soil? What does this say about the importance of organic matter in sandy soils?
9. Describe the basic structure of silicate clays, and explain the difference between expanding clays and others.
10. Explain why kaolinite has a lower CEC than do smectites.
11. Using information from this chapter, explain why tropical soils are often less fertile than temperate-climate soils.
12. Several problems with vegetable and fruit crops are caused by calcium shortages in the developing edible part, and they tend to happen as the soil dries. Why might soil drying contribute to such problems?

ENRICHMENT ACTIVITIES

1. Using molecular model kits, construct models of silica tetrahedra and alumina octahedra. Then try to construct a portion of a clay layer.
2. Examine granules of horticultural vermiculite. Note that it is made of expanded mica sheets, and that it can soak up water between the sheets. Physically and chemically, the granule resembles the structure of a vermiculite micelle.
3. Gentian violet is a positive dye, and eosin is a negative dye. Prepare a water solution of each dye. Pour each solution into a pot of soil until water begins to drain from the bottom. Collect the drainage water. Which dye passed through the soil? Why? Try this on both a very sandy soil and a finer-textured soil to see whether there is a difference.
4. This little test can demonstrate dissolution and precipitation of nutrients. Mix a little silver nitrate (used in photo processing) in distilled or deionized water. It will dissolve, like nutrients in solid form dissolving in soil water. Also mix a bit of table salt into some other distilled water. Now mix the two solutions together. The white material that results is silver chloride, which is not soluble in water. This process is called *precipitation*, and the white solid is the *precipitate*. In the soil, chemical reactions that have the same effect can occur, tying up nutrients like phosphorus or iron in insoluble forms. Do not allow silver nitrate to come into contact with your skin or eyes; it is best to wear appropriate gloves and goggles. For more safety information, browse the Web for "silver nitrate safety."
5. At this point it might be worthwhile to review much of what the text has covered so far by reading Graeme Buchan's "Ode to Soil" published in the *Journal of Soil and Water Conservation* in 2010, Volume 65(2), pp. 48A–54A. A copy of the ode can be purchased at http://www.jswconline.org/content/65/2.toc

CHAPTER 11

Soil pH and Salinity

TERMS TO KNOW

acid (soil)
agricultural lime
alkaline (soil)
basic (soil)
buffer test
buffering capacity
burned lime
calcareous soil
calcitic limestone
calcium carbonate equivalent (CCE)
chemical guarantee
dolomitic limestone
effective neutralizing power (ENP)
fluid lime
halophytes
hydrated lime
leaching fraction
marl
pH (soil)
physical guarantee
saline soil
saline-sodic soil
salinization
sodic soil
sodium adsorption ratio
soil reaction
soluble salt
total neutralizing power (TNP)

OBJECTIVES

After completing this chapter, you should be able to:

- describe soil pH and its development
- describe how pH affects plant growth
- tell how to lime or acidify soil
- perform lime calculations
- describe saline and sodic soils
- describe methods to treat and manage saline and sodic soils

Each workday your author passes down a street lined with pin oaks as boulevard trees. Some are green and healthy, some others are a bit stunted and pale green, while still others are severely stunted with considerable dieback and yellow leaves. Since the last edition of this text, many have been removed. The leaves in Figure 10–2 were plucked from those trees. What is the problem with these trees, a problem shared with many pin oaks planted in this midwestern city? The problem is one of **pH**, a fundamental soil chemical property that is the main topic of this chapter and a problem faced by many growers, landscapers, and gardeners around the nation.

There have always been a host of problems faced by humans tilling the soil, such as improper pH, erosion, or loss of organic matter and nutrients. But one of the most serious and persistent over the history of agriculture, in so many of the drier regions of the world where human civilizations have arisen, has been salinity. Soil salinity, introduced in earlier chapters, is the second topic of this chapter. As a broad generalization, soils of humid regions tend to become acid, while soils of arid regions tend to become saline.

Readers should review the discussions of salts, acids, and bases in Appendix 1 before beginning this chapter.

SOIL pH

Soil reaction describes acidity or alkalinity of a soil. Soil users are concerned about soil reaction because it strongly affects plant growth. Reaction is measured by the pH scale, as shown in Figure 11–1, which gives sample pH values for common substances. The scale runs from a pH of 0 to a pH of 14.0. Readings between 0 and 7.0 are said to be **acid**. A pH of 1.0 is extremely acidic and a pH of 6.0 is slightly acidic. Examples of acid materials include vinegar, tomato juice, and lemon juice. These acid foods have a sour taste.

Readings between 7 and 14 are **alkaline** or **basic**. The larger the number, the stronger the base. Soap is slightly basic, while household ammonia, with a pH of 11, is strongly basic. Bases, or alkaline substances, taste bitter.

The midpoint of the scale, pH 7.0, is the neutral point, which is neither acid nor base. Pure water, which has a neutral pH, can be a model in our discussion of pH. A very small number of water molecules break up to form a cation and an anion, as shown in reaction (*a*):

$$(a)\quad \underset{\text{water}}{H_2O} \rightleftharpoons \underset{\text{hydrogen ion}}{H^+} + \underset{\text{hydroxyl ion}}{OH^-}$$

The cation in the reaction is the hydrogen ion (H^+). It makes a solution acid. The anion is the hydroxyl ion (OH^-). It makes a solution basic. In pure water, the number

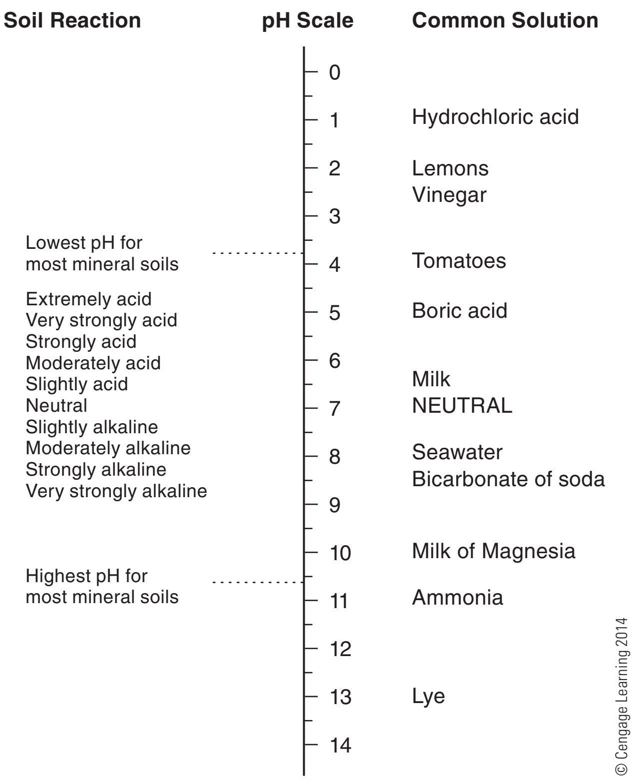

Figure 11–1
The pH scale runs for 0 (most acid) to 14.0 (most alkaline). The pH values for several common substances are shown. Note soil pH extends from about 3.5 to 10.5.

of hydrogen ions equals the number of hydroxyl ions, to maintain a balance. Thus, pure water is neither acid nor base, and the pH of pure water is 7.0. However, substances dissolved in water may change the balance, causing one ion to outnumber the other.

For instance, if pure water is exposed to air, carbon dioxide from the atmosphere dissolves in the water to form carbonic acid. Some portion of carbonic acid, a weak acid, quickly breaks down to liberate hydrogen ions (*b*).

$$(b) \qquad CO_2 + H_2O \rightarrow H_2CO_3 \rightarrow HCO_3^- + H^+$$

Now there is an excess of hydrogen ions, so this dilute solution is acidic. Water in equilibrium with air has a pH of about 5.6. In fact, rainfall itself is acidic even without air pollution that creates even lower pH "acid rain."

The pH scale indicates how acidic or basic a solution is by giving the concentration of hydrogen ions. The pH scale is a special scale for expressing hydrogen ion concentration as one over the log of the hydrogen ion concentration (1/log $[H^+]$). The smaller the number on the pH scale, the stronger the acidity of a substance. Each pH point multiplies acidity by a factor of 10. A pH of 5.0 is 10 times more acid than pH 6.0 and 100 times more acid than pH 7.0.

The balance between hydrogen and hydroxyl ions dictates pH. Soil with far more hydrogen ions than hydroxyl ions is very acid. With only a few more hydrogen ions, it is slightly acid. On the basic or alkaline side of the scale, the reverse is true.

DEVELOPMENT OF SOIL pH

Soil does not reach the extreme pH limits shown in Figure 11–1—the most acid soil has about a pH 3.5 and the most basic soil is pH 10.5. These are extreme values. Soil users more commonly find that soil ranges between pH values of 5.0 and 8.0.

Soil pH results from the interaction of soil minerals, ions in solution, and cation exchange. In the simplest terms, high pH is caused by the reaction of water and basic compounds of calcium, magnesium, and sodium to form hydroxide ions. Low pH is caused by the percolation of mildly acidic water, which neutralizes the bases and replaces the base cations on the cation exchange complex with hydrogen ions. To understand the full range of soil pH, it is easiest to start with alkaline soil.

The Math and Chemistry of pH

More precisely, pH is the negative logarithmic value of hydrogen ion concentration in moles per liter. In the term *pH,* "p" stands for negative log and "H" stands for hydrogen ion concentration. For more information about molar concentrations and the math of logarithms, refer to other resources available on the Internet or in such books as *Chemistry for Dummies,* or the text mentioned in the Enrichment Activities section.

Very basic soils (pH greater than 8.0) are more than 100 percent base-saturated—that is, not only are all exchange sites filled with base cations, but the soil contains free particles of mineral carbonates (CO_3) such as calcium carbonate or lime ($CaCO_3$). The pH of very alkaline soils results from reactions of carbonates with water to form hydroxyl ions, according to reactions (*c*) and (*d*):

$$(c) \quad CaCO_3 + 2H_2O \rightarrow Ca^{+2} + H_2CO_3 + 2OH^-$$

$$(d) \quad Na_2\,CO_3 + 2H_2O \rightarrow 2Na^+ + H_2CO_3 + 2OH^-$$

This reaction with water is called hydrolysis. It is important to note that carbonate acts as the base (see Appendix 1 for a definition of acids and bases), not calcium, in spite of the confusing terminology of calling calcium a base cation. The hydrolysis of calcium carbonate in reaction (*c*) results in a pH range of about 8.0–8.5. Soils in this range, which are 100 percent base-saturated and contain enough free calcium carbonate, are called **calcareous soils**. Calcareous soils can be tested with dilute hydrochloric acid—they fizz from carbon dioxide given off by reaction with lime. They result from soils whose parent materials are high in lime.

If the sodium saturation of a soil exceeds 15 percent, then reaction (*d*) produces lye, which can raise pH to 10.0. Such soils are termed *sodic*, to be covered later in the chapter.

Soils tend to be alkaline in climates where annual precipitation tends to be lower than annual evapotranspiration, generally where rainfall is less than 20 inches per year. In wetter climates, mildly acidic water containing hydrogen ions (whose sources will be discussed shortly) creates a process of soil acidification. Weathering and leaching removes the excess free basic minerals, such as lime. When these minerals reach a low level, soil ceases to be calcareous. This occurs at a pH of about 8.0, though it varies for different soils. At this point, pH begins to be controlled by continuing accumulation of hydrogen ions and exchange processes.

Hydrogen ion inputs continue over time, and cation exchange allows them to accumulate in the soil on the cation exchange complex. Base cations such as calcium are displaced in the process, to be taken up by plants or leached out of the soil. Each lost base cation is replaced by a hydrogen ion. As more cation exchange sites become occupied by hydrogen ions, they become a source of hydrogen ions for the soil solution, reaction (*e*). Soil pH is determined by the size of this hydrogen ion contribution to the soil solution, over a range of slightly acid to slightly alkaline soil.

$$(e) \quad \boxed{\text{micelle}}\text{—}H^+ \rightleftarrows H^+ + \boxed{\text{micelle}}\text{—}$$

When pH declines to about 6.0, aluminum begins to leave the structure of silicate clays. Aluminum ions react in several steps with water to form hydrogen ions and aluminum hydroxide compounds. The reactions are summarized in reactions (*f*) and (*g*):

$$(f) \quad \boxed{\text{micelle}}\text{—}Al^{+3} \rightarrow Al^{+3} + \boxed{\text{micelle}}\text{—}$$

$$(g) \quad Al^{+3} + 2H_2O \rightarrow Al(OH)_2^{+1} + 2H^+$$

pH Range	Determining Reaction	Saturation
8.5–10.0	Na_2CO_3 hydrolysis	100 percent base saturation, sodium saturation more than 15 percent (sodic soil)
7.0–8.5	$CaCO_3$ hydrolysis	100 percent base saturation (calcareous soil)
5.5–7.0	Hydrogen exchange	Base saturation below 100 percent, some hydrogen saturation
<5.5	Aluminum hydrolysis	Low base saturation, may be high Al saturation

Figure 11–2
Reactions that determine pH range.

Aluminum hydrolysis can lower soil pH to about 4.0. This is the most acidic the majority of upland soils become. Figure 11–2 summarizes the pH ranges and associated conditions.

Causes of Acidity

Relatively young soils—those not exposed to long periods of weathering and leaching—share the pH of their parent materials. Acidic parent materials include granite, sandstone, and shale. These materials are common in New England, the Great Lakes, and the Appalachian states. The soils of many states, including many in the Great Plains and some near the Great Lakes, developed from calcareous parent materials like limestone. When young, these soils tend to be neutral to alkaline.

The pH of older soils is controlled by the percolation (or lack of percolation) of acidic water. This percolating water leaches away bases and replaces them on the exchange sites with hydrogen and aluminum ions, reaction (*h*):

$$(h) \qquad \boxed{\text{micelle}}\text{—}Ca^{+2} + 2H^{+} \rightarrow \boxed{\text{micelle}}\!\!<\!\!\begin{matrix}H^{+}\\H^{+}\end{matrix} + Ca^{+2}$$

Figure 11–3 portrays this reaction graphically. This type of percolation occurs in humid climates, where precipitation exceeds evapotranspiration. In a humid climate, net movement of water over the course of a year is downward, leaching out bases. In semiarid or arid zones, net water movement is upward, since water is being pulled out of the root zone by evaporation or transpiration. With little or no percolation, soils of dry regions tend not to become acidic. They may even become quite alkaline from calcium or sodium being carried upward into the root zone by capillary movement. Figure 11–4 shows that leaching has the greatest effect on the soils of the eastern half of the United States and the Pacific Northwest, though higher-pH soils still appear on limey soils.

A number of processes produce the hydrogen ions that make soil more acidic. Some processes occur naturally, and others result from human activities. A major natural process that contributes to soil acidity is the reaction of carbon dioxide with water to produce the weak acid carbonic acid, which breaks down to produce hydrogen ions and bicarbonate, as in reaction (*i*):

$$(i) \qquad CO_2 + H_2O \rightarrow H_2CO_3 \rightarrow HCO_3^{-} + H^{+}$$

Rainfall is a dilute solution of carbonic acid, since carbon dioxide in the atmosphere dissolves in droplets of water in the air. Reaction (*i*) also occurs in the soil as the respiration of plant roots and other soil organisms puts carbon dioxide into

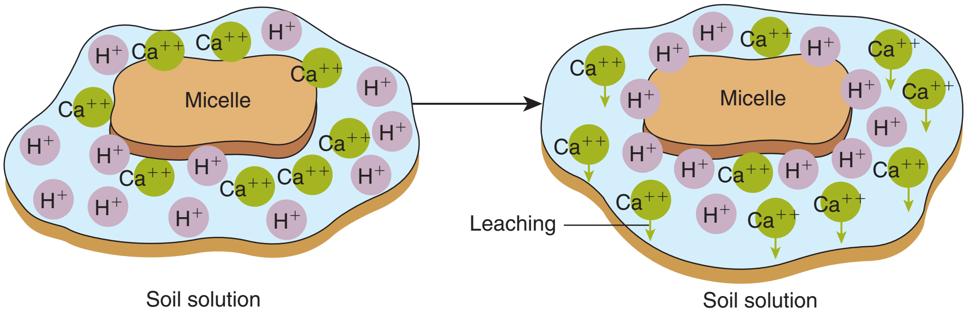

Figure 11–3
Percolation of acidic water causes hydrogen ions to replace exchangeable bases on colloids. The calcium and magnesium thus replaced can leach away.

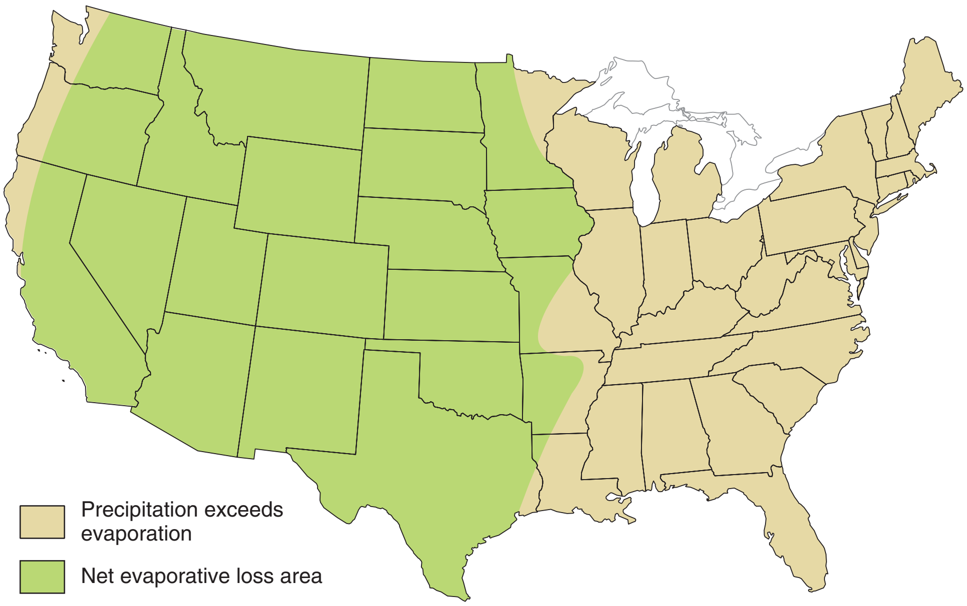

Figure 11–4
Soil acidity is greatest where average annual precipitation is greater than average annual evapotranspiration, so there is potential for leaching. Where there is a net evaporative loss, soils tend to be alkaline.

contact with soil water. As a consequence, plant growth and the decay of organic matter are acidifying.

Plants acidify soils in two additional ways. First, when roots take up cation nutrients such as potassium, they "give back" an equivalent number of hydrogen ions (Figure 10–15). Second, growers take calcium and magnesium with each crop harvested. For example, every ton of alfalfa hay is a loss from the soil of 30 pounds of calcium and 8 pounds of magnesium. Each atom of a basic cation removed in cropping is replaced by a hydrogen ion, speeding soil acidification.

Nitrification also contributes hydrogen ions to the soil. When nitrifying bacteria oxidize ammonium ions NH_4^+, it results in hydrogen ions, as in reaction (*j*):

$$(j) \quad NH_4^+ + 2O_2 \rightarrow NO_3^- + H_2O + 2H^+$$

This reaction is a natural contribution to acidity from normal nitrogen cycling and decay of organic matter (Chapter 6). Human-made contributions include common fertilizers that contain ammonium nitrogen, like anhydrous ammonia, so fertilization with ammonium-containing fertilizers itself drives down pH over time.

Other sources also contribute hydrogen ions to the soil. Some products of decay are weak organic acids, and soil organisms contribute weak organic acids to the soil as well. There are also a number of redox and other reactions in the soil involving elements such as iron, aluminum, sulfur, and others that generate hydrogen ions, beyond the scope of this text.

To summarize, soil acidification results over time from biological activity such as decay and nitrification, from leaching in humid regions, and from presence everywhere of carbonic acid in rainfall and from respiration in the soil. These processes are slowed in dry regions and in soils whose parent materials contain high levels of basic cations.

EFFECTS OF pH ON PLANTS

Each plant grows best in a specific pH range. The pH ranges for a selection of crops are shown in Figure 11–5, and Appendix 5 lists pH preferences of selected trees. Most plants growing on mineral soils do well at a pH range of 6.0–7.0. For organic soils, most plants prefer a pH of 5.5–6.5. An exception is a group of acid-loving

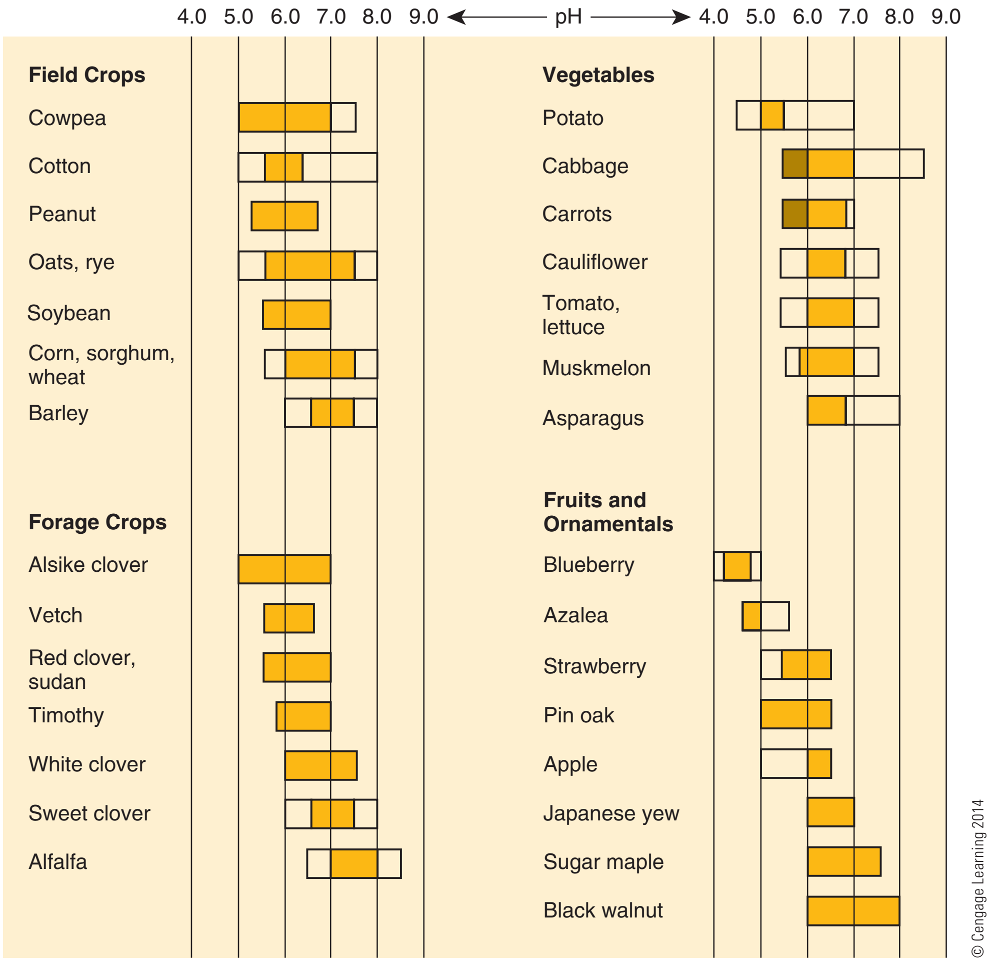

Figure 11–5
Preferred pH ranges of several crops. The shaded area of each bar shows preferred pH; the unshaded areas show tolerances. For sample landscape trees, see Appendix 5.

plants that includes mostly woody plants such as blueberry and azaleas and many evergreens. Alfalfa is one of the few crops that prefers a slightly basic soil.

Except at pH extremes, the actual number of hydrogen or hydroxyl ions does not seem to be the main factor in plant growth. Rather, several soil conditions related to pH are more important to plants. These include (1) the effect of pH on nutrient availability, (2) the buildup of toxic levels of aluminum or other metals, and (3) the effects on soil microbes. Which factor has the greatest effect on limiting plant growth varies from soil to soil and from plant to plant.

Effect of pH on Nutrient Availability

Many soil elements change form as a result of reactions in the soil. These reactions, controlled by pH, alter the solubility, and therefore the availability, of nutrients. A good example is phosphorus, which gets tied up with aluminum and iron at low pH, and with calcium at high pH. Therefore, phosphorus is most available to plants at near-neutral pH.

Figure 11–6 shows the availability of nutrients at different pH levels. Note that the major nutrients and molybdenum are most available in near-neutral or higher-pH soil. The other trace elements are more available in acid soil. Note that pH in the range of 6.0–7.0 is a good average level for all nutrients. This range is also the best pH range for most plants.

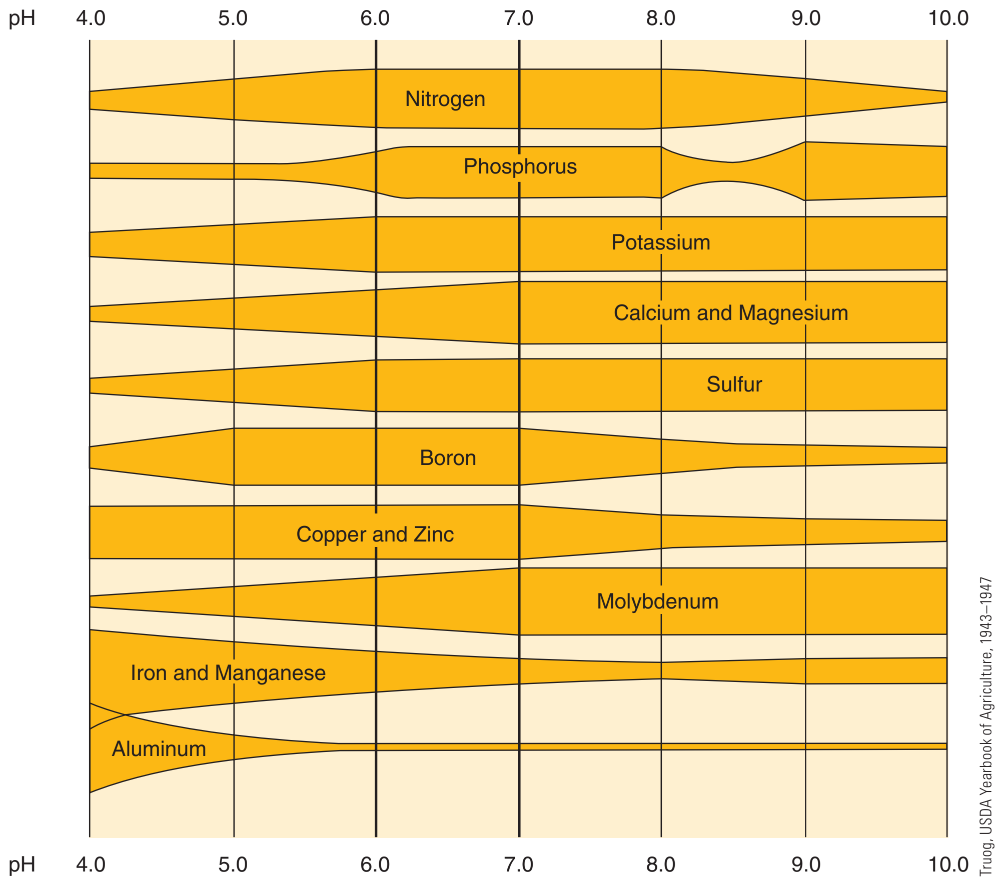

Figure 11–6
Soil pH affects nutrient and aluminum availability, here for mineral soils in temperate climates. The thicker the bar, the more available the nutrient. The bars are not to scale, and the effect is more extreme than it appears here.

Image courtesy of Ed Plaster

Figure 11–7
Solubility of iron compounds depends on pH. Iron sulfate dissolved in acidic water on the left, so the colored solution is clear. Iron compounds precipitated out when pH was raised, making the solution cloudy in the beaker on the right.

Figure 11–7 illustrates the effect of pH on nutrient availability. The beaker on the left shows iron sulfate dissolved in acidic water. The colored solution is clear, showing the material dissolved successfully. In the soil, iron would be available to roots. In the beaker on the right, a base was added until the solution became alkaline. Iron precipitated out as insoluble iron hydroxides, forming a cloudy suspension. When this happens in the soil, iron deficiencies result, as in Figure 10–2.

Calcium and magnesium become unavailable at low pH, not so much from being tied up but from simple loss from the soil. At low pH, aluminum and hydrogen will replace those cations on the cation exchange complex; they will then leach out of the soil. Therefore, treating strongly acidic soils must involve the addition of new calcium and magnesium through liming, described later in the chapter.

Soils that cannot supply enough of a nutrient may actually contain the element, but the nutrient is tied up because of acid or alkaline soil. Figure 10–2 showed an oak leaf deficient in iron; the deficiency resulted from growing on an alkaline soil.

pH and Element Toxicity

At low pH, particularly below 5.5, aluminum and manganese, or even iron, can reach toxic levels in the soil. Aluminum actually leaves the structure of clay minerals, reaches high concentrations in the soil solution, and occupies most of the cation exchange sites. Aluminum toxicity severely inhibits root growth, especially in acidic subsoils, and restricts the uptake of calcium and magnesium. Roots growing under such conditions—high aluminum, low calcium—become short, stubby, and unbranched. Aluminum toxicity also increases water stress during dry periods because of poor root growth.

Figure 11–8

The dwarf petunia (*Callibrichoa cv.*) on the left is normal. The one on the right was treated with too much iron sulfate, causing iron toxicity.

Manganese problems are less common but can be equally toxic under certain conditions. In the greenhouse, iron toxicity may occur in certain plants such as geraniums, if the pH of the potting mix drops too low (Figure 11–8). Figure 11–6 shows that these three elements become highly soluble below pH 5.5.

Aluminum toxicity occurs primarily in mineral soils of warm, humid climates. Aluminum problems seldom appear in organic soils because these soils contain little aluminum. In fact, plants tolerate acid organic soils better than acid mineral soils mainly because of the low aluminum level.

Low pH may also mobilize toxic heavy metals that might be in the soil, such as lead or cadmium, allowing them to be taken up by plants or move into water supplies. pH controls may be necessary on contaminated soils, or on soils receiving biosolids (sewage sludge, discussed in Chapter 15) that might contain heavy metals. Chapter 19 discusses heavy-metal soil contamination.

A word here about acid rain and natural forest ecosystems. Acid rain accelerates the acidification of forest soils, which liberates toxic soil aluminum and induces calcium and magnesium shortages. The effect on sensitive forests can be devastating. Forests on poorly buffered soil (described later in the chapter) are most sensitive.

pH and Soil Organisms

Soil organisms grow best in near-neutral soil. In general, acid soil inhibits the growth of most organisms, especially bacteria and earthworms. Thus, acid soil slows many important activities carried on by soil microbes, including nitrogen fixation, nitrification, and organic matter decay. Rhizobia bacteria, for instance, thrive at near-neutral pH and are sensitive to aluminum. A pH between 6.5 and 7.3 is generally optimum for these beneficial activities.

LIMING SOIL

The simplest way to ensure proper pH is to choose a plant that matches the present soil pH. Indeed, matching the plant and pH may be the only answer in some cases—growers may find it impractical to lower the pH of calcareous soils or to raise the pH of acid peat soils. Tropical soils may be very difficult to adjust profitably.

In many of these situations, it is best to raise crops or select landscape plants that tolerate the existing soil pH. Refer to Figure 11–5 and Appendix 5 for examples. Breeders are also creating crop varieties tolerant of poor-pH conditions, such as high-pH-tolerant soybeans.

The other approach is to change the soil pH to match plant needs. Many field crops grow best in slightly acid soil. However, leaching of exchangeable bases, acid fertilizers, and other factors may slowly make soil more acidic than is best for good growth. Liming is practiced by growers to counteract soil acidity, mostly in those parts of the country where soil acidification occurs naturally.

Benefits of Liming

Liming acid soils has long been an important agricultural practice. Liming improves crop response to fertilizers by improving nutrient uptake, especially phosphorus, reducing aluminum toxicity, and promoting the activities of such desirable organisms as the *Rhizobia* bacteria that fix nitrogen for legumes.

Because calcium is itself a plant nutrient, lime is also a fertilizer, especially for high-calcium crops such as alfalfa. Certain limes also supply magnesium, which is important to many acid sandy soils.

Liming Materials

We apply the term **agricultural lime** to ground limestone or other products made from limestone. Lime materials are carbonates, hydroxides, and oxides of calcium or magnesium, described below. While lime contains calcium, and calcium ions play a role in raising soil pH, calcium itself does not neutralize acidity. It is the carbonate or other base anion that neutralizes acidity when mixed into the soil. Common liming materials include calcitic limestone, dolomitic limestone, burned lime, and hydrated lime.

Calcitic limestone is nearly pure calcite or calcium carbonate ($CaCO_3$). It forms on the sea floor when deposits of calcium precipitate out of solution in seawater. Limestone deposits, widespread in the United States, are mined and ground into agricultural lime.

Dolomitic limestone is a mixture of calcium carbonate and magnesium carbonate ($CaCO_3$ and $MgCO_3$). Liming with dolomitic lime helps the calcium–magnesium balance in soil. Dolomite is especially helpful in sandy soils because they often lack sufficient magnesium.

Burned lime, or quicklime, is made by heating limestone. Heating drives off carbon dioxide, resulting in the lighter calcium oxide:

$$(k) \qquad CaCO_3 \rightarrow CaO + CO_2 \text{ (gas)}$$

Because calcium oxide is lighter (has a lower molecular weight), a smaller weight of it has the same effect as a larger weight of ground limestone. Burned lime also reacts more quickly in the soil. However, the material costs more and is hard to handle. Burned lime is caustic and may cake during storage. Burned lime can be used where fast action is needed but is not usually recommended.

Hydrated lime, or slaked lime, is produced by adding water to burned lime, forming hydrated lime, or calcium hydroxide:

$$(l) \qquad CaO + H_2O \rightarrow Ca(OH)_2$$

Like burned lime, hydrated lime is unpleasant and hard to handle, but fast acting. Hydrated lime is used more often than burned lime. Because of processing steps, it is more expensive than regular ground lime, but it may be used where speed of reaction is needed.

Growers may find other locally useful materials:

- **Marl** is a soft, chalky freshwater deposit in swamps that receive alkaline runoff water from nearby land. Although marl is difficult to harvest and spread, it may be useful where locally mined.
- Ground seashells, a by-product of shellfish industries, may be used in areas where those industries thrive.
- Lime-rich by-products of several industries may also be locally available.
- Wood ashes contain oxides of calcium and other cations and can be used with care. The ashes of charcoal and coal cannot be used for this purpose.

It should be noted that gypsum ($CaSO_4$) does not change soil pH, because the sulfate ion does not accept hydrogen ions the way carbonate ions do. It is considered a *neutral* salt, so it cannot be used as an agricultural lime. Under certain circumstances, however, it can help relieve aluminum toxicity by improving calcium content of the soil. The calcium can replace some aluminum in the soil, improving the calcium content and reducing soil aluminum levels.

How Lime Works

Lime neutralizes soil in two ways. First, the anion base (carbonate, hydroxide, oxide) neutralizes acidity by accepting hydrogen ions from the soil solution and making them part of water molecules. Second, calcium (or magnesium) replaces hydrogen and aluminum ions on exchange sites by mass action, freeing them into the soil solution, allowing them to be neutralized. Let us look at a couple of examples to see how this works.

The simplest reaction is that of hydrated lime (Figure 11–9). As hydrated lime dissolves, it releases calcium and hydroxyl ions. Calcium replaces hydrogen and aluminum on exchange sites, releasing those cations to the soil solution. Aluminum ions

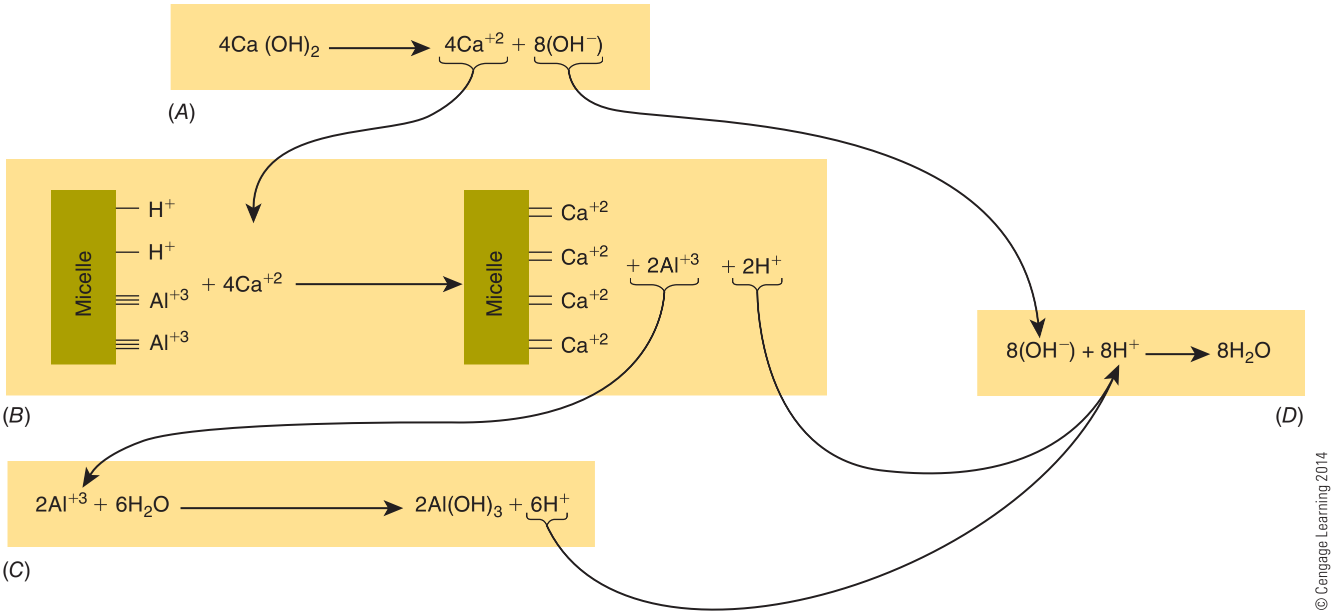

Figure 11–9

Hydrated lime neutralizes soil acidity in a sequence of reactions. When calcium hydroxide dissolves *(A)*, calcium replaces aluminum and hydrogen on cation exchange sites by mass action *(B)*. Aluminum is tied up by reacting with water to form insoluble aluminum hydroxide *(C)*. Hydrogen ions released by these reactions combine with hydroxyl ions from lime to form water *(D)*.

undergo complete hydrolysis to form insoluble aluminum hydroxide, with release of more hydrogen ions. All the hydrogen ions react with hydroxyl ions from the lime, forming water.

Calcite and dolomite act in a similar fashion, with a couple of additional steps. Hydrogen ions resulting from the other steps react with the carbonate to form carbonic acid, which quickly decomposes to carbon dioxide and water. Figure 11–10 shows this process.

Other liming materials undergo similar reactions. The important thing to remember is that calcium (or magnesium) replaces hydrogen and aluminum on cation exchange sites and hydrogen ions are changed to water. The speed of this overall process varies according to the type of material. Hydrated lime dissolves quickly in the soil and reacts quickly. Ground limestone, on the other hand, dissolves more slowly and takes more steps to neutralize acid.

Buffering Capacity

Four factors tell the grower how much lime is required: present pH, desired pH, buffering capacity of the soil, and the liming material to be used.

By testing present pH, and by knowing the correct pH for a given plant, a grower or soil-testing laboratory can determine how much a pH should change. For example, if alfalfa grows well at a pH of 6.5, and the present pH is 5.0, then pH must be raised 1.5 points. Acidity of the soil solution can be measured with methods described in Chapter 13. However, pH by itself does not tell how much lime to apply because it measures only the hydrogen ions in solution, not potential acidity (hydrogen and aluminum) adsorbed on the colloids. Hydrogen ions in solution can

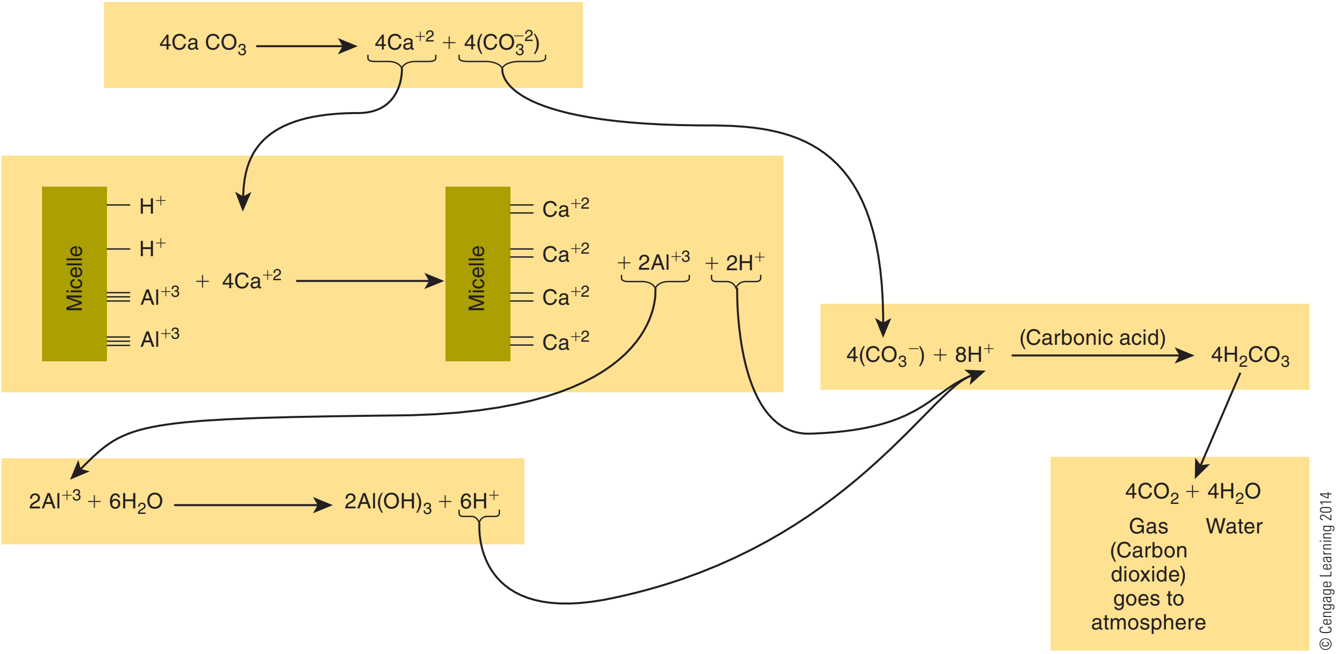

Figure 11–10

Ground limestone neutralizes soil acidity in the reactions shown. The cation exchange reactions are the same as in Figure 11-9. Hydrogen ions react with carbonate (a base) ions to form unstable carbonic acid, which immediately breaks down to carbon dioxide and water.

be termed *active acidity*, while adsorbed hydrogen and aluminum is *reserve acidity*. Although some soil scientists consider these terms out of date, they are useful concepts for this discussion.

Effect of Buffering Capacity on Liming

Picture soil (Figure 11–11) storing hydrogen and aluminum ions in a large bin; this is acidity stored on the cation exchange complex, or reserve acidity. Attached to the large bin is a small one; this is active acidity in the soil solution that actively affects plant growth. Soil pH depends on the equilibrium between the large and small bin. The bigger the large bin, the more acidity is available for the small bin, so the lower the soil pH.

pH measurements measure only concentration of active acidity in the small bin. If one adds enough lime to neutralize that acidity, hydrogen ions are quickly replaced from the large bin. Thus, soil resists a pH change so long as the large bin is well stocked with hydrogen ions. Resistance to a pH change is termed buffering, and the ability of the soil to do so is **buffering capacity**. In order for pH to rise, the large bin must be emptied of enough acidity to create a new equilibrium at a higher pH. This works because lime contains calcium to displace the hydrogen on cation exchange sites.

The greater the buffering capacity of the soil, the more lime must be applied, a subject continued later in this chapter. Another effect is that if we lime the soil enough to fill the large bin with base cations, the soil is now buffered in the other direction; that is, for the soil pH to fall, lots of hydrogen ions are needed to displace the calcium, to refill the large bin with acidity. As a consequence, it will take longer for highly

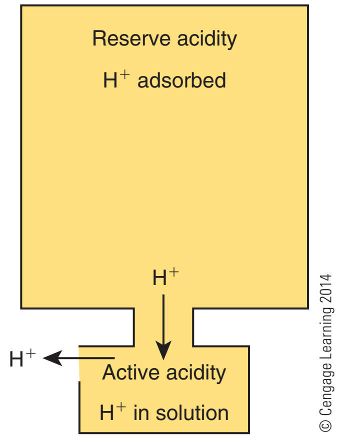

Figure 11–11

pH buffering in the soil. As hydrogen ions are removed from the soil solution by liming, they are replaced by ions held on clay and humus.

Textural Class	Change 4.5–5.5	Change 5.5–6.5
Sand, loamy sand	25	30
Sandy loam	45	55
Loam	60	85
Silt loam	80	105
Clay loam	100	120
Muck	200	225

Data from Kellogg, Soils: 1957 Handbook of Agriculture

Figure 11–12
Amount of limestone needed to raise pH in a 7-inch soil layer in pounds per 1,000 square feet. The values apply to soils of northern and central states.

buffered soils to become acidic again over time. One might say that well-buffered soil requires more lime applied less often than poorly buffered soils such as sandy soil.

The size of the large bin, or its buffering capacity, depends on cation exchange capacity (CEC)—the larger the CEC, the more hydrogen a soil can hold, and the more lime it needs. A soil with a CEC of 20 needs twice as much lime as a soil at the same pH with a CEC of 10.

Buffering capacity of a soil depends on the amount of clay in the soil, the type of clay, and the amount of humus. The amount of clay can be estimated by knowing the textural class of a soil. Figure 11–12 suggests how much lime to apply to soils of various textures. The type of clay modifies the effects of texture, being highest for vermiculite and lowest for sesquioxides. The buffering capacity is also increased by the amount of organic matter in the soil, because humus is a particularly strong buffer.

The lime requirement of an acid soil depends on both pH and buffering capacity. The total lime requirement can be measured directly by a **buffer test**, for example, measuring the reaction of soil to a pH 7.5 buffer solution. A buffer solution is a mixture of chemicals dissolved in water that is buffered, that is, it resists a pH change. The test does not measure actual pH; it is a guide to the amount of lime needed to correct pH.

The pH of a soil sample is first measured to see whether liming is needed. Let us say a soil sample has a pH of 5.5. The laboratory technician adds pH 7.5 buffer solution to the soil sample and measures pH of the new mixture as 6.2. This means that the acidity of the soil lowered pH of the buffer solution from 7.5 to 6.2. The pH of 6.2 is called the "buffer index." Looking at a table of buffer indexes (Figure 11–13), the technician reads the amount of lime needed to raise soil pH to the correct value. In this example, the table suggests applying 4 tons of lime per acre of mineral soil to bring the pH to 6.5–7.0. The result from a buffer index table will be found on a soil-test report (Chapter 13) as a lime recommendation. Note that the caption of Figure 11–13 recommends a specific liming material, but perhaps a different material will be used by the grower. This means that someone has to do a series of calculations to determine the correct amount of that lime, covered in the following discussion.

Lime products are regulated in most states by a set of laws and regulations known as lime guarantees. Each state has its own rules, so this discussion can cover only basic principles. The vocabulary, and numbers, may vary in your state. Next we turn to a series of topics involved in lime calculations.

	(Tons of Lime/Acre)	
Buffer pH	Mineral Soil	Organic Soil
7.0	0	0
6.8	1.0	0
6.6	2.0	0
6.4	3.0	1.0
6.2	4.0	2.5
6.0	5.5	4.0
5.8	6.5	5.0
5.6	8.0	6.0

Based on data from A & L Agriculture Laboratories, Inc.

Figure 11–13
Buffer index tables like this simplified one can be used to determine the amount of lime needed to bring a 7-inch soil depth to a pH between 6.5 and 7.0 with 90 percent pure calcitic lime.

Lime Calculations

Buffer tests suggest lime needs of a soil based on an "average" calcitic limestone, or on pure calcium carbonate. However, different lime products have different capacities to neutralize acidity. This capacity is called **total neutralizing power (TNP)** or **calcium carbonate equivalent (CCE)**. CCE compares an agricultural lime to pure calcium carbonate or calcite. Two factors affect the comparison: the chemical nature of the lime and its purity.

One molecule of calcium carbonate ($CaCO_3$) and one molecule of calcium hydroxide ($Ca(OH)_2$) each have the same neutralizing power, but the latter weighs less. Calcium carbonate has a molecular weight of 100 atomic mass units, while calcium hydroxide weighs 74. Translated into a weight of lime, 74 pounds of pure hydrated lime has the effect as 100 pounds of pure calcitic lime. Neutralizing power is expressed as a percent per weight material relative to pure calcite. In this case:

$$\%\ \text{CCE} = \frac{100\ \text{grams}}{74\ \text{grams}} \times 100 = 135$$

For any pure liming material, then, the CCE is the molecular weight of calcite divided by the molecular weight of the pure material in question, multiplied by 100 to convert to percent. Figure 11–14 gives the CCE of several pure limes.

The second influence on neutralizing power is purity. For example, calcitic limestone is mostly calcite. However, it also contains other materials, like silt, that have no effect on acidity. A ground limestone that is 90 percent pure is only 90 percent as active as pure calcite. Since calcite has a neutralizing power of 100, the power of the limestone would be 90.

Figure 11–14 gives neutralizing values of several agricultural limes. If a lime recommendation were based on 90 percent pure calcitic lime, and a grower plans to use a different form of lime, a conversion is needed. The following problem shows how much burned lime with a neutralizing power of 150 would replace 3 tons per acre of the calcitic lime:

$$\text{rate burned lime} = \text{rate calcitic lime} \times \frac{\text{CCE calcitic lime}}{\text{CCE burned lime}}$$

$$\text{rate burned lime} = 3\ \text{tons/acre} \times \frac{90}{151} = 1.8\ \text{tons/acre}$$

Form of Lime	Percent Purity	Neutralizing Value
Pure Substances		
Calcium carbonate	100	100
Magnesium carbonate	100	119
Hydrated lime	100	135
Burned lime	100	178
Commonly Available Forms		
Calcitic limestone	85	85
Dolomitic limestone	85	88
Hydrated lime	85	115
Burned lime	85	151
Marl	—	50–70
Basic slag	—	60–90
Wood ashes	—	45–80
Ground seashells	85	85

Figure 11–14
Neutralizing values for major sources of lime. The first four values are for pure chemicals; the remaining values are averages for commonly available products.

These two factors, CCE and purity, are usually combined into a single factor labeled CCE or purity. Most states regulate the purity of agricultural lime to protect the customer. These laws set **chemical guarantees** for the neutralizing power of lime products offered for sale in the state. Again, these vary from state to state and terminology and values differ.

But wait, as late-night television commercials say, there's more! In addition to chemical purity, lime recommendations also take into account how finely ground the lime is—the topic of our next section.

Lime Fineness

The fineness of ground lime affects how rapidly lime acts. The finer the grind, the smaller the particle, and the greater the surface area in a ton of lime. Smaller particles expose more surface area to the soil solution and react more quickly. Thus, finer lime particles are more *reactive* than coarser ones.

Two rules result. First, finer grinds neutralize acidity more quickly. Second, it takes less of a finer grind to achieve a given pH rise in a reasonable time than a coarser grind. We can call this lime efficiency, and a lime recommendation has to take into account efficiency as well as chemical purity.

While finely ground limes react rapidly and efficiently, they are used up rapidly as well. For a longer-lasting effect, some coarse particles are useful. Most commercially available ag limes contain a range of size particles to ensure a rapid and prolonged effect.

Particle size is measured by passing them through various sizes of wire mesh sieves, ranging from 8-mesh screens to 100-or higher mesh screens. A mesh rating is the number of openings per linear inch, so an 8-mesh screen has 8 openings per inch, while a 100-mesh screen has 100 openings per inch. The larger the mesh rating, the smaller is the particle that can pass through it.

State laws specify particle sizes based on percentages passing through a sequence of mesh sieves, varying from state to state. In the author's home state, fineness of an ag lime is specified as the percent passing through an 8-mesh sieve (very coarse), percent passing through an 8-mesh but not a 20-mesh screen, percent passing through a 20-mesh but not a 60-mesh sieve, and the percent that passes through a 60 (fine). Generally, particles larger than the 8-mesh sieve have little liming value. Figure 11–15 provides some efficiency comparisons of various mesh limes.

Most states regulate the grind of agricultural lime as well as its purity. These laws specify the **physical guarantee** of agricultural limes. With the addition of fineness to chemical purity, we come to the final measurement of effectiveness of lime, the **effective neutralizing power (ENP)**, used to calculate actual lime application rates.

Effective Neutralizing Power

ENP, or a variety of other terms in a variety of states, is the final measure of how effective a lime product is at neutralizing acidity. The way it is calculated and used varies between states, but all are similar in principle. The method described here is used in Minnesota (merely as the author's most familiar example).

ENP can be calculated as a percent of the effectiveness of pure calcium carbonate that is ground fine to be 100 percent effective. We calculate percent ENP for a particular lime product with the formula:

$$\% \text{ ENP} = \% \text{ CCE} \times \text{FI} \times \% \text{ Dry Matter},$$

where FI is a fineness index. The last factor simply subtracts value for any weight that is water, and here we will assume a completely dry product to simplify calculations.

The fineness index assigns a value to each particle size range, where particles small enough to pass a 60-mesh screen are assumed to be completely effective and thus assigned a value of 1, with larger particles given a smaller index value. The

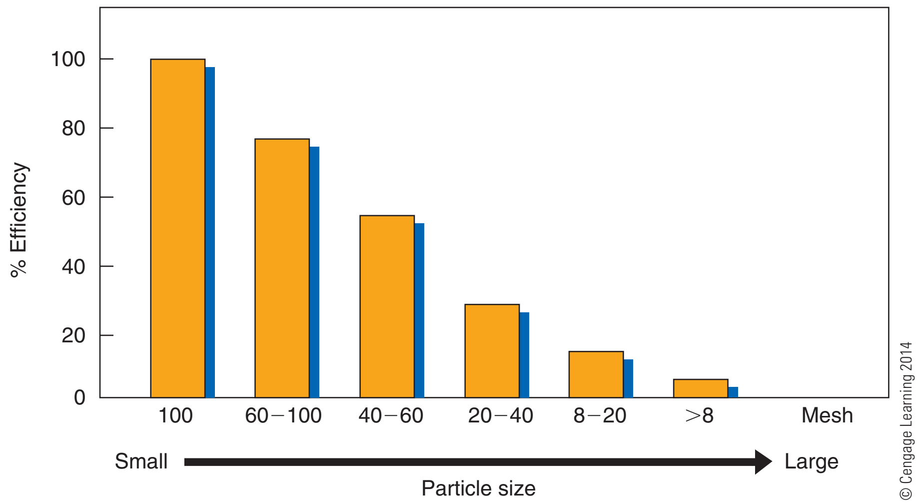

Figure 11–15
The neutralizing efficiency of lime depends on its grind (particle size). Coarser grades are compared with a 100-mesh grind, which is here assigned a value of 100.

index values are multiplied by the percent by weight of particles in each size range, and the sum of all these is the FI. Here, the formula for FI is

$$\begin{aligned} \text{FI} = {} & 0.2 \times (\text{\% passing 8 mesh but not 20 mesh}) + \\ & 0.6 \times (\text{\% passing 20 mesh but not 60 mesh}) + \\ & 1.0 \times (\text{\% passing 60 mesh}) \end{aligned}$$

Note that particles larger than those that pass an 8-mesh screen are ignored—they have essentially zero effectiveness. Figure 11–16 puts this into chart form and provides numbers for a sample we can work with.

So let us try this out with an example. We have a dolomitic limestone product with a CCE of 88, and all of it passes an 8-mesh screen, 10 percent lies in the 8–20 mesh range, 10 percent in the 20–60 range, and the rest passes a 60-mesh screen. What is ENP?

$$\text{FI} = (10\% \times 0.2) + (10\% \times 0.6) + (80\% \times 1.0) = 88\%$$

$$\text{ENP} = 88\%\ (\text{CCE}) \times 88\%\ (\text{FI}) = 77\%$$

In Minnesota, ENP is expressed on a lime label in pounds per ton. Some states leave it as a percent. But in Minnesota, ENP in pounds per ton would be

$$\text{ENP pounds/ton} = \%\text{ENP} \times 2{,}000$$

$$\text{ENP pounds/ton} = 77\% \times 2{,}000 = 1{,}540 \text{ pounds/ton}$$

This means that in a ton of this sample lime product, 1,540 is considered to be effective. Mathematically speaking, we are applying not pounds of lime but pounds of ENP.

Other Lime Calculations

We are now ready to calculate a lime application rate. To do this, we need a recommendation from a soil test—one should not lime without a soil test—and ENP of the product we will be using. Different states report lime recommendations differently, and measure ENP differently, so there are various ways of calculating application rates.

		Fineness Index	
Sieve	Fineness Factor	Sample % Passing	Sample % Available
>8 mesh	0	100	—
8–20 mesh	0.2	25	5
20–60 mesh	0.6	25	15
<60 mesh	1.0	50	50
		Sample total fineness index (FI)	70%

Based on data from Rehm, G. et al. 1992. Liming Materials for Minnesota Soils. Extension Bulletin AG-FS-557A

Figure 11–16
Chart of fineness factors for calculating fineness index in Minnesota. The first two columns are the factors; the last two represent a sample product and the resulting calculations.

In Minnesota, lime recommendations are expressed as pounds of ENP per acre. Thus, a soil-test report might suggest applying 3,000 pounds ENP per acre. How many tons per acre of the product just described would we apply? The answer would be

$$\text{tons lime/acre} = \frac{3{,}000 \text{ lbs ENP/acre}}{1{,}540 \text{ lbs ENP/ton}} \approx 2.0 \text{ tons lime/acre}$$

In other states, the recommendation might be expressed as pounds of calcium carbonate (assumed 100 percent effective) per acre. One then uses percentage ENP as an adjustment. For example, if one used the above lime and the recommendation was 3,000 lbs calcium carbonate per acre, how much lime would we apply?

$$\text{lbs lime/acre} = \frac{3{,}000 \text{ lbs/acre}}{0.77} \approx 3{,}900 \text{ lbs/acre}$$

Other procedures may be found in other states. Keep in mind that these recommendations are for a typical plow depth. If one wants to amend soil more or less deeply, the lime recommendation must be adjusted accordingly.

Besides calculating application rate, one might also want to compare prices for various available lime products. In choosing a lime, one might have specific goals, like adding magnesium to the soil (dolomitic lime) or very fast reaction (fine grinds). Otherwise, price decides. The important issue here is not price per ton of lime but cost per pound ENP, calculated as

$$\text{cost/lb ENP} = \frac{\text{price/ton lime}}{\text{lb ENP/ton}}$$

Rather than solve a sample problem here, there will be a problem to be solved in the review questions, using the above formula.

Lime Application

Best results are obtained from liming when there is close contact between the grains of lime and the soil. To achieve this, lime should be spread evenly over the field and then mixed well into the soil. Lime-spreading trucks do a good job of spreading the material (Figure 11–17).

Lime may also be applied in pelletized form, which is more easily applied than ground lime with common application equipment. Pelletized lime is particularly useful when applying over existing vegetation and in small applications like landscapes.

While most lime is spread in a dry form, some is finely ground and mixed with water or a fertilizer solution and sprayed on the field. To prepare **fluid lime**, lime is ground very finely (e.g., all passing through a 300-mesh sieve) and suspended in water. Because the particles are so fine, they react quickly, with pH rising measurably in days instead of weeks. However, fluid lime remains active for a shorter time, so it must be reapplied sooner.

After lime is spread, plowing and/or discing mixes the lime into the soil. In established pasture or other situations where plowing is not possible, lime is spread

Figure 11–17
Application of lime to an Iowa field.

evenly on the soil surface. If it is not mixed into the soil, the lime slowly moves into the soil.

Growers may lime at any time that is convenient. To avoid compaction, however, it is best not to drive the trucks on wet soil. Lime should not be applied with certain forms of nitrogen fertilizer because it can cause nitrogen losses (see Chapter 14). The most important consideration is reaction time, because it takes a few months for lime to break down in the soil. If faster action is needed, a grower can use fluid lime, hydrated lime, or more finely ground lime grades.

It is worth noting here that when pH is adjusted by liming, pH begins to return to its former level, since soil-acidifying processes continue to operate after liming. This is particularly true for farmers, who will, after liming, continue to remove base cations in harvested crops and will continue to rely on ammonium fertilizers. Both drive down pH.

ACIDIFYING SOIL

Sometimes soil can be too basic for good plant growth. This may occur with acid-loving plants preferring a pH range from 4.0 to 5.5, such as blueberries (Figure 11–18) or azaleas, in even slightly acid soils. These plants apparently have a high iron requirement that can be met only in soils acid enough for iron to be readily available. New types of locally bred, hardy azaleas are quite popular in the author's home area, but the soil is not acidic enough for their needs and must be amended for success.

High soil pH is also a problem in parts of the country where soil is naturally too alkaline for a wide range of plants, common to the more arid parts of the country


Courtesy of Carl Rosen, University of Minnesota

Figure 11–18
The pale green blueberry plants are suffering iron chlorosis from high pH. Notice the drip irrigation lines. If the water coming out of these is "hard"—high in calcium bicarbonates—the irrigation water itself will raise soil pH.

indicated in Figure 11–4. Here, excess lime or sodium keeps soil pH high, as shown earlier in reactions (*c*) and (*d*). Overlimed soils may also become alkaline. The Midwest also has more alkaline soils where limey glacial drift was deposited by the most recent glacial advance.

High pH primarily ties up micronutrients such as iron, manganese, zinc, and others, leading to micronutrient deficiencies. In high-molybedenum soils that element may also become toxic. Lowering pH answers these problems by improving availability of micronutrients. Unfortunately for those who need to acidify the soil, it is more challenging to lower pH than to raise it. Because of cost, soil acidification is most practical for high-value horticultural crops like blueberries or in landscapes.

For planting a few acid-loving shrubs, landscapers often incorporate large amounts of sphagnum moss peat into the planting soil. Certainly your author recommends this. Its very acid nature, plus the physical improvement of the soil, serves very well as a soil amendment. However, as peat decays, its activity declines and pH will rise. Peat is also not a practical amendment for large areas.

For longer lasting pH reduction, and for larger areas, sulfur is preferred. Once applied and mixed into the soil (as described earlier for lime), *Thiobacillus* bacteria alter sulfur to sulfuric acid:

$$(m) \qquad 2S + 3O_2 + 2H_2O \rightarrow 2H_2SO_4 + \text{energy}$$

Sulfuric acid releases hydrogen ions, and the soil becomes more acidic.

Sulfur is available in granular and powdered forms and as a flowable liquid. The powdered form acts most rapidly but is more difficult to handle. Granular sulfur, while slower acting, spreads much more easily with application equipment. Figure 11–19 suggests sulfur application rates. As with lime, finer-textured soils and those with high-organic-matter content need more sulfur than sandier soils.

To Lower pH by This Amount	Ground Sulfur Pints/100 ft^2 Sand	Loam	Pounds/Acre Sand	Loam
0.5	2/3	2	360	1,100
1.0	1⅓	4	725	2,200
1.5	2	5½	1,100	3,000
2.0	2½	8	1,350	4,400
2.5	3	10	1,650	5,400

Adapted from USDA, Kellogg, Soil: 1957 Handbook of Agriculture

Figure 11–19
Amount of sulfur needed to lower pH for an 8-inch plow layer.

Sulfur reacts slowly, so treat soils several months, or at least weeks, before planting if possible. It should be incorporated into the soil several inches for best results. Sulfur may be spread over the soil surface, but results will be slow and only the top couple inches of soil will be acidified. Your author has had good results amending soils with both sphagnum peat and sulfur, to improve the physical conditions, get some immediate acidification from the peat, and get longer-term results from the sulfur.

A number of other chemicals also acidify the soil, and are used much the same as sulfur. These include iron sulfate, $Fe_2(SO_4)_3$ and aluminum sulfate, $Al_2(SO_4)_3$. Iron sulfate acts rapidly by a reaction involving iron that releases hydrogen ions. Iron sulfate acts faster than sulfur, but more is needed, a bit more than six times as much.

With aluminum sulfate, aluminum hydrolysis releases hydrogen ions according to reaction (*g*). Because of the potential toxicity of aluminum, discussed earlier in this chapter, the author does not normally recommend aluminum sulfate, except for turning hydrangea flowers blue. In this particular case, it is aluminum ions dissolved in flower cell sap that produces blue color. Iron toxicity can also occur if excessive amounts of iron sulfate are used (Figure 11–8).

Acidifying fertilizers, those containing ammonium nitrogen, also lower soil pH. However, these cannot be employed for sharp, rapid drop in soil pH—the amount needed would cause fertilizer burn. They may be usefully applied annually to acid-loving plants to sustain a lower pH after other amendments create the proper initial pH. Many water supplies are alkaline in effect; simple irrigation with such water slowly raises pH. Annual fertilization with an acid fertilizer helps neutralize a pH rise. The most potent of acid fertilizers is ammonium sulfate. Chapter 14 provides more detail on fertilizer effects on pH. Mulching with acidifying materials like pine needles may also delay a pH rise, though the effect is usually slight.

Some individuals mistakenly apply gypsum ($CaSO_4$) in the hope of lowering soil pH. As a neutral salt, it does not do so.

Calcareous soils may be very difficult to acidify because there is such a large reserve of lime that must be leached out. The bin example in Figure 11–11 pictures this, except one would relabel “reserve acidity” with “reserve alkalinity.” Here, free lime buffers soil from pH changes. Nevertheless, in the American Southwest, sulfur is often included in the preparation of flower beds. When soils are calcareous, more sulfur will be needed to counteract the buffering effect, and repeat treatments over time will no doubt be required.

pH adjustment to established plants presents more challenges. Incorporation into the soil will damage the root system, especially of shallow-rooted plants like azaleas.

The materials listed earlier may be surface-applied, but improvement will be slow and only the top couple inches of soil will be acidified (which will still be helpful). Changing pH of an acid-loving tree like pin oak really presents difficulties. Here, drilling a grid of small holes under the tree (or at least, around the drip line) and backfilling the holes with a mixture of sulfur (say a quarter cup) and soil will create acidified zones that may be just enough to allow iron or manganese uptake. Chapter 17 describes fertilizing trees—the same technique could be used here.

Where pH reduction is impractical, fertilization and crop selection are required. Deficiencies may be temporarily corrected by fertilizing with the proper nutrients. Repeated foliar sprays of nutrients can temporarily but effectively resolve micronutrient deficiencies from high soil pH, discussed in more detail in Chapter 14. Crops should also be selected for tolerance to high pH. In alkaline soils, for instance, alfalfa would outperform soybeans. Varieties of the same species will vary in tolerance, so one soybean variety may grow where another would not. Appendix 5 lists pH preferences of common landscape trees.

SOIL SALINITY

In humid regions of the United States, acidity is a common problem for growers because percolation leaches calcium, magnesium, and sodium from the soil. Growers in the more arid parts of the nation often have a different but related problem—an accumulation of **soluble salts** of these same bases. This accumulation tends to be a problem in dry climates where natural levels of rainfall cannot flush salts out of the soil. It is particularly associated with irrigation in dry climates because irrigation water flows through materials naturally high in salt, because a lot of water must be applied in such climates, and because there is less natural precipitation to flush out the salts. We also associate this **salinization** with poor drainage in irrigated fields. Irrigation imports salts into fields, and when drainage is poor, irrigation raises the water table, bringing salt-laden water into the root zone of crops.

A soluble salt is defined as a salt (see Appendix 1) that is as soluble or more soluble in water than gypsum (calcium sulfate, $CaSO_4$). The soluble salts of greatest concern in the soil are sulfates (SO_4^{-2}), bicarbonates (HCO_3^{-}), and chlorides (Cl^{-}) of the bases calcium, magnesium, and sodium. These salts may come from parent materials, irrigation with salty water, or even deicing salts.

Prominent locations for salinity problems in the United States include the San Joaquin Valley of California, the lower Rio Grande Valley of Texas, and such western and southwestern states as Arizona, New Mexico, Utah, and some of the northern Great Plains. Even farmland around estuaries of the East Coast may suffer some salinity problems. Salinity problems affect about 25 percent of the irrigated lands of the United States.

A great many Americans live in coastal cities and towns, and on-shore winds transport salt-laden mist surprisingly far inland. In these areas, property owners and landscapers must be aware of the salt tolerance of landscape plants. And in the snowbelt states, deicing road salt can present a serious problem along roads and highways (discussed in Chapter 19). Your author has also seen numerous examples of turf and plants turned crispy by overfertilization. This is a form of salt damage we call *fertilizer burn*.

Growers of potted plants—greenhouses, nurseries, and interior landscapers—also experience soluble salt problems. Here high volumes of water, often containing dissolved salts, are poured into a small soil mass. Because fertilizers are salts, fertilization compounds the problem. Chapter 17 discusses this further.

Some natural ecosystems, of course, have developed on salted soils or wet areas like coastal marshes. These are occupied by plants called **halophytes** that have evolved adaptations to high salt and sodium levels. Some halophytes merely tolerate the salt, whereas some live only in salted conditions. Interestingly, some of these halophytes have begun to appear in areas affected by human salting, such as roadsides, sometimes as invasive weeds.

Effects of Soil Salts

In nonsalted soils, salt effects are too minor to be of concern. But in salted soils, salts cause a number of problem conditions. Primary among these are osmotic effects. Ordinarily, solute concentrations inside root cells are higher than those outside in the soil solution, which promotes water uptake. Put another way, osmotic water potential inside the cell is lower than on the outside, so water moves into the cell by osmosis. High soil salinity reduces the potential gradient between soil water and cell water, inhibiting uptake. Or, we could say it reduces the availability of soil water (Figure 11–20), making it harder for plants to take up and increasing the percentage of soil water that is unavailable. A saline soil of the same water content as a nonsaline soil seems drier (lower water potential). If soil salts rise high enough, water could even be drawn out of roots by osmosis.

Other effects include the following:

- Roots can adjust somewhat to salted soil by raising their own solute levels to lower osmotic potential inside the cell and reestablish a potential gradient. But this takes energy that could go into growth and other functions.
- Specific ions, mainly chlorine and sodium, may be taken up by plant roots and accumulate in plant tissue to toxic levels. These are called *ion-specific effects.*

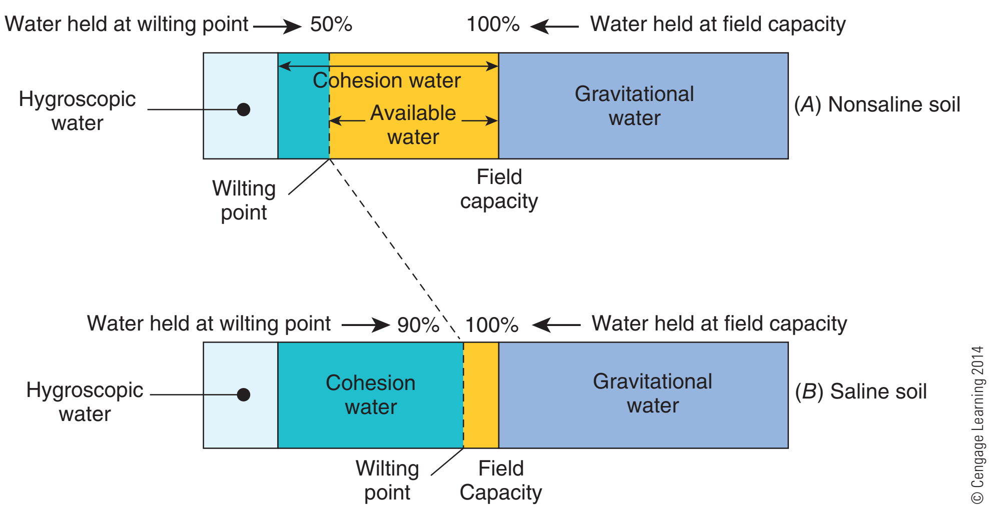

Figure 11–20
(A) In a nonsaline soil, about half the water held at field capacity in available to plants. *(B)* In saline soil, as little as 10 percent may be available because of osmotic potential.

- Stress on roots from salinity makes them more prone to root rot organisms.
- Nutrient imbalances in the plant can result from excess of some ions at the expense of others. For instance, high levels of sodium can induce potassium or calcium deficiencies.
- High soil salt levels inhibit populations of some soil microorganisms while encouraging others, changing the biological nature of the soil.
- In certain cases, extremely high pH occurs.

Different plants react more or less to these different effects. Citrus fruits are an example of plants that suffer from all of them. Figure 11–21 shows salt damage on a tomato as yellowing and death of leaf margins from some combination of the factors just mentioned. Soil scientists define three types of problem soils based on type of soluble salts: saline, sodic, and saline-sodic. Figure 11–22 summarizes these three, described next.

Saline Soils

Saline soils have high levels of soluble salts except sodium. Soil salinity can be easily measured by passing an electrical current through a solution extracted from a soil sample—the greater the salt content, the greater the electrical current. The value is called *electrical conductivity*, or EC, and is the means by which we measure salinity.

Courtesy of Carl Rosen, University of Minnesota

Figure 11–21
Salinity damage on tomato. Yellowing and browning of leaf margins and tips is typical of salinity damage.

Salted Soil Class	Conductivity (mmhos/cm)	Exchangeable Sodium (%)	Sodium Adsorption Ratio	Soil pH	Soil Structure
Saline	>4.0	<15	<13	<8.5	Normal
Sodic	<4.0	>15	>13	>8.5	Poor
Saline-sodic	>4.0	>15	>13	<8.5	Normal

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Figure 11–22
Characteristics of salted soils.

For many common day-to-day uses, EC is measured as *millimhos per centimeter* (mmhos/cm). For scientific publication, the units *siemen per meter* are preferred, and 1 siemen per meter equals 10 millimhos per centimeter.

A saline soil is defined as a soil with an EC of 4 or more millimhos per centimeter. However, salinity levels as low as 2 millimhos per centimeter can injure sensitive plants. Most salts are chlorides or sulfates. Less than half of the cations are sodium, and little sodium is adsorbed on soil colloids. Soil pH is 8.5 or less. A white crust may be seen on the soil surface, due to salts migrating to the surface by capillary rise (Figure 11–23); this is also commonly observed on the soil surface in potted plants.

Soils can be classified for use based on salinity. Figure 11–24 shows the classification system. Figure 11–25 classifies common crops according to their salt tolerance. Appendix 5 lists salt tolerances of common landscape trees. For plants growing in pots, as in greenhouse production, the values of Figure 11–24 are much too high, and EC must be kept lower. Enrichment Activity 10 at the end of this chapter provides a Web site with information on EC levels for greenhouse crops.

Photo by Ron Nichols, USDA Natural Resources Conservation Service

Figure 11–23
Salt deposits on soil surface in Utah.

Class	EC (mmhos/cm)	Crop Response
Nonsaline	0–2	Salinity effects unimportant
Slightly saline	2–4	Yields of sensitive crops lowered
Moderately saline	4–8	Yields of many crops lowered
Strongly saline	8–16	Only tolerant crops yield well
Very strongly saline	More than 16	Only most tolerant crops yield well

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Figure 11–24
Crops responses to soil salinity.

Type of Crop	Tolerant	Medium	Sensitive
Field crops	Barley	Corn	Beans
	Sugar beet	Soybean	Flax
	Cotton	Sorghum wheat	Broadbean
Forage crops	Bermuda grass	Alfalfa	Clovers
	Wheatgrass	Orchard grass	
	Tall fescue	Perennial rye	
Vegetables	Beets	Spinach	Lettuce
	Asparagus	Tomato	Bell pepper
		Broccoli	Onion
		Cabbage	Carrot
		Potato	Beans
		Sweet corn	Celery
Fruits	Date palm	Grape	All others
		Fig	
		Olive	

Figure 11–25
Tolerance of selected crops to soil salinity. For trees, see Appendix 5.

Sodic Soils

Sodic soils are lower in the kinds of salts found in saline soils but high in sodium. The exchangeable sodium percentage (or sodium saturation) is 15 or more, and pH is in the range 8.5–10.0. Sodium is often measured by the **sodium adsorption ratio (SAR)**. The SAR compares concentration of sodium ions with the concentration of calcium and magnesium ions according to the formula:

$$\mathrm{SAR} = \frac{[\mathrm{Na}^{+}]}{\sqrt{\dfrac{[\mathrm{Mg}^{+2}] + [\mathrm{Ca}^{+2}]}{2}}}$$

Using this measurement, a sodic soil has an SAR greater than or equal to 13.

Sodic soil has a number of effects on plant growth. The importance of these effects varies according to soil and crop.

- Sodium reacts with water, reaction (*d*), to form lye. The resulting high pH, 8.5 or higher, limits growth of most plants.
- For many crops, the main effect of sodium is the destruction of soil structure (Figure 11–26). When sodium ions saturate cation exchange sites, colloids separate, and disperse soil aggregates. Tiny soil particles lodge in the soil pores, sealing the soil surface and creating wet "slick spots." Tilth suffers and crusts hard enough to stop seed germination may form. Sodic soils may also show a poorly drained columnar subsoil structure. The effect of sodium is most extreme on fine-textured soils and least extreme on coarse soils.

Photo by Peggy Greb. Courtesy of USDA ARS

Figure 11–26
A sodic soil. Sodium has dispersed soil aggregates, destroying soil structure. Vegetation is sparse.

- Plants may take up enough sodium to injure plant tissues. Crops vary in their tolerance to sodium. For the most sensitive plants, such as citrus fruits, the nutritional effects of sodium are more important than its effects on structure. For sodium-tolerant plants, poor growth results mainly from soil conditions. Figure 11–27 lists the sodium tolerance of selected crops. There are wild plant species adapted to high-sodium soils, but none of these are of economic importance except for use in the appropriate natural restoration projects.

Saline-Sodic Soils

Saline-sodic soils contain high levels of both soluble salts and sodium. EC is greater than 4.0 millimhos per centimeter, SAR is greater than 13, and pH is less than 8.5. The physical structure of these soils is normal. However, after periods of heavy rain or irrigation with low-salt water, soluble calcium and magnesium may leach out of the soil, leaving behind sodium salts. Soil may then become sodic, with poor physical structure and drainage.

Reclaiming Salted Soils

People who grow plants in pots know what to do about potting soil that has gotten too salty: they water heavily to leach out the excess salts and then dispose of the excess (it is never left in a tray, where salts can be reabsorbed). This leaching process, on a grand scale, is how growers leach salted fields.

The first step in reclamation of salted soils is to decide whether the project is practical and will pay for itself. The basic step to reclaiming soil is to leach out salts, so there must be a source of acceptable water. Very fine-textured soils may not allow sufficient drainage. If a decision is made to reclaim the soil, the next step is to

Sensitive Sodium Percentage [Exchangeable (ESP) = 2–20]	Moderately Tolerant (ESP = 20–40)	Tolerant (ESP = 40–60)	Most Tolerant (ESP Above 60)
Deciduous fruit	Clovers	Wheat	Crested wheatgrass
Nuts	Oats	Cotton	Tall wheatgrass
Citrus fruit	Tall fescue	Alfalfa	Rhodesgrass
Avocado	Rice	Barley	
Bean	Dallisgrass	Tomato	
		Beets	

USDA Agriculture Information Bulletin 216, 1960

Figure 11–27
Tolerance of some crops to exchangeable sodium. Damage to the most sensitive crops is from sodium toxicity. Damage to tolerant crops is due to poor soil conditions.

ensure good drainage to allow salted water to leave the soil profile. After proper drainage has been installed, the next steps depend on the type of problem.

Saline soils are most easily reclaimed. Growers flood the soil surface so that percolation leaches salts out of the soil profile. High-quality water works best, but larger amounts of fairly saline water will also work. Treatment water should, however, be low in sodium. Ponding is one way to apply leaching water. In ponding, heavy equipment constructs low earthen dikes to divide the affected land into ponds, which are then flooded. The field may be ponded several times, allowing time for drainage between floodings.

Sodic soils cannot usually be reclaimed simply by leaching, because the sealed soil surface inhibits drainage. It is usually necessary to first remove the sodium. This is typically done by treating the soil with gypsum, the material contained in sheetrock. Granular gypsum may be spread on the soil surface, or finely ground gypsum may be applied through an irrigation system. When gypsum enters the soil, it dissolves and calcium replaces sodium on the cation exchange sites. The soil slowly begins to aggregate, and sodium sulfate leaches out of the soil:

$$(n) \quad \boxed{\text{micelle}} \begin{matrix} Na^+ \\ Na^+ \end{matrix} + CaSO_4 \rightarrow \boxed{\text{micelle}} — Ca^{+2} + \underset{\text{(leaches)}}{Na_2SO_4}$$

A few additional words about gypsum may be added here. Gypsum is often sold to loosen clay soils in gardens and lawns. Possibly in very tight, low-organic-matter soils it might help slightly (though adding organic matter would help more). However, more often, unless the soil is salt-affected, it is likely to have little effect. It may possibly improve soils damaged by road deicing salts that contain sodium, like the most common deicing salt, sodium chloride.

Saline-sodic soils must be treated to remove sodium. If they are simply leached with low-salt water, calcium and magnesium salts are removed but sodium remains in the soil, forming a sodic soil. Thus, gypsum treatments are useful. In the initial stages of reclamation, some growers leach these soils with fairly saline water. The calcium and magnesium salts in the water replace some of the sodium on the soil colloids, preventing destruction of soil structure.

Managing Salted Soils

Saline soils, especially irrigated land in arid climates, may be managed to reduce salt problems. One answer, of course, is to grow salt-tolerant crops. This step, however, does not really solve the problem but causes a shift over time to increasingly salt-tolerant crops. A number of practices can be used to help reduce salt problems, as follows:

- If possible, use high-quality irrigation water. Figures 9–24 and 9–25 list the irrigation water classes.
- Keep soil moist. Water dilutes soil salts, lowering the effect of osmotic potential. Salts tend to be most damaging in dry soil, when the salts are concentrated and both osmotic and matric potential are high.
- Overirrigate enough to leach salts out of root zones. The amount of extra water needed is called the **leaching fraction**.
- Avoid overfertilization. Most fertilizers are salts and can compound salinity problems. Selection for low-salinity fertilizers (Chapter 15) may help in certain situations like turf.
- Maintain a good soil-testing program to monitor salinity and avoid overfertilization.
- Plant on ridge shoulders in furrow-irrigated fields. Salts tend to concentrate on the top of the ridge.
- Use drip irrigation—it tends to reduce salt stress because it keeps the soil uniformly moist and moves salts out of the root zone and into the soil between plants and rows (Figure 11–28). If the soil is allowed to dry between watering, however, salts reinvade the root zone.

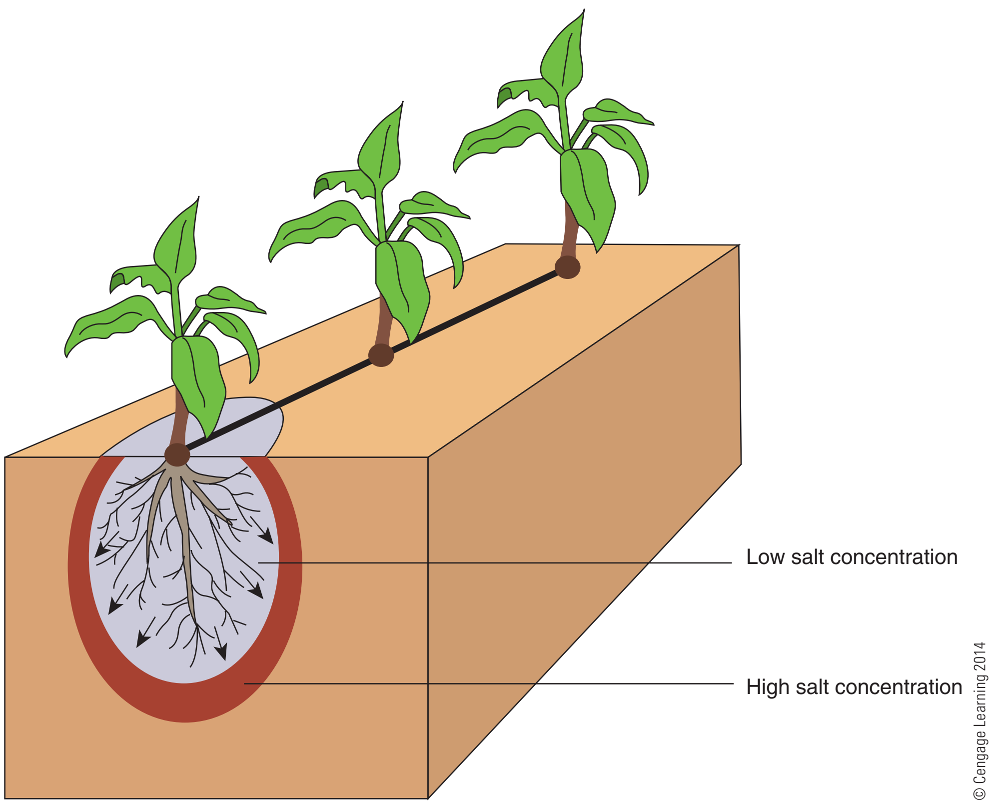


Figure 11–28
Drip irrigation can reduce salt stress. As water moves away from the emitter by capillary action, it carries dissolved salts out of the root zone. This is an example of managed accumulation: keeping salts out of the root zones of plants rather than removing them from the field.

Salted Water Disposal

One difficulty with methods for reclaiming and managing salted soils is that they do not eliminate soluble salts but move them to another place. Salty drainage water reappears in rivers downstream of affected farms, making that water even saltier. Individual growers do have some options to help reduce saline discharges from their fields. Improving irrigation efficiency and practicing minimum leaching are examples of practices that minimize the problem. Where necessary, collection of drainage water in evaporation ponds may be possible but expensive.

Managing Salts in Potted Plants

Growers of potted plants work constantly to maintain a proper EC in their pots. This means frequent monitoring of EC with conductivity meters (Chapter 13 illustrates one device), often on a weekly basis. Where irrigation water is saline, a little extra water is added at each irrigation to leach out salts that might otherwise accumulate. In some cases water must be treated to reduce salinity, though this is expensive. Growers also tightly manage the fertilizer program to avoid fertilizer buildup. If tests reveal that the EC has risen too high, growers leach pots with a heavy watering. This is done by watering pots heavily until water runs out of the bottom, allowing more salts to dissolve for a half-hour, then repeating the heavy water application. Since this treatment leaches out all the fertilizer, it is followed by an appropriate fertilizer application.

SUMMARY

Soil pH depends on the balance of hydrogen and hydroxyl ions in the soil solution. Alkaline soil results from the reaction of base anions such as carbonates to remove hydrogen ions from the soil and release hydroxide ions. At higher pH, high base saturation prevents hydrogen ions from occupying cation exchange sites. Over time, leaching with acidic water removes the base anions and cations such as calcium, making the soil more acidic and replacing calcium on the cation exchange complex with hydrogen ions. At low enough pH, aluminum enters the soil solution and drives down pH even more.

Acid soils affect plant growth by lowering the availability of phosphorus and other nutrients, freeing toxic levels of aluminum or other metals, and inhibiting helpful soil organisms. Alkaline soils render several micronutrients unavailable and create many problems associated with salted soils. Most plants grow best between pH 6.0 and 7.0. A few, like potatoes, perform best in acid soil, while very few, like alfalfa, do best in neutral or mildly alkaline soil.

Acid soils are treated with various forms of agricultural lime, mostly ground limestone. Lime replaces hydrogen and aluminum on the cation exchange sites with calcium and magnesium and converts hydrogen ions to water. The amount of lime needed depends on the amount of pH change required, buffering capacity of the soil, and the form of lime. Soils too alkaline for the plants being grown may be treated with sulfur or other acidifying treatment

Salted soils may be saline, sodic, or saline-sodic. Saline soils, which are high in soluble salts but low in sodium, reduce the water available to plants. Saline soils can be treated by flooding to leach out salts. Sodic soils are high in sodium and exhibit poor physical structure. They are treated with gypsum to displace the sodium. Saline-sodic soils contain both soluble salts and sodium. Care must be taken with these soils to avoid leaching the salts while leaving the sodium. After a salted soil is treated, it must be managed carefully to reduce salt problems.

REVIEW

1. It is said that in humid regions, soil is either acidic or in the process of becoming acid. Explain.
2. What are the effects of low pH on plant growth? High pH?
3. A buffer test on a sample of mineral soil produces a buffer index of 6.4. How many pounds per acre of 90 percent pure lime should be applied according to Figure 11–13? Ignore ENP for this question. How many pounds would we apply to a 5,000-square-foot lawn before laying sod (1 acre = 43,560 square feet)?
4. How many pounds per acre of 85 percent hydrated lime would replace the lime in question 3, using Figure 11–14?
5. Name soil conditions for which gypsum is an effective treatment and for which it is probably not. Explain your answer.
6. For a greenhouse grower, pH of the growing media is a major concern because the media are poorly buffered and can change dramatically quickly. Such growers have two simple rules that apply to all soil users and that you should know: Low pH causes micronutrient ___________ and high pH causes micronutrient _______________. Explain.
7. Why would rising salinity be a problem in greenhouse production and in interior landscapes? What can be done about it?
8. Rhododendrons and azaleas require a low-pH soil. Many gravel mulches used in the landscape trade are made from limestone materials. Would you recommend their use on azaleas? If not, what might be alternatives? Explain your answer.
9. How does common calcitic lime neutralize acidity?
10. "Hard water" contains a lot of calcium and bicarbonate (HCO_3^-) ions. What effect would frequent irrigation with hard water have on soil pH? Explain. *Hint:* Consider reaction (*b*), a quite reversible reaction, and chemical equilibrium, as described in Appendix 1.
11. Assume you want to grow river birch (*Betula nigra*) in your yard. Your soil is moderately well drained with a pH of 7.0 and a salinity of 2.0 millimhos per centimeter. Looking at Appendix 5 and the charts in this chapter, do you find this soil suitable for river birch as is? If needed, how might you amend the soil?
12. If you see a soil-test report for a sand-based golf green with a pH of 5.0 and a CEC of 2, what would you guess about the availability of magnesium for the turf? How would you treat the condition?
13. The author went to a local garden center and checked labeling on a 40-pound bag of "high-calcium pelletized ground limestone," a product for homeowners (though the author doubts any homeowner needs lime on local soils). He found information on the label about CCE, the grind, and ENP value listed according to state. Here we will use the Minnesota value of ENP, which was on the label, but which you will calculate for yourself. Answer these questions from this information and tables in the text:

Chemical Purity	
Calcium Carbonate Equivalent	87%
Particle Size Distribution	
100% passing	8-mesh sieve
100% passing	10-mesh sieve
100% passing	20-mesh sieve
100% passing	40-mesh sieve
100% passing	50-mesh sieve
98% passing	60-mesh sieve
90% passing	100-mesh sieve
70% passing	200-mesh sieve
Effective Neutralizing Power	
Minnesota effective neutralizing power = X pounds per ton	

a. What percentage of this lime product is ineffective for neutralizing acidity?
b. Would you think this is a fine, medium, or coarse grind?
c. Would you expect this product to be fast acting compared to other lime products?
d. Would you expect this product to be long lasting compared to other lime products?
e. Assuming the product has no water content, what is the ENP of this product using the Minnesota method? If you are from a state that

does it differently, you may use that method as requested by your instructor.

f. A soil test recommends applying 4,000 pounds ENP per acre. How much of this product would you apply?

g. Another soil test recommends 2 tons per acre pure calcium carbonate. How much of this product would you apply?

14. Compare the cost of two lime products: Product A: ENP = 1,300 pounds per ton costing $15 per ton. Product B: ENP = 1,200 pounds per ton costing $12 per ton. What is the cost per pound ENP for each, and which is the better buy?

15. What would be the materials cost (ignore equipment and labor) of the cheaper lime per acre in question 14 if the lime recommendation was 6,000 pounds ENP per acre? What would be the savings of selecting the less expensive lime?

16. Greenhouse growers use distilled water in soil testing. When a grower first opens a gallon of distilled water, the pH should be about 7.0. Many growers are surprised that over time, the distilled water becomes somewhat acidic. Explain.

ENRICHMENT ACTIVITIES

1. Put a few drops of a strong acid on a piece of limestone, and observe the fizz. Can you explain the bubbles? See Figure 11–10. How does this relate to calcareous soil?
2. Use pH paper to test a number of household solutions such as vinegar, lemon juice, tapwater, and ammonia.
3. Check a soil sample for pH by mixing one volume of soil with two volumes of distilled water. Let it sit for 20 minutes, then filter with a coffee filter or other filtering device. Measure the pH of the liquid with pH paper or a pH meter. This is a 2:1 extraction, commonly done for pH and EC testing in greenhouses.
4. At the beginning of the course, the instructor can mix finely ground lime, sulfur, and gypsum into separate soil samples in pots. Keep warm and moist for several weeks. Then check for pH in class, as described in question 3.
5. Open a fresh can of soda and measure the pH immediately. Measure it again a few hours later. How has the pH changed? Explain [see reaction (*b*)].
6. Re-create the demonstration of Figure 11–7. The author dissolved iron sulfate from a local garden center in acidified distilled water and divided the solution into two parts. In another beaker he created a basic solution, then poured it into one of the acidified beakers until a precipitate formed. All the ingredients except iron sulfate were from the kitchen. What were they?
7. For more information on the mathematics of logarithms and pH, see: Coyne, M. S., & Thompson, J. A. (2006). *Math for soil scientists.* Clifton Park, NY: Delmar, Cengage Learning.
8. This chapter claims that rainfall is acidic. Check out this map of the rainfall pHs for the United States from the U.S. Geological Survey (http://water.usgs.gov/nwc/NWC/pH/html/ph.html). Why might pH vary?
9. For more information on salted soils, try this Web page on "Managing Saline Soils" by G.E. Cardon, et. al on the Colorado State University Extension's website http://www.ext.colostate.edu/pubs/crops/00503.html.
10. A Web site from Purdue presents information on greenhouse soil testing, including recommended EC and pH levels. It can be found at http://www.extension.purdue.edu/extmedia/ho/ho-237-w.pdf.
11. For more information on amending the soil to lower pH, especially for more detailed application rates than shown here, try the A&L Great Lakes Laboratory's Web site at http://www.algreatlakes.com. Fact sheet #28 presents information on field crops (including blueberries!) and #29 on lawns, landscapes, and gardens.

CHAPTER 12

Plant Nutrition

TERMS TO KNOW

ammonia volatilization
chelate
chlorosis
enzyme
lodging

OBJECTIVES

After completing this chapter, you should be able to:

- discuss nitrogen nutrition and the nitrogen cycle
- discuss phosphorus nutrition
- discuss potassium nutrition
- answer questions about the secondary nutrients
- answer questions about trace elements

When a customer walks into a garden center and asks a salesperson about a difficulty in the garden, the salesperson may not recognize the problem or know the solution. After all, lots of things can be wrong, and none of us can know everything. Sometimes, the salesperson will offer a bag of fertilizer. Everybody knows about fertilizer; shortages of nutrients are not uncommon, and it is easy to apply. So give it a try.

Such an unsophisticated approach to plant nutrition and fertilizer is obviously not very professional. Compared to some other characteristics of soil, nutrient status can be modified fairly easily, and fertilization is a standard practice of growing plants. But there is a lot to know about effective management of nutrients without causing environmental damage.

This chapter begins a sequence of chapters about plant nutrients and their management in the soil by soil testing and fertilization. It provides details about the nutrients first mentioned in Chapter 10. We will begin with nitrogen.

NITROGEN

Nitrogen, more than any element, promotes rapid growth and dark green color. Plants require more nitrogen than any other mineral element as an essential part of protein and chlorophyll. As the most mobile of mineral nutrients in the environment, readily lost from the soil, it is usually most in need of annual replenishment. Plants respond to nitrogen in the following ways:

- Nitrogen speeds growth. Plants receiving adequate nitrogen have vigorous growth, large leaves, and long stem internodes.
- Robust root systems need adequate (but not excess) nitrogen.
- Plants make large amounts of chlorophyll, the green pigment that performs photosynthesis. On well-fed plants, leaves are dark green; on poorly fed ones, they are pale green (Figure 12–1).
- Plants use water best when they have ample nitrogen.
- Nitrogen increases utilization of carbohydrates and increases their transformation into protein.
- Crops are more productive.
- Turf is thicker, greener, and lusher.

Plants with too much nitrogen do not grow properly, however. High tissue nitrogen contents cause a very *succulent* growth, that is, growth that is high in water content but lower in dry matter. This weakens the plant. Here are some problems associated with too much nitrogen:

- Easily injured growth is encouraged. Plants stems are weaker and more easily topple, or *lodge,* in rain.
- Succulent, high-nitrogen growth is more prone to many insects and diseases.
- Overly rapid growth slows maturity and ripening of many crops.

Courtesy of Carl Rosen, University of Minnesota

Figure 12–1
Nitrogen deficiency. Potatoes growing in the foreground on this sandy soil are deficient in nitrogen. Compared to plants in the background, they are stunted and pale green.

- Overly rapid growth also delays the hardening-off process that protects many plants from cold, exposing them to winter damage. For that reason, in cold climates people are discouraged from applying nitrogen to perennial and woody plants in late summer.

About half the nitrogen in a leaf occurs in enzymes involved with photosynthesis, so a well-supplied plant photosynthesizes much more efficiently than a deficient plant. This partially explains why nitrogen stimulates growth. On the other hand, we also know that leaves high in nitrogen also respire—use up the food produced by photosynthesis—more rapidly. In low-light situations, where photosynthesis is light-limited, high nitrogen merely depletes food more quickly. Plants growing under low light, such as shady turf or indoor plants, should be fertilized more lightly than plants grown in the sun.

In general, nitrogen promotes vegetative growth—stems and leaves—more than the reproductive growth of flowers and fruit. Home gardeners see the effect if they overfertilize their tomato plants, promoting lush growth but few fruit. Or they may grow lush vines of morning glory and nasturtium, but with few flowers (both plants very sensitive to high nitrogen). Also, while nitrogen aids growth in both root and shoot, shoot growth tends to be favored. This can be a problem in turf, where high-nitrogen fertilization can yield lush growth with an inadequate root system to support it during times of stress.

Nitrogen nutrition affects product quality of many crops. Good nitrogen content increases the protein content of forage, feed, and human foods. It increases succulence in crops such as lettuce, which improves their acceptability in the market. Excess nitrogen, on the other hand, may reduce quality measures such as flavor components or sweetness in a wide range of crops. For example, excess nitrogen reduces oil quality in olives, and reduces sugar content in crops such as sugar beet or cantaloupe. Also, in some plants, high nitrate levels in plant tissue may present health problems for animals and people who consume them.

Protein content, hence nitrogen content, declines in any plant tissue, like a leaf, over time. Nitrogen moves readily in the plant, and as tissue ages, nitrogen is mobilized to younger, more biologically active tissues. At the same time, the carbon content in cellulose and lignin rises in that same older tissue. Thus, a young grass blade may have a carbon–nitrogen ratio of 15:1, while an old blade's ratio might be 80:1.

In the natural world, low nitrogen tends to be the primary nutrient limiting growth in land ecosystems of cooler climates, on young soils, and many marine ecosystems.

The Nitrogen Cycle

Of the essential elements, nitrogen undergoes the most movement and change. The series of gains, losses, and changes is termed the nitrogen cycle. The central portion of the nitrogen cycle operates by the action of soil microorganisms. To review briefly (see Chapter 5), nitrogen comes from nitrogen gas (N_2) in the atmosphere, a form unusable to plants. Symbiotic or nonsymbiotic bacteria use that nitrogen to form protein for their own bodies or supply it to host plants. When these bacteria, or host plants, die, other microbes mineralize the protein to ammonium ions (NH_4^+).

Ammonium nitrogen can be taken up by plants, but most is converted by bacteria (nitrification) to nitrite ions (NO_2^-) and then to nitrate ions (NO_3^-). Nitrates are taken up by plants or microbes (immobilization) or return to the atmosphere as nitrogen gas through the process of denitrification. The solid lines in the simplified cycle pictured in Figure 12–2 summarize this portion of the cycle.

The complete nitrogen cycle includes some nonbiological processes as well, shown in Figure 12–2 as broken lines. Two other forms of fixation add usable nitrogen to the soil. First, lightning during storms provides energy to combine gaseous nitrogen and oxygen in the atmosphere to form nitrogen dioxide (NO_2). The gas dissolves in water vapor to produce nitric acid (HNO_3). About 5–10 pounds per acre of nitrogen fall to earth yearly in rain and snow from this source. Second, large amounts of nitrogen are fixed from the air in fertilizer factories (see Chapter 14) and applied to soil by growers. The latter is quite new in earth's history, making its appearance in the middle of the 20th century. The development of human-fixed nitrogen is probably one of the least known of all the most important inventions, profoundly affecting human society and the environment; more about this later.

Two nonbiological losses of nitrogen from soil may be important as well. The nitrate ion is negatively charged and so is not adsorbed by soil colloids. Nor is it held in soil by other means, so nitrates easily leach from the soil. Although ammonia does not leach readily (being adsorbed by soil colloids), it too can be lost by a process called **ammonia volatilization** Ammonium ions react with hydroxyl ions in the following reaction:

$$NH_4^+ + OH^- \rightleftarrows \underset{\text{ammonia (gas)}}{NH_3} + H_2O$$

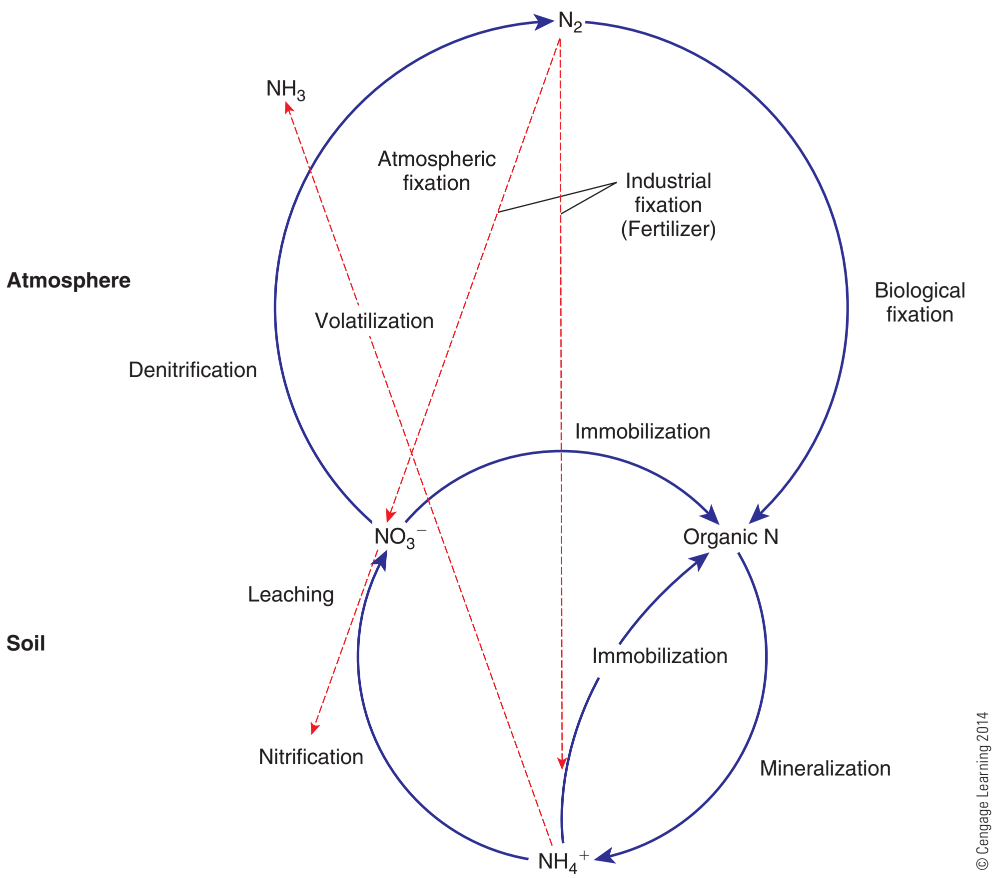


Figure 12–2
In this simplified version of the nitrogen cycle, dark lines indicate the biological process described in Chapter 5. Broken lines indicate nonbiological processes described in this chapter.

The smell of an open bottle of household ammonia (ammonia gas dissolved in water) is a result of this reaction. Normally, this is a balanced reaction in the soil, with nitrogen changing back and forth between the two forms. However, the balance can be shifted by soil conditions to cause a loss of ammonia. If soil dries, for instance, water is lost from the right side of the equation. As a result, the reaction shifts to the right and releases ammonia gas (see Appendix 1 for an explanation). If the soil is made more alkaline (by liming, for instance), the reaction again shifts to the right because of an excess of hydroxyl ions. Thus, substantial losses of ammonium nitrogen can occur when ammonium fertilizers or manure are applied to soil, especially if it is alkaline, or recently limed.

In native habitats, including virgin forests or prairies, gains and losses in the cycle balance over time. Little nitrogen leaks from the system into streams and rivers. This is one reason municipalities like to surround their reservoirs with forest. In comparison, agricultural land leaks large amounts of nitrogen. Growing crops (or even turf lawns) changes the balance greatly in ways that increase nitrogen losses:

- Nitrogen is removed by harvest, or removal of grass clippings from a lawn.
- Nitrogen is often applied heavily in excess of plant needs; this excess will not be taken up by plants and is free to move.
- Cropped soil is more likely to erode, so nitrogen and other nutrients are carried off in running water.
- Irrigation increases percolation of water through the soil profile, increasing nitrate losses by leaching. At the same time, wetter soil may increase denitrification losses.
- Liming may increase the loss of ammonia by volatilization.

To compensate for increased nitrogen losses and to meet the needs of modern high productivity, growers supply more nitrogen by manuring, growing legumes, or by fertilization. Figure 12–3 shows the nitrogen cycle as it operates on modern farms that raise both crops and animals. There is a strong trend away from a mixed farming operation toward one that specializes in either cash crops or raising animals. This trend improves economic efficiency, but exacts an obvious penalty in view of the nitrogen cycle. For the cash crop grower, more money must be spent on fertilizers. For the animal raiser, manure becomes a waste disposal problem (see Chapter 15).

A similar cycle even operates on the vast acreages of turf in the United States. Crop removal is replaced by clipping removal, fertilizers are applied heavily to grow a good stand of turf, and manuring may be replaced by organic fertilizer products.

One of the more dramatic yet unnoticed alterations of the natural world we humans have created is a very rapid acceleration of the nitrogen cycle. We have dramatically increased the addition of biologically useful nitrogen into the biosphere by fertilization and by growing legumes like alfalfa, while speeding up its loss from land. Although this has multiplied our ability to provide food to the world's population, it has also had negative environmental consequences. More about this in Chapter 15.

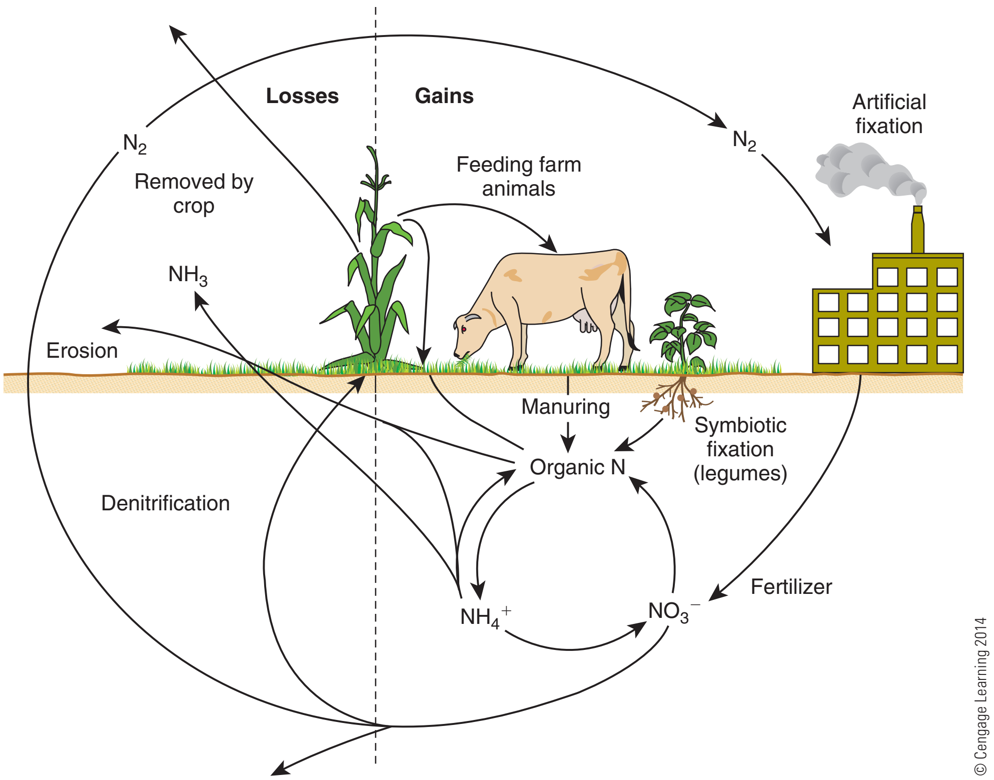


Figure 12–3
Agriculture breaks the natural nitrogen cycle by removing a nitrogen-containing crop. Growers adjust nitrogen levels by fertilizing, by adding organic sources of nitrogen like manure or compost, and by growing legumes.

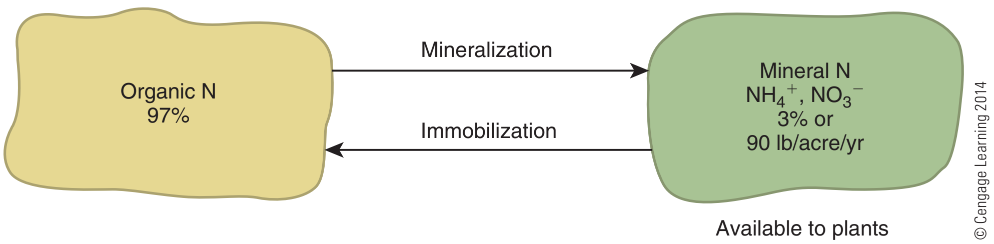


Figure 12–4
Organic matter serves as the storehouse of soil nitrogen; a small amount exists at any moment as usable nitrate and ammonium ions. Plants also take a small amount of simple, water-soluble organic nitrogen compounds.

Forms of Nitrogen in the Soil

About 97 percent of soil nitrogen resides in organic matter, the soil's storehouse of nitrogen. At any time, only a small percentage of nitrogen is mineralized to usable forms. On the average, decay makes available about 90 pounds of mineral nitrogen per acre per year (see Figure 12–4). It follows that cropping systems that preserve soil organic matter, such as no-till and some organic farming, also retain more soil nitrogen. The difference can be substantial. In one 1996 study, after 23 years of continuous corn, there were 9 milligrams of mineralizable nitrogen per kilogram of soil (in the top 7.5 centimeters) under no-till, compared to 1.4 milligrams of nitrogen under conventional tillage.[1]

Both mineral forms of nitrogen—ammonium and nitrates—are taken in by plants. In forest and woodland, ammonium is the most common form. Some

[1] Handayani, I. (1996). *Soil carbon and nitrogen pools and transformations after twenty-three years of no-tillage and conventional tillage.* Doctoral dissertation, University of Kentucky.

plants, such as blueberries, prefer a largely ammonium nitrogen diet, while many others, such as most crop plants, prefer nitrates. Plants need to process ammonium nitrogen internally to make protein, an energy-consuming process easily avoided by taking up nitrate nitrogen instead. As a broad generalization, good growth is obtained by some mixture of the two. In the greenhouse, growers manage ammonium nitrogen carefully because it becomes toxic in high doses; growers of potted plants favor nitrate forms of fertilizer. For agricultural growers, ammonium forms dominate.

There is evidence that plants may also take up a limited amount of simple, water-soluble forms of organic nitrogen, like amino acids. Researchers are still investigating the importance of organic nitrogen uptake, but it is probably not high in most agricultural settings. It may assume greater importance in organic growing, and is likely of greater significance in natural settings like forests.

Ammonium and nitrate nitrogen behave very differently in the soil (Figure 12–5). Ammonium nitrogen bears a positive charge. Negatively charged soil colloids attract the cation, protecting it from leaching. The nitrate ion, by contrast, moves freely in the soil because of its negative charge. Free movement allows nitrate to diffuse easily through soil to plant roots. However, nitrate losses from soil can be high. Nitrate ions leach out of the soil readily, and may disappear as nitrogen gas in wet soil.

The amount of ammonium and nitrate nitrogen in the soil depends on amounts and type of nitrogen applied to the soil and rates of transformation, removal, or loss. Some nitrogen fertilizers contain nitrates. Most modern fertilizers, however, mainly provide ammonium nitrogen. Nitrifying soil bacteria change this to nitrates, the preferred form for crops. Nitrifying bacteria grow best in warm, moist, loose, well-drained soil at a pH of 6.0–7.5, and function little below 50°F. Cold, wet, or acid soils slow the conversion of ammonium to nitrate nitrogen.

Waterlogged soil prevents nitrifying bacteria from thriving. However, anaerobic denitrifying bacteria thrive in the same conditions. Denitrification causes the greatest loss of nitrogen when soil users apply nitrate fertilizers to wet soils. Similarly, overirrigation of turf wastes fertilizer by stimulating both denitrification and leaching.

Because of potential losses of nitrates, it is useful to control the ammonium nitrification rate. Several chemicals have been developed to inhibit (but not stop) nitrification. In practice, results have been variable, often of benefit but sometimes not. Ammonium nitrogen can also purposely be applied to colder soils, as in the fall in cold climates.

	Organic N	Ammonium N	Nitrate N
Storage	In humus	Adsorbed	Little storage
Losses	Mineralization, erosion	Volatilization, erosion	Leaching, denitrification
Plant Use	Not used	Usable	Usable
Changes	Mineralization	Immobilization, nitrification	Immobilization, dentrification

Figure 12–5
Characteristics of three types of soil nitrogen.

Nitrogen Deficiency

In all plants, slow growth and stunting are the most obvious signs of nitrogen shortage. Because nitrogen is part of chlorophyll, nitrogen-deficient plants lack the dark green color of well-fed plants (Figure 12–1). This symptom is called **chlorosis**. Because nitrogen is highly mobile in the plant, under conditions of low nitrogen it is translocated from older to younger leaves to continue growth. This means that older leaves display poor color first. It may progress to being generalized over the whole plant. In grasses, yellowing starts at the blade tips, progresses down the midvein, and finally the entire leaf yellows. In extreme cases, the leaf dries up, a symptom called *firing*. In broadleaf plants, leaves are small with overall yellowing.

When growing plants, growers can add nitrogen to the soil by applying fertilizers (Chapter 14), incorporating higher-nitrogen organic amendments (Chapter 15), or growing legumes in rotation or as cover crops.

PHOSPHORUS

Phosphorus also spurs growth but to a lesser extent than nitrogen. Phosphorus is second only to nitrogen in its importance to plant productivity around the world, and its impact on the natural world is profound. However, plants use only about one-sixth the amount of phosphorus as nitrogen, leading to common overapplication and environmental pollution. Phosphorus affects plant growth in a number of ways:

- Phosphorus is part of genetic material (chromosomes and genes) and so is involved in plant reproduction and cell division.
- Phosphorus is part of the chemical that stores and transfers energy in all living things (adenosine triphosphate, ATP). Without it, all biological reactions come to a halt.
- Cell membranes contain large amounts of phosphorus, making it important for cell membrane integrity and function.
- Phosphorus spurs early and rapid root growth and helps a young plant develop roots.
- Phosphorus helps plants use water more efficiently by improving water uptake by roots.
- Phosphorus helps plants resist cold and disease, speeds maturity, aids blooming and fruiting, and improves the quality of grains and fruits.

In many ways, phosphorus acts to balance nitrogen. While nitrogen delays maturity, phosphorus hastens it. Nitrogen aids vegetative growth; phosphorus aids blooming and fruiting. As a rule of thumb, phosphorus is most important for plants from which we use the floral parts—that is, flowers, fruits, or seeds. One should not over apply this simple rule, however: nitrogen and phosphorus must both be sufficient for both vegetative and flower growth, and supplying more phosphorus than necessary does not stimulate more bloom.

Because phosphorus is needed for root growth, it is often a major element in *starter fertilizers,* those applied at planting. However, there is no evidence that amounts of phosphorus greater than adequate encourage heavier rooting. In fact, at low phosphorus levels, plants tend to favor roots over shoots to improve uptake, and in greenhouse production of bedding plants, the best root systems are achieved under low (but not deficient) phosphorus rates. Many greenhouse growers, in fact, grow crops under low-phosphorus regimes because high phosphorus levels cause greenhouse plants to stretch undesirably.

In the natural world, phosphorus tends to be the primary nutrient limiting growth in tropical land ecosystems, on old soils, and in freshwater and some marine ecosystems. Since naturally low aquatic phosphorus levels generally limit growth of algae in freshwater systems, increasing water phosphorus content from fertilizer pollution increases algal growth, with consequent water-quality issues, discussed in Chapter 15.

Many soils have less available phosphorus than needed for optimal growth, so most plants have evolved adaptations to improve uptake. Many small mammals like rodents chew shed antlers and bones to get the phosphorus and calcium that is otherwise lacking in their diet. In tropical land systems, agricultural land can be so short in phosphorus as to limit production and contribute to food shortages.

Forms of Phosphorus in the Soil

Soil phosphorus is provided by the weathering of minerals like the apatites, which are calcium phosphate minerals (as are bones and many types of antlers). As apatite weathers, it releases anions that can be used by plants. These anions are primary orthophosphate ($H_2PO_4^-$) and a secondary orthophosphate (HPO_4^{-2}). For simplicity, the text refers to them both as phosphates.

Many soils contain large amounts of phosphate, but most is unavailable to plants. Phosphate in insoluble forms that are not free for plant growth is said to be "fixed." The reactions that fix phosphate depend on soil pH. In strongly acid soil (pH 3.5– 4.5), insoluble iron phosphate forms. Between pH 4.0 and 6.5, phosphorus reacts with aluminum. Calcium phosphates are important between pH 7.0 and 9.0. Maximum availability lies at pH 6.5 in mineral soils, but 6.0–7.0 is satisfactory for most plants.

Between 25 percent and 90 percent of all soil phosphorus resides in organic matter, an important storehouse of phosphorus. Figure 12–6 summarizes the main forms of phosphate in the soil.

This figure does not show another way that phosphorus tends to be tied up in the soil: tightly bound to clay particles. Phosphate ions can replace hydroxyl groups in the alumina octahedral in the aluminum sheet; phosphate becomes part of clay and is fixed in place.

A typical acre of soil holds hundreds or even thousands of pounds of phosphorus in the plow layer, but at any given moment, only a couple of pounds will be in solution and available to plants. This may be sufficient for a few hours' growth. Growth, therefore, depends on rapid movement of phosphorus out of soil stores. As plants remove phosphate from solution, mineral and organic phosphate become soluble by mineralization and the activities of P-dissolving bacteria. At the height of the growing season, soluble phosphorus may be replaced from soil stores several times daily.

Because phosphorus availability is low in so many of the world's soils, plants have developed adaptations to improve access to it. These include mycorrhizal associations, specialized root systems, high root length densities, longer root hairs, and exudates given off by roots and mycorrhizae that free phosphorus. While these can

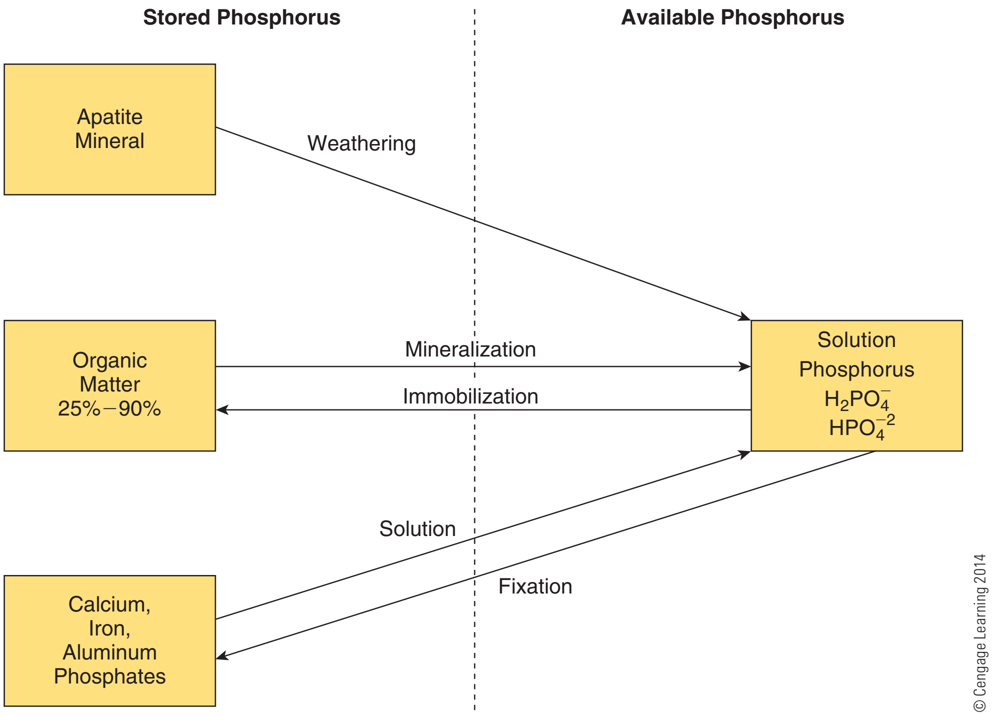


Figure 12–6
Phosphorus comes from weathering of soil minerals such as apatite. Most phosphorus is stored in organic matter or fixed forms. At any one time, only a tiny amount of phosphate is in solution and available to plants.

be effective responses in natural ecosystems, plants often cannot tap soil stores fast enough to produce a full crop. For this reason, growers fertilize soil with phosphate to compensate for fixation.

Movement and Uptake in the Soil

Phosphorus moves very slowly in mineral soil, diffusing over a distance as small as 0.25 inch. This limited movement has important implications for soil management.

Phosphorus does not readily leach downward in soil as do nitrates. Instead of leaching, phosphorus is more commonly lost by runoff, erosion, or blowing soil. It also increases the difficulty of plants in obtaining adequate phosphorus. Because of low mobility, it is critical that phosphate fertilizer be placed near seed when planted or mixed into soil near plant roots, such as in the laying of new sod.

Uptake of phosphorus depends on a number of soil conditions:

- Soil pH largely sets the degree of fixation. Phosphorus is most free at a pH of 6.5–6.8.
- Dry soil stalls diffusion of phosphorus to roots. Therefore, plants take up phosphate best in moist soils.
- Oxygen is needed for the breakdown of organic phosphates. Roots also need oxygen to take up nutrients. A loose, well-drained soil improves phosphorus uptake, while compacted or poorly drained soil reduces access.
- Cold soil slows the activity of microorganisms that place phosphorus in solution, slows diffusion to roots, and retards root growth. Root

Figure 12–7
Greenhouse geraniums show classic phosphorus deficiency symptoms. The deficient plant on the right is stunted and dark green with purpling of older leaves. The symptoms may result from low soil phosphorus or cold soil inhibiting phosphorus uptake.

Image courtesy of Ed Plaster

respiration also declines, depriving roots of the energy needed to absorb phosphorus. Phosphate shortages are commonly seen on cold, wet soils (Figure 12–7).

- Any condition that limits root growth limits ability to forage for phosphorus.
- Mycorrhizal infection of plant roots helps the plant absorb phosphorus, especially in low-phosphorus soils.

A crop uses only 10 percent to 30 percent of the phosphate fertilizer applied to it. The rest goes into reserve and may be used by later crops. Many growers, in fact, have built up large reserves of soil phosphorus, especially on land used for manure disposal. With annual fertilizer applications, many turf and landscape areas are also well supplied. Only soil testing can tell soil users how much phosphorus plants need. With large soil reserves in excess of plant needs, phosphorus easily becomes a pollution problem.

While phosphorus does not readily leach, if the soil's phosphorus storage mechanisms become saturated by overapplication of fertilizer or manure, it can move downward and out of a field in drainage water. This contributes to environmental problems discussed in Chapter 15. Phosphorus also moves more readily in sandy soils, so phosphorus pollution appears more often in areas of sandy soils. Phosphorus actually moves readily in most greenhouse potting mixes, so leaching of phosphates is an environmental concern for greenhouse growers. This is another reason greenhouse growers keep phosphorus levels low in their fertilization programs.

Deficiency

A shortage of phosphorus can cause stunting and fewer, smaller leaves. Plants remain dark green or may even become darker green than normal. Phosphorus-deficient plants often have a purple tint to leaves and stems, starting on lower, older leaves. The purpling develops from an increase in the pigments responsible for red plant colors (*anthocyanins*); plants that do not synthesize the pigment will not show the color (Figure 12–7). For some plants, stunting without other obvious symptoms is typical.

A phosphorus shortage may delay maturity of several crops, including corn, cotton, soybeans, and others. Some crops, such as carrots, develop poor root systems. On the other hand, excess soil phosphorus ties up several plant nutrients, such as iron.

POTASSIUM

Potassium, often called potash, is a key plant nutrient. Plants consume more potassium than any other nutrient except nitrogen, and some plants, such as Kentucky bluegrass, may use more. No organic compound in a plant contains potassium, but many life processes need it. Potassium is dissolved in plant fluids; as the major cell solute, it regulates many functions related to osmosis. These include:

- Opening and closing of leaf stomata (osmotic process related to potassium ions regulate the guard cells), which controls water loss by transpiration and the exchange of oxygen and carbon dioxide with the atmosphere. Low potassium is associated with water stress in plants.
- Osmotic uptake of water by roots, necessary for keeping the plant well supplied with water. This also contributes to water stress in low-potassium plants.
- Providing of cell pressure that increases the size of plant cells, and thus growth.

Potassium is instrumental in moving sugars produced by photosynthesis within the plant, so is important in ripening of fruits such as apples or tomatoes. For instance, muskmelon fails to develop proper sweetness when not supplied enough

Potassium and Stomata

When a plant becomes water stressed, or the leaves receive a signal from roots that soil is dry, guard cells expel potassium ions. Their osmotic potential rises, and osmotic pressure “sucks” water out of the cell. The guard cell becomes more flaccid, and the stomatal opening closes. Under reverse conditions, companion cells next to the guard cells pump potassium ions into the guard cells, whose osmotic potential falls, water swells the guard cells, and stomata open. Other ions such as chlorine also play a role in the operation of stomata.

potassium. Because structural carbohydrates such as cellulose are made from sugar, potassium is needed to create the dry mass of cell walls, fibers, and other sources of plant strength. Potassium also activates a number of plant enzymes.

Potassium and nitrogen in proper balance stimulate a less succulent growth with greater dry mass. This produces a stronger, tougher sort of growth. Indeed, in many respects, potassium can be said to balance nitrogen. For instance, high nitrogen and low potassium increases water content of perennial ryegrass, reducing its winter hardiness.[2] A proper balance also strengthens stems, reducing lodging. Plants well supplied with potassium tend to resist disease infections. The effect of adequate potassium on turfgrass summarizes the importance of potassium: well-fed plants are less disease prone, more winter hardy, stand up better, and better resist wear and tear. Interestingly, palms appear to have a particularly high need for potassium, and on sandy soils common in Florida, one may need to add more potassium than nitrogen.

The more potassium in soil, the more plants take up. However, there is no evidence that supplying potassium beyond plant needs will additionally increase hardiness or toughness. In addition, excess potassium uptake may inhibit uptake of calcium or magnesium. Unlike nitrogen and phosphorus, there appears to be little environmental harm when potassium leaves its point of application and enters the surrounding environment.

Forms of Potassium in the Soil

Weathering releases potassium ions into the soil solution from a number of common minerals such as feldspars and micas. These ions can be easily taken up by plant roots. Little potassium becomes part of soil organic matter, so most is stored in soil by adsorption and fixation.

Potassium ions bear a positive charge and so are adsorbed on soil colloids. In most mineral soils, a few pounds of potassium are dissolved in the solution of an acre of soil at any one time. In contrast, several hundred pounds per acre of exchangeable potassium occupy cation exchange sites.

Potassium can also be fixed by certain 2:1 clays, trapped between the 2:1 layers, as shown in Figure 12–8. This potassium can be released slowly if potassium concentration in the soil solution declines. Montmorillinite clay layers are so loose that potassium ions can enter and leave easily, allowing potassium to remain available. Figure 12–9 shows the forms of potassium.

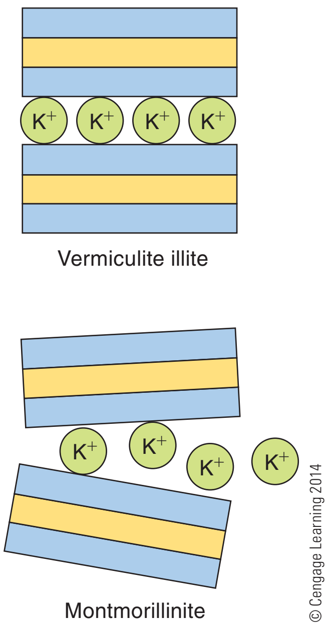


Figure 12–8
Potassium fixation occurs when potassium ions are trapped between the 2:1 layers of illite and vermiculite. The layers of montmorillinite open up so potassium does not get trapped.

Movement in the Soil

Potassium moves more readily in soil than does phosphorus, but less readily than nitrogen. Because potassium is held on clay or other colloids, it is least mobile in fine-textured soil and most readily leached from sandy soils.

Most plant uptake of potassium occurs by diffusion. Because the element moves more readily than phosphorus, fertilizer placement is less crucial, but still important.

[2] Webster, D. et al. (2005). Effects of nitrogen and potassium fertilization on perennial ryegrass cold tolerance during deacclimation in late winter and early spring. *HortScience, 40,* 842–849.

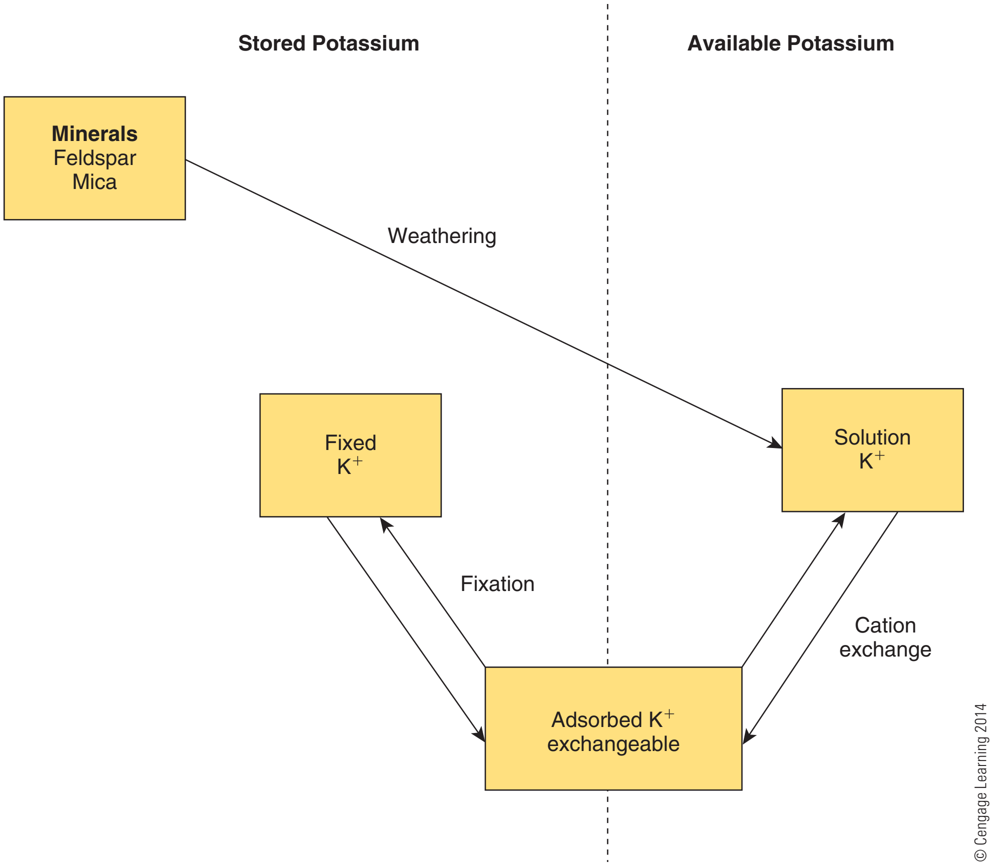


Figure 12–9
Potassium comes from weathering of minerals such as feldspar. Soil stores potassium by adsorbing it on soil colloids and fixing some in certain clay particles.

Deficiencies

Growers see potassium deficiencies less often than those of other primary nutrients. Shortages occur primarily in sandy, heavily leached soils, especially if irrigated, or in organic soils. Overfertilization with nitrogen can cause plant tissues to lack potassium. Dry, cold, or poorly aerated soil may also slow uptake. Potassium uptake is most rapid at near-neutral pH.

Plants show a lack of potassium by a "marginal scorch," or burnt look on the edges of the lower, older leaves (Figure 12–10). This symptom can be easily mistaken for moisture shortage during hot, dry weather or for salt damage. In some cases, the margins merely turn yellow. Potassium deficiencies can promote lodging in small grains and weak stems in turfgrasses.

SECONDARY NUTRIENTS

The three secondary elements—calcium, sulfur, and magnesium—are just as important as the primary elements, but are less commonly a problem and less commonly used in fertilizers. We will begin our discussion with calcium, which is actually used in greater amounts by plants than the primary element phosphorus.

Figure 12–10
Symptoms of potassium deficiency in cotton, as in many plants, include yellowing or browning of leaf margins.

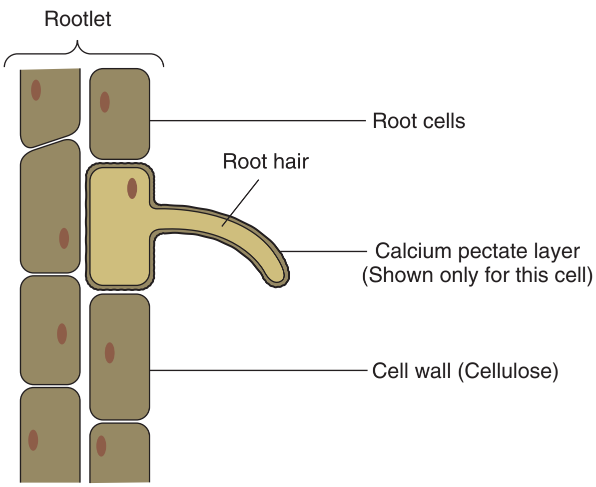


Figure 12–11
Calcium pectate lends strength to cells and "glues" them together, as in this root hair. Calcium is important for cell wall and membrane integrity as well as holding adjacent cells together.

Calcium

Calcium, the nutrient used in third greatest amounts by most plants, is a critical component of both cell walls and membranes. In cell walls, much is found as calcium pectates, located especially in a layer in the outer part of the cell wall where it lends strength (Figure 12–11). The crispness of apples, for instance, derives from a high calcium pectate content. Pectins are the same materials used to jell preserves, and one can make jellies using apple pectins. Calcium also stabilizes plant cell membranes to prevent leakiness.

By enhancing the integrity of cell walls and membranes, and also by inducing formation of stress-protective proteins in plant cells, calcium increases stress resistance in plants. For instance, a 2005 study showed that fall fertilization with calcium

Courtesy of Carl Rosen, University of Minnesota

(A) (B)

Figure 12–12

(A) potato grows normally in this hydroponic nutrient study when supplied with calcium. *(B)* Shoot tips die in the calcium-deficient plant, where cells are actively dividing. The new cells lack strong cell walls and membranes. If roots were examined, their tips too would be dead.

nitrate, but not other nitrate fertilizers, improved both hardiness and salt resistance in urban trees.[3]

Calcium also plays a role in protein formation and carbohydrate movement in plants, and plays a signaling, or regulatory, role in several plant functions—like directing roots to grow down rather than up. It also largely controls soil pH and helps soil aggregation.

Because of its role in cell walls and membranes, calcium shortages present the greatest problems where cells are actively dividing and enlarging, such as root and shoot tips (Figure 12–12) and developing fruit. In recent years, greenhouse growers have become more cognizant of the role of calcium in robust root systems and have increased their calcium fertilization. Calcium moves poorly in the plant, tending to be bound to cell walls, and moves entirely via water in the transpiration stream. Organs that receive little water via the transpiration stream, such as developing fruit, are prone to calcium deficiencies. Calcium deficiencies also commonly occur during conditions that reduce transpiration, such as cool, humid, cloudy weather or the highly humid air that can occur inside a greenhouse. Calcium shortages in specific plant organs often relate to problems with translocation in the plant rather than calcium content of soil.

Calcium shortages occur rarely in most agronomic crops, particularly in grass family plants, which have low calcium requirements. However, many horticultural crops commonly experience challenging problems. Most familiar to home gardeners is blossom end rot of tomato and pepper, in which cells at the blossom end of the fruit

[3] Percival, G., & Barnes, S. (2005). The influence of calcium and nitrogen fertilization on the freezing and salinity tolerance of two urban tree species. *Journal of Arboriculture, 31*(1), 10–20.

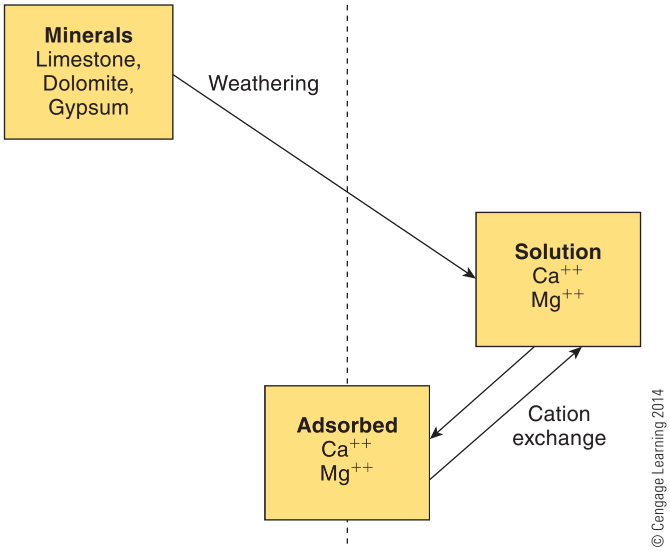


Figure 12–13
Weathering releases calcium and magnesium from soil minerals like dolomite, and stores them on soil colloids.

(furthest from the stem where water [hence calcium] enters the fruit) collapse and rot. Other vexing problems include bitter pit and water core in apples, bract burn in poinsettias, black-heart of celery, or leaf burn in lily. Calcium shortages also impair storage of horticultural products.

These problems often relate to water stress, and actions to reduce water stress, like mulching tomatoes, are helpful. In greenhouses, increasing the transpiration rate by reducing humidity and increasing air movement helps. Foliar sprays of calcium chloride or nitrate directly on sensitive tissue is a common solution. Incorporation of gypsum into potting mixes or soil may also reduce problems. Try it on potted tomato plants.

Soil calcium content figures prominently in the health and productivity of natural ecosystems, for a variety of complex reasons. An example familiar to fly fishermen is the high productivity of "limestone" trout streams high in dissolved calcium, which comes from land surrounding the stream.

Calcium relations in plants also impact human diets. Much of plant calcium is tied up in forms unusable by humans. Those who cannot or do not consume dairy products must rely largely on vegetable sources, and care should be taken to find foods with more available calcium content, such as green beans.

Calcium comes from weathering of common minerals, including feldspars, limestone, or gypsum. These materials are so common that most soils contain enough calcium to supply most plant needs. Calcium is neither fixed in the soil nor held in organic matter. It is the main occupant of the cation exchange complex, and calcium storage depends on cation exchange capacity (Figure 12–13). In fields, calcium shortages are most likely on irrigated sands, acid soils, or where excessive potassium levels inhibit calcium uptake.

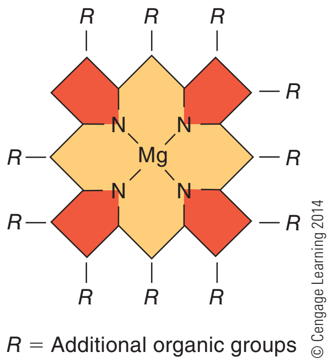


Figure 12–14
In chelation of a metal ion, very complex organic molecules surround the ion and form several bonds with it. Chelation helps protect the ion from other soil processes. Artificial trace element chelates are also common in fertilizers. The chelate pictured is the chlorophyll molecule.

Magnesium

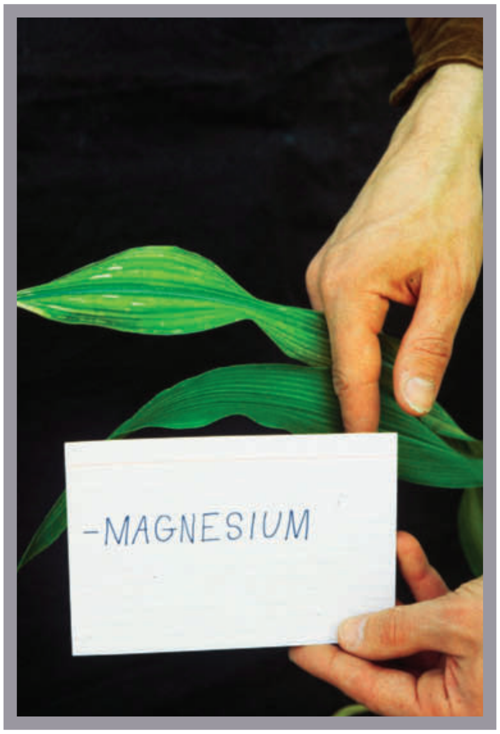
Magnesium resembles calcium chemically and in its action in soil. Its role in the plant differs, however. Magnesium is the essential ingredient in chlorophyll—each molecule has one magnesium atom at its center (Figure 12–14). Magnesium also aids the uptake of other elements, especially phosphorus. Like potassium, magnesium activates a number of important enzyme systems. Magnesium is involved in protein, carbohydrate, and fat synthesis, as well as a wide range of other compounds. Deficient plants offer less resistance to drought, cold, and disease.

Magnesium weathers from minerals as a cation (Figure 12–13). However, clay holds magnesium less strongly than calcium, so it is more easily leached. As a result, low-magnesium soils are more common than low-calcium soils. Highly leached coarse soils are most likely to need fertilization with magnesium, especially if treated with low-magnesium lime. Sand-based golf greens have a low CEC and are heavily irrigated, so magnesium shortages often lead to poor turf color. Magnesium also leaches readily from greenhouse potting soils, so greenhouses often use high-magnesium fertilizers. High levels of soil potassium may also induce a magnesium shortage in plants.

Hunger signs result from low levels of chlorophyll. These include *interveinal chlorosis* (Figure 12–15) and mottling of older leaves. Forage low in magnesium can cause grass tetany disease in cattle.

Sulfur

Plants need less sulfur than the other macronutrients, but it is still a crucial nutrient used in large amounts. Several proteins include sulfur, and it is needed for making chlorophyll. It aids nodulation of legumes and seed production of all plants. Overall, sulfur improves protein and chlorophyll content, stress tolerance, animal nutrition, and the appearance of plant products. Alfalfa, members of the mustard family (including cabbage), and members of the onion family need much sulfur. The pungent flavors of those plants derive from sulfur compounds. As opposed to this,



Courtesy of Carl Rosen, University of Minnesota

Figure 12–15

Magnesium deficiency on corn shows interveinal chlorosis. Remember that deficiency and toxicity symptoms vary between plant species.

the famous Vidalia onions are special varieties grown on low-sulfur soils in Georgia to be less pungent.

Most soil sulfur comes from the weathering of sulfate minerals such as gypsum. The sulfate anion is the form used by plants. Organic matter contains 70 percent to 90 percent of the soil sulfur; it is neither adsorbed nor fixed to any degree. Because it is readily leached, surface layers of soil are often low in sulfur. Figure 5–8 reviews the sulfur cycle.

Interestingly, acid rain supplies sulfur in many areas. In many parts of the country, sulfur from acid precipitation has been reduced by burning low-sulfur coal and by better clean-air controls on exhaust stacks required by government regulation. Older fertilizer types contained sulfur as a by-product of their manufacture. The fertilizers that are most popular now are much purer. Because pollution- and fertilizer-supplied sulfur have both been reduced, shortages are increasingly common. Leached and low-organic-matter soils are likely candidates for sulfur shortage. Soils high in organic matter or soils located near industrial centers are least likely to be short of sulfur.

Plants that are short of sulfur may be stunted and older leaves will be pale green, like those of nitrogen-deficient plants.

METALLIC TRACE ELEMENTS

Trace elements, or micronutrients, play many roles in plants, many difficult to describe without knowing plant chemistry. Most micronutrients are classified by chemists as *metals.* These metallic trace elements, with the exception of molybdenum, will be treated in this section. Soil molybdenum behaves very differently than these other metallic elements, and so will be covered in the next section.

Metallic trace elements interact with special molecules, called **enzymes**, that control important biological reactions. Enzymes are "keys" that activate biological reactions in living systems. They are not consumed in the process, but are reused repeatedly. Therefore, very little of the enzyme is needed; hence little of the associated trace element is required. Without this tiny amount, however, important processes suffer.

On the other hand, an excess of a trace element can be toxic to plants (Figure 11–8) or animals feeding on them. The difference between enough and too much can be narrow. Excesses of one micronutrient can induce deficiencies of another, such as high iron being antagonistic to manganese. This has been a particular problem for greenhouse growers. All growers should apply trace elements with caution, after proper soil and tissue testing.

Metallic trace elements have certain similarities. They are taken up by plants as simple cations, like the ferrous ion (Fe^{+2}). These are listed in Figure 10–1. Much of the metallic micronutrient soil content is held in the soil as compounds like oxides and hydroxides of low solubility, and their improved solubility at low pH is a reason they are more available in acid soil.

They also form complex metallic-organic molecules called **chelates**, in which a metal ion is surrounded by a large organic molecule. Chorophyll itself is an example of a chelated magnesium (Figure 12–14). In the soil, humic acids act as chelating agents. Chelates are an important form of storage for metallic ions, and in this form they are somewhat protected from being tied up by other chemical reactions, though in some situations, chelation itself may tie up a micronutrient. Artificial chelates are also used as micronutrient fertilizers (Chapter 14).

As cations, metallic trace elements also adsorb to colloid surfaces, so the cation exchange process both stores them and makes them available to plants.

Iron

Iron, the trace element used in the greatest amount by plants, is part of many enzymes necessary in the formation of a number of chemicals, especially chlorophyll. Iron compounds also transfer electrons during many of the reactions involved in respiration and photosynthesis.

Iron minerals are widespread in soil. Most soils have sufficient iron, but much is in the form of insoluble compounds, such as ferric hydroxide, $Fe(OH)_3$. Humus chelates iron in the soil. Interestingly, some soil microbes living in the rhizosphere emit compounds that chelate iron, probably improving iron uptake by plants.

The solubility of iron compounds relates directly to pH, declining about 100 times for each rise of 1 pH point. Acid-loving plants suffer iron shortages when pH rises above 5.0 or 6.0, while many plants become deficient at higher pH. Iron hunger is most likely in alkaline or calcareous soils, or with excesses of phosphate, zinc, copper, or manganese. Anything that inhibits nutrient uptake, such as cold, wet soils, or drought, may induce iron deficiencies.

Iron chlorosis is the usual symptom of iron hunger. It is easy to see as an *interveinal chlorosis* on new, growing leaves (Figures 10–2 and 11–18). While leaf veins remain green, tissue between the veins becomes light green or yellow. In trees, branches begin to die back. Fruit and other horticultural crops commonly show these symptoms. Examples include azaleas, pin oaks, and blueberries.

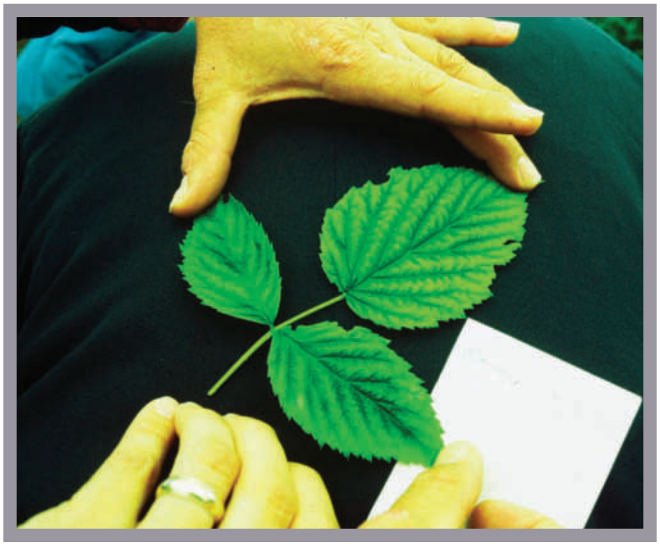
Iron toxicities can also occur when pH drops below the favorable range for a plant or iron is overapplied. This is a common problem in the greenhouse production of geraniums. While symptoms, as is true of all nutrient deficiencies and toxicities, are plant specific, they often involve necrotic (brown, dead) spots on leaves, development of a bronze color on the leaf, or bronze speckling. Note the following comments on manganese problems.

Various treatments are available to overcome a lack of iron: (1) soil pH can be lowered to free the iron; (2) soluble iron compounds such as iron sulfate may be mixed into the soil, sprayed on leaves, or even injected into the trunks of trees; (3) artificially prepared chelates may be used in the same way; and (4) animal manures can be mixed into the soil.

Manganese

Manganese resembles iron in that weathering releases a cation that is tied up in nonacid soil. Manganese acts with iron in the formation of chlorophyll. Manganese speeds seed germination and crop maturity and helps plants take up several other nutrients.

Manganese deficiencies are usually seen on calcareous soils or on soils that have been overlimed. Dwarfing is a common symptom of manganese deficiency,



Courtesy of Carl Rosen, University of Minnesota

Figure 12–16
Interveinal chlorosis as a manganese deficiency on raspberry.

accompanied by interveinal chlorosis of middle to younger leaves (Figure 12–16). Sometimes, flecks of dead tissue appear in the leaf. When soil pH is below 5.0, so much manganese may be free that it reaches toxic levels, with a wide variety of species-dependent symptoms. Excessive steaming or fumigation of greenhouse soils can also liberate enough manganese to create toxicity.

Deficient soil can be treated by mixing manganese sulfate into the soil. Lowering pH by applying sulfur may also be helpful. Leaves may be sprayed with a solution of manganous sulfate or chelate. Oats, soybeans, sugar beets, and several vegetables are most likely to respond to manganese treatments. Liming cures manganese toxicity in acid soil.

Iron and manganese can interact in soil or plants in ways that can induce deficiencies or toxicities of one or the other. For instance, if a tree has a manganese deficiency with symptoms resembling iron chlorosis, one might apply iron. The new iron will only reduce manganese uptake and aggravate the real problem. These interactions can confuse treatment unless careful soil and tissue testing is done.

Zinc

The zinc cation is weathered out of soil minerals, where it can be adsorbed, form a chelate, or form slightly soluble zinc compounds. Several biological reactions use zinc, including chlorophyll and protein production. Zinc also controls the synthesis of a plant hormone, indoleacetic acid, that stimulates plant growth.

Low zinc levels are widespread in many crops, including beans, corn, and rice, and pecan on alkaline soils. Some nutritionists have voiced fears that these shortages could be passed on to human consumers. The symptoms of zinc deficiency in plants are quite varied but include tight growth of small, closely spaced leaves, interveinal chlorosis, and dead spots on leaves.

Zinc is most available in acid soil, least available in alkaline or recently limed soils. Soils that have lost topsoil by leveling, terracing, or erosion may also be poor in zinc. Low levels may also appear on very coarse soils because the parent materials lacked zinc and the soils tend to be low in organic matter. Cold soils or excess levels of phosphate inhibit uptake. Like iron, a lack of zinc can be treated by fertilizing soil or spraying foliage with zinc compounds or chelates. Sewage sludge is an excellent source of zinc (see Chapter 15).

Copper

Copper is held by cation exchange and combines chemically with organic matter. Some organic–copper complexes are so stable that the copper is unavailable to plants. Copper is part of a number of important enzymes, especially for the formation of chlorophyll and lignin. Copper affects how well a plant resists disease and how well it controls moisture. Copper shortages also inhibit pollen formation, reducing fruit yields. Shortages are not common, but symptoms include poor fruiting, distorted new growth, stunting, and leaf bleaching.

Shortages are most likely to be seen in either leached sands or peats and mucks. A few pounds per acre of copper sulfate mixed into the soil usually supply all the copper that is needed. Carrots grown on organic soils may need extra copper, but small grains and other vegetables sometimes suffer as well.

Nickel

Nickel is the most recently identified essential element, and one needed in the least amounts. It is required by plants and microorganisms for the proper metabolism of the simple nitrogen compound urea and perhaps other uses. While deficiencies are rare, a symptom of tiny leaves called *mouse-ear* has been observed on river birch and some other trees. Nickel can be toxic to biological systems at relatively low levels.

ANIONIC TRACE ELEMENTS

While plants acquire the metallic trace elements as cations, the following elements behave as anions. Molybdenum, while a metal, behaves as an anion as well. As anions, they do not participate in cation exchange. Storage is mostly in organic matter.

Boron

Boron exists in the soil largely as boric acid, H_3BO_3, which is taken up by plants and gathers in organic matter near the soil surface. Fixation at high pH and leaching limit the amount of boron plants can use. Shortages sometimes appear if a soil is overlimed. Conditions that limit organic matter decay also limit the amount of free boron.

While the functions of boron are still not well understood, a number of functions have been proposed. Unlike other trace elements, it does not appear to be involved in any enzyme system. It does appear to be important in cell wall and cell membrane integrity, so, like calcium, deficiencies cause collapse of shoot and root tips. Regulation of carbohydrate metabolism, protein synthesis, and other roles have also been indicated. Short of boron, pollination may suffer.

Boron deficiencies are fairly widespread in alkaline soils that limit its availability, in high rainfall areas where it leaches readily, and under drought conditions that

Figure 12–17

Black-heart of cauliflower is one symptom of boron deficiency.

limit uptake. There is a wide range of deficiency symptoms, many associated with weakened cell walls. A shortage of boron often appears as death of terminal buds, followed by tight, bushy growth, known as *rosette* growth. Thick, fleshy tissues such as cauliflower stems may crack, become hollow, and begin to rot, causing a black-heart symptom (Figure 12–17).

Boron toxicities are also relatively common in arid and semiarid regions with soils of parent materials rich in boron or where irrigation water contains boron. Boron tends to migrate to leaf margins, where it may cause marginal yellowing and cupping (Figure 12–18). Many indoor foliage plants are especially sensitive, and should not be fertilized with materials containing boron.

A number of boron fertilizers may be applied to the soil or sprayed on plant leaves. The oldest form, the common laundry product Borax, may be applied at the rate of a few pounds per acre. However, the window between sufficient boron and too much boron is narrow, and even slightly high boron levels hurt plants, so it should not be used without first testing the soil.

Molybdenum

Molybdenum, the nutrient with the smallest plant requirement except nickel, is necessary for proper nitrogen metabolism by plants and for nitrogen fixation by both symbiotic and free-living bacteria. Molybdate, MoO_4^{-2}, gathers in soil organic matter. Unlike other micronutrients, it is most available at a high soil pH. Shortages are most common on acid, leached, and low-organic-matter coarse soils, as well as acid peats.

Several plants, in addition to legumes, respond to treatment. Plants in the mustard family are especially sensitive. Whiptail of cauliflower, for instance, results from a lack of molybdenum. An ounce of a soluble molybdenum material, often mixed with phosphate fertilizer, will usually treat an acre of deficient soil. Frequently, liming

Courtesy of Carl Rosen, University of Minnesota

Figure 12–18
Yellowing and cupping of leaf margins is a symptom of boron toxicity on cauliflower.

releases enough of this trace element to cure shortages. Greenhouse poinsettia growers find molybdenum fertilization necessary to avoid such symptoms as yellowing leaf margins and leaf curling.

Chlorine

Chlorine is a common substance on the planet, found everywhere to some degree. Its compounds are highly water soluble and easily taken up and translocated by plants, which need very little of it. Not surprisingly, chlorine deficiencies are very rare, most commonly found in palms, which have a higher requirement than most plants.

Chlorine is mainly found as the simple chloride (Cl^-) anion in both soil and plants. Its biological role is not well understood, but it seems to act as a solute along with potassium in certain plant roles, such as guard-cell functioning. As a consequence, it is needed for controlling the opening and closing of leaf stomata. It also plays a role in photosynthesis.

Most plants actually contain more chlorine than they really need, and toxicity is a bigger issue than deficiency. In salted soils of arid regions, and in potted plants, chlorine toxicity can occur in such sensitive species as most fruit trees, bean, and cotton.

BENEFICIAL ELEMENTS

A number of other elements contribute to nutrition of certain plants, though they may not be currently considered universal essential elements. In fact, they can be quite important in the nutrition of some plants.

Cobalt, considered to be an essential element by some, is needed for nitrogen fixation. In a sense, it is an essential element for nitrogen-fixing bacteria. This makes cobalt an important element for legumes and other nitrogen-fixing plants. There is some evidence that it plays some other role in nitrogen metabolism in legumes besides fixation. Cobalt is, however, an essential element in animal nutrition.

Silicon is needed by some grasses and horsetail (*Equisitum* sp.), especially wetland grass species. These and a few other plants are known to accumulate silicon. Adequate silicon is needed for best yields in rice and sugarcane. Research also shows that high silicon content strengthens cell walls and reduces disease infections and insect attack. It also appears to have some protective effects against manganese toxicity.

Sodium appears to be required for many plants native to sodium-rich soils. Plants that need sodium also include species that have special types of photosynthesis adapted to hot, sunny climates (C_4 and CAM photosynthesis). These include cacti, succulents, and many warm-season grasses such as corn and sugarcane. In some plants, sodium can have a variety of beneficial effects and can substitute for some potassium; in others, sodium can be toxic.

SUMMARY

The 14 mineral nutrients perform many important tasks in the plant. Of the major elements, nitrogen promotes rapid succulent growth. Phosphorus promotes growth, especially early root growth and flower development, while imparting resistance to pest and weather damage. Potassium lends toughness, strength, and pest and stress resistance. Plants need a balance of these three nutrients for strong, vigorous, and healthy growth.

Anyone who grows plants should know how nutrients behave in the soil. An important consideration, for instance, is how a nutrient is stored in the soil. Some nutrients, such as nitrogen and boron, are stored predominantly in organic matter. Some nutrients, such as calcium and magnesium, are adsorbed primarily on soil colloids. Many nutrients are part of slightly soluble compounds, including phosphorus and iron. Many trace elements, like copper, react with organic matter in the soil to form chelates. Most nutrients are found in several of these forms.

Other important traits of nutrients include their solubility and mobility. The solubility of most nutrients depends on pH. For example, phosphorus compounds are most soluble between pH 6.5 and 6.8. Highly mobile nutrients, such as nitrate nitrogen, can leach easily from the soil. Elements that move only a short distance, such as phosphates, must be placed where roots or seeds will use them.

Plants grow best when each nutrient is present in the right amount. A lack of any one nutrient causes poor or abnormal growth. In addition, plants need a balance of nutrients. One should remember that plant nutrients can be environmental pollutants, especially nitrogen and phosphorus, if they fail to be taken up by the plants they were applied to. Chapter 15 takes this up in more detail. An early step to ensure the correct levels of nutrients and to avoid environmental damage is soil testing, the subject of the next chapter.

REVIEW

1. Construct a table with four columns for the four major pools of nutrients in the soil. Place each of the macronutrients in the correct columns. In the soil solution column, write the chemical form the nutrient is in.
2. Soil professionals whose background is agronomic often consider calcium deficiencies an uncommon problem, but horticulturists deal with them often. Explain the difference.

3. Compare and contrast the roles of the primary macronutrients in top growth, root growth, flowering, hardiness, toughness, and pest resistance.
4. How is nitrogen lost from the soil? How can these losses be reduced?
5. This chapter mentions a relationship between nitrogen and potassium that influences strength and toughness of plant tissue. Describe a couple of examples.
6. If you go to a garden center and look at boxes of fertilizer designed to stimulate flowering, you will find extremely high phosphorus contents. Is such a fertilizer essential for good flowering?
7. Once, while on a tour with a forester, the author noted an oak tree badly infected with a leaf fungal disease called anthracnose. The forester thought that the cool, wet spring had caused a calcium shortage in leaf tissue as the leaves were expanding, disposing the leaves to attack. Explain.
8. Potassium and to a lesser degree chlorine are involved in controlling water loss in leaves. Why is this?
9. You want to fertilize a large tree with nitrogen, phosphorus, and potassium (NPK). Discuss the importance of fertilizer placement for each of these elements for successful fertilization.
10. Some elements move readily in the plant, and when deficiencies occur, the plant moves those elements out of the older leaves into new growth. Deficiency symptoms thus tend to occur on old leaves first. Other elements do not move so readily, and symptoms occur on new leaves first. Go through this chapter and categorize the nutrients on this basis.
11. Excess amounts of many nutrients can also have negative consequences on plant growth. Describe several examples.
12. It has been recommended to homeowners who do not like pesticides to treat creeping Charlie (*Glechoma hederacea*) in the lawn with Borax, which can be bought in any grocery store. Why might this work? Why does it make this author uneasy?
13. Both Chapter 10 and this one describe reasons why plants growing under low light should be fertilized less than those in full sun (especially with nitrogen). A good example is indoor plants in interior landscapes, which are fertilized much less than the same plants when grown outdoors. What are those reasons?
14. Many greenhouse growers use fertilizers with enhanced levels of calcium and magnesium, so-called Cal-Mag specials. Why?

ENRICHMENT ACTIVITIES

1. Color images of nutrient deficiencies for a number of crops are available on the Internet at http://www.hbci.com/~wenonah/min-def/list.htm. This website presents “Color Pictures of Mineral Deficiencies in Plants” from *The Diagnosis of Mineral Deficiencies in Plants by Visual Symptoms*, by Thomas Wallace, M.C., D. Sc., A.I.C. These are older images taken from plants growing in sand culture.
2. Using the image function in a Web search engine like Google or Yahoo should also result in images of nutrient deficiencies for various crops. Deficiency and toxicity symptoms vary from species to species.
3. Images for nutrient deficiencies on woody landscape plants can be found at the University of Florida IFAS Extension website. Refer to an article by Timothy K. Broschat on “Nutrient Deficiency Symptoms of Woody Ornamental Plants in South Florida” at http://edis.ifas.ufl.edu/ep362. These images are from Florida, where apparently magnesium is a commonly deficient nutrient in such plants.
4. PhysicalGeorgraphy.net has a web page on nitrogen cycle which can be found at http://www.physicalgeography.net/fundamentals/9s.html. This site lists some environmental consequences of human disturbance of the nitrogen cycle, covered in this text in Chapter 15.
5. Figure 12–3 shows the nitrogen cycle as it operates on a mixed farm. Redraw the cycle as it operates on, say, a golf course, an apple orchard, or other growing area of interest.

CHAPTER 13

Soil Sampling and Testing

TERMS TO KNOW

- amendment (soil)
- composite sample
- green-tissue test
- precision agriculture
- site-specific management
- soil sampling
- soil testing
- tissue testing

OBJECTIVES

After completing this chapter, you should be able to:

- explain why soils are tested
- sample soils correctly
- describe soil testing
- interpret soil test reports
- explain how plant tissue tests are used

Applying synthetic or organic fertilizers can increase yields, and increased crop yields add to a grower's income. However, because fertilizers cost money, a grower must use the amount that is most profitable. If too little is applied, the most profitable yields will not be obtained. Similarly, such fertilizers can stimulate healthy growth of turf, flowers, or trees. But if a grower, or gardener, or golf course manager applies too much, nutrients can run off into streams or leach into groundwater, creating environmental problems. The most severe losses of nutrients into the environment occur when fertilizers or **amendments** are applied in excess of plant needs. How does a soil user know how much fertilizer to apply for the best return at the least environmental risk? Sampling the soil, and testing the sample, or testing samples of the plant itself, can provide answers.

WHY TEST SOILS?

Figure 13–1 shows a stylized relationship between nutrient levels in the plant tissue and productivity, divided into four levels:

- LEVEL I: DEFICIENT. The nutrient is clearly deficient; plant health, growth, and productivity are affected. After the missing mineral is applied, growth response is strong and profitable.

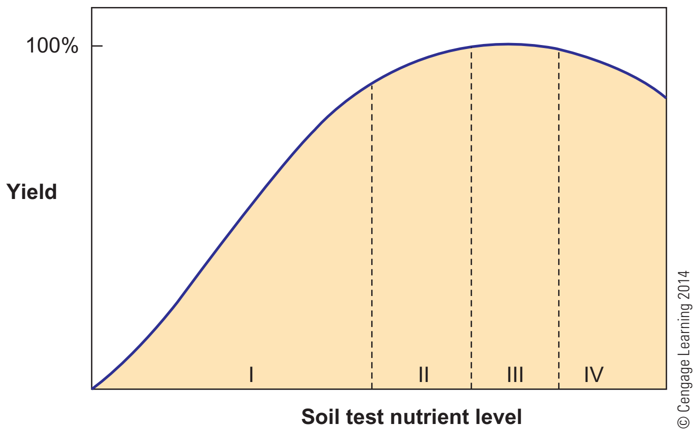


Figure 13–1
Plant growth and health, crop yield, and chance of nutrient pollution relate to nutrient levels of the soil. Fertilization is most profitable for crops in Level 1. Most public labs recommend fertilization to sufficiency.
Note: I = deficient; II = sufficiency; III = optimum; IV = toxic.

- LEVEL II: SUFFICIENT. A critical level is reached that satisfies plant needs. More fertilizer may increase yields slightly, but not enough to pay for fertilizer. Growers may fertilize to replace nutrients lost in harvest.
- LEVEL III HIGH: Nutrient levels are high; yields are maximum. Additional nutrients would be stored in the plant (luxury consumption). Fertilization could also shift the plant to Level IV or contribute to water pollution.
- LEVEL IV: TOXIC. Nutrient levels in plant tissue are so high as to be toxic, or an excess of one nutrient induces a shortage of another. Yields decline. This level presents great potential for environmental pollution.

The most economically efficient and environmentally sound level of fertilization is somewhat less than that needed for optimum harvest. Overapplication of fertilizer is always an economic waste, creates environmental problems, and may create other nutrient difficulties. Therefore we need a system for determining the need for, and amount of, fertilizers, whether growing corn in the field, turf on the playing field, or geraniums in the greenhouse.

Growers can use three methods to find nutrient shortages in plants:

- Visual inspection of crops for deficiency signs may uncover clear shortages (Figure 13–2). Unfortunately, this method notes only critical shortages after yield damage has occurred. In addition, visible symptoms may be unreliable. Chlorosis, for example, may result from low nitrogen, nematode feeding, dry or salty soil, diseases, or other problems unrelated to soil nutrient levels. Deficiency symptoms are also very species dependent; that is, a shortage may look very different on one plant than another. This complicates visual diagnosis. Nor does visual inspection tell us how much nutrient to apply.
- Soil tests measure nutrient levels in soil as well as other soil features. Growers depend on these tests to determine lime and fertilizer needs for crops. Soil tests have limits, however. Conditions that affect nutrient uptake, such as wet soils, cannot be detected in the laboratory.
- Tissue testing measures nutrient levels in plant tissue itself. This type of testing may uncover problems that soil testing misses.

Figure 13–2
Two geranium plants with different nutrient deficiency symptoms. Growers watch for such symptoms to monitor nutritional status of crops, but by itself, this is not adequate. Soil and tissue testing can be used to determine the cause of these symptoms.

Of the three methods described, soil testing is most important for a majority of crops, especially annual farm crops.

SOIL TESTING

In a broad sense, soil testing is any chemical or physical measurements that are made on soil. In common usage, the term means rapid chemical analysis to assess available nutrient status and pH of soil, including interpretation and fertilizer recommendations.

Four separate activities are involved in soil testing: (1) *Soil sampling:* the grower, gardener, turf manager, or greenhouse manager samples the soil and sends the sample to a testing center. (2) *Soil testing:* the laboratory tests the sample and obtains raw numbers. (3) *Interpretation:* the laboratory interprets the numbers in light of prior research results such as yield trials at different nutrient levels. (4) *Recommendation:* the laboratory issues a report with the results and recommendations for the grower. Let us first look at **soil sampling**.

Soil Sampling

Soil laboratories use the most modern testing methods and tools. However, the material to be tested is the sample provided by the grower. This means that test results are no better than the sample itself. Sampling methods are described here, but local recommendations may vary. Ask the local testing center or cooperative extension agent to recommend the best sampling method for your area.

Sampling Frequency

Frequency of **soil testing** depends on the crop and how it is grown. For most annual farm crops, sampling every two or three years should be adequate. Intensive crops such as fruits or vegetables benefit from annual sampling, and greenhouse crops are tested even more often. Soils should be tested before any crop is planted that occupies the soil for longer than one season, such as turf, trees, or perennial forages. This practice allows the grower to mix potash and phosphate into the soil, or to adjust pH, before planting.

Any change in cropping practices should be preceded by thorough soil testing. For example, if a grower intends to shift from regular to conservation tillage, the soil should be tested before the first year. A grower changing crops, such as a corn grower trying out sunflowers, should also test the soil before planting the new crop.

Field growers may sample soil whenever it is convenient, so long as the soil is not frozen. Others collect samples as needed, such as before planting a golf green or every two weeks in a greenhouse.

Selecting the Sampling Area

Land should be divided into sampling areas of uniform texture, topography, and cropping history. For example, a coarse-textured field should be sampled separately from a nearby fine-textured field. If half a field received manure last year and half did not, each section should be tested separately. Sampling areas vary in size from a homeowner's garden to a maximum of 20 acres on farm fields. In practice, uniform areas seldom exceed 10 acres in size. Some labs recommend using a soil map to determine sampling areas, keeping cropping history in mind.

A sampling area will be fertilized or limed as a unit, using the same rate throughout the area. In truth, however, even in a seemingly uniform sampling area soil varies from spot to spot. To account for this, we take many samples from around the field to create a sample representing a satisfactory average. We take many samples from random spots in the sampling area and combine them for a **composite sample,** as described below.

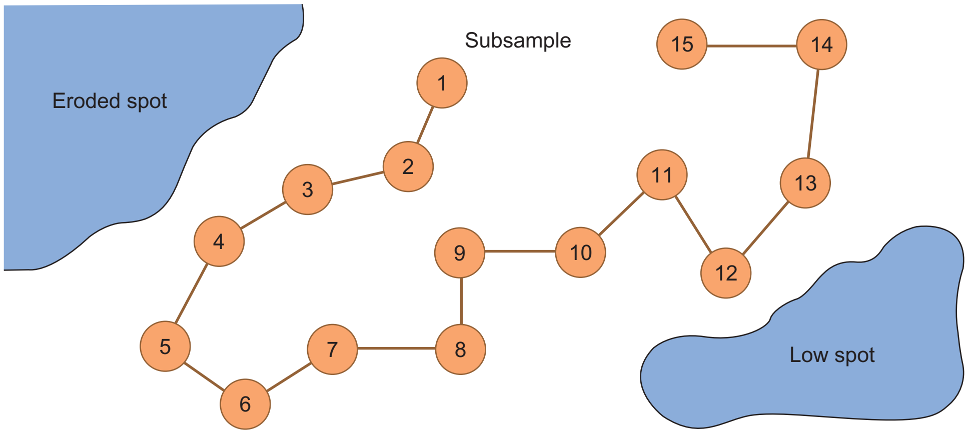
Sampling Depth

For field crops grown by conventional tillage, herbaceous perennials, and vegetables, the top 6–9 inches of soil should be sampled. Sod or pasture need only be sampled to a 2- to 3-inch depth. Tree crops, on the other hand, may need to be sampled as deep as 18–24 inches. Testing laboratories suggest that nitrogen tests be made on samples taken as deep as 3 feet. The deeper samples measure how much nitrate is in the subsoil.

Sampling Procedure

For each sampling area, follow these procedures:

1. As shown in Figure 13–3, gather many topsoil subsamples from random spots in the field. Take samples no closer than 100–300 feet from such odd areas as dirt roads, barns, or fencerows. Also avoid dead furrows, fertilizer spills, and other spots with unusual conditions. Large areas need 15 or more subsamples.



Based on information from University of Minnesota, Agricultural Extension Service

Figure 13–3

When taking soil samples, up to 15 subsamples should be taken at random locations. Avoid sampling low spots and other unusual areas. Sampling areas could be in farm fields, nurseries, lawns, or even greenhouse benches. Mix these subsamples to form a composite sample.

Photo by Ron Nichols, USDA Natural Resources Conservation Service

Figure 13–4

Using a probe to sample soil in a banana plantation in Hawaii.

2. Scrape away surface litter at each testing spot and remove a sample of the soil. Augers or soil-sampling tubes (Figure 13–4) are convenient sampling tools. A spade can also be used. Dig a V-shaped hole, remove a 0.5-inch slice from the side of the hole, and shave away most of the sample on the blade as shown in Figure 13–5. Each soil sample should include soil from the entire sampling depth. Drop each soil sample in a clean plastic bucket as it is collected.

3. Mix all subsamples from one sampling area, and remove about one cup of soil. This composite sample represents the average soil in the field. Label the composite sample and let it dry in the air. Do not oven-dry the sample.

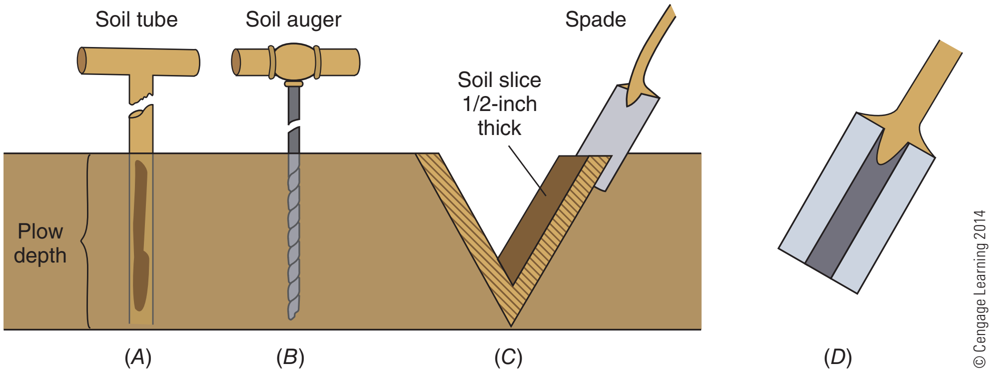


Figure 13–5
Soil samples can be taken to the depth of interest, such as plow depth in farm fields, using *(A)* a soil probe, *(B)* a soil augur, or *(C)* a common spade. Using a spade, a 0.5-inch slice of soil is taken from the side of a triangular hole. As shown in *(D)*, most of the soil in this sample is removed to leave a 1-inch wide strip on the blade.

4. Fill a mailing container with the dried composite sample. Mark the container according to the instructions provided by the testing center. Complete the sample sheet (Figure 13–6), including the intended crop, production goals, cropping history, and other necessary information.
5. Mail the samples to the laboratory, or deliver them to the lab or county extension agent. The sample containers and sheets can be obtained from the soil laboratory or extension agent.

Other soil users modify these procedures. A turf specialist, for example, will sample a yard much the same way, except collect a smaller number of samples because of a smaller area. He or she will also keep in mind the extreme variability that urban soils can exhibit.

Sampling Greenhouse and Container Plants

The fertility program for greenhouse and container plants is very different from the plan for field crops. Field growers depend mainly on nutrient reserves in the soil, such as organic nitrogen or exchangeable potassium, and fertilize to add the extra nutrients needed for best growth.

Container growers, in contrast, use potting mixes (Chapter 17) that contain essentially no nutrient reserves. Thus, all nutrients the plants need must be supplied by fertilization. This need is increased by the small soil volume, high watering rates, and soluble salt problems of greenhouse plants.

Greenhouse or container soils should be sampled before being planted to the crop. They should then be tested periodically during the growing period. The soil should also be tested at any sign of a growth problem. In sampling potted plants, the top 0.5-inch of the growing medium, which is likely to be high in salts from capillary rise, is first scraped away. A core of soil is then removed. The core must include soil from near the top to the bottom of the pot or flat. Several containers should be tested, perhaps six to a bench, and composite samples prepared.

Sampling in Precision Agriculture

Precision agriculture or **site-specific management** are terms naming a management system that relies heavily on exhaustive soil sampling. The system recognizes that soil, even over a seemingly uniform sampling area, varies from spot to spot. In the

SOIL SAMPLE TESTING FORM

REQUESTOR'S CONTACT INFORMATION

Mail completed report to:

Name ____________________________________

Address __________________________________

City, State and Zip Code _________________________

Phone Number (Include Area code) ___________________________________

E-mail Address (if provided, we will email results to you) ___________________________________

INFORMATION ABOUT SOIL BEING TESTED

County ____

City, Town, or Village _____________________________

Sample Identification Number Create a unique ID for each sample for tracking purposes.	Laboratory Number (Assigned by the lab)	Crop Code (See reference chart below)	Last Crop Grown	Tests Ordered: Routine, $10 Organic matter, $7 Soluble salts, $7	Other Tests Ordered (see below)	Total Cost of Tests Ordered

TOTAL AMOUNT ENCLOSED: _______________

Recommendations available for these crops

Crop Code	Name: Grains and Corn		Legumes		Other		Vegetables				Fruit		Horticulture, other
01.	Barley	07.	Alfalfa, new	15.	Buckwheat	23.	Asparagus	31.	Onions	39.	Apples	45.	Flowers, field production
02.	Corn, grain	08.	Alfalfa, established	16.	Flax	24.	Beans, snap	32.	Peas	40.	Blueberries	46.	Nursery, deciduous field stock
03.	Corn, silage	09.	Beans, edible	17.	Grass hay	25.	Beets, table	33.	Peppers	41.	Grapes	47.	Nursery, conifer field stock
04.	Oats	10.	Bean, soy	18.	Grass pasture	26.	Cabbage	34.	Pumpkins/ squash	42.	Raspberries	48.	Trees, Christmas
05.	Rye	11.	Birdsfoot trefoil	19.	Potatoes	27.	Cole, other	35.	Radishes	43.	Stone fruit	49.	Turf, cultured sod
06.	Wheat	12.	Legume pasture	20.	Rapeseed	28.	Carrots	36.	Rutabaga/turnips	44.	Strawberries	50.	Turf, landscape
		13.	Legume hay	21.	Sudan cover	29.	Lettuce	37.	Spinach				
		14.	Red clover	22.	Sugarbeets	30.	Melons	38.	Tomatoes/eggplant				

Note: For all greenhouse and containerized plants, use the Florist's Test form.

Figure 13–6

Soil samples should be accompanied by a completed information sheet when delivered to the laboratory.

standard sampling just described, we account for this by finding an "average condition," but this ensures some areas will be provided more fertilizer, or lime, or some other input than needed, while other areas receive too little. By more precisely accounting for field variation, precision agriculture aims to reduce production inputs, increase production, and reduce pollution.

Precision agriculture begins by imposing a grid of smaller cells over a field. While one might begin with a soil map, the grid is formed using a *Global Positioning System (GPS)*, computer, and *Geographic Information System (GIS)* software. Various types of information about the conditions in each cell can be stored in the computer, but here we are concerned about soil test information. Composite samples are gathered for each cell, tested, and entered into the computer. Later, with a GPS unit mounted on the tractor cab (Figure 13–7), fertilizer can be applied at variable rates as it traverses the field, using fertilizing equipment with *variable rate technology.*

A second element of precision agriculture is gathering yield data from each cell using yield monitors attached to harvesters. These measure yield continuously. Yield data can then be combined with soil test data for more highly refined fertilizer applications.

A third element of precision agriculture is use of *remote sensing,* like aerial photographs taken during the growing season. These might, for instance, be used to monitor crop health. Various types of photography reveal information about crop stress, chlorophyll content, and other measures. In a sense, this is a high-tech version of crop inspection for symptoms. The information gathered here can be combined with other information such as yield and soil data for very precise management decisions.

Obviously, there is expense in equipment, highly detailed soil mapping, services needed such as aerial photography, and the very extensive soil sampling and testing.

Courtesy of John Deere, Inc.

(A) *(B)*

Figure 13–7

(A) The Global Positioning System (GPS) unit mounted on this tractor cab and *(B)* an on-board computer are elements of precision agriculture, which calls for detailed soil sampling.

Precision agriculture is still undergoing development, and more complicated than can be thoroughly covered here.

Sampling for Diagnosis

So far, we have discussed sampling for routine soil testing to maintain proper soil fertility. Figure 13–2 suggests another approach: testing to diagnose a visible problem. Why are lower leaves on one geranium purplish, on the other one bleached? Testing can help provide an answer.

For diagnosis, soils hosting affected plants, perhaps part of a field or some of the pots in a greenhouse, should be compared to soils with unaffected plants. So one should collect separate composite samples from unaffected and affected soils, and submit them to the lab separately. The results can now be compared. This procedure is best if validated by tissue testing.

Soil Testing

There are two basic ways to test soil samples. The oldest method uses chemical reactions that produce color changes. The exact color depends on the amount of available minerals in the soil. In the case of the pH test, color depends on soil pH. With test kits used by home gardeners, a certain amount of soil is placed in a test tube. A measured amount of chemical, or reagent, is dripped into the tube (Figure 13–8).

Photo by Lynn Betts, USDA Natural Resources Conservation Service

Figure 13–8
A soil test kit can be used for quick, simple soil testing, but is not as complete or reliable as laboratory testing.

The color of the resulting mixture is then compared with known standards, and the amount of nutrient is read from the standard.

Simple chemical tests are easy to use, but not fully reliable. One problem is the human element, because results are based on technique of the tester and what he or she sees. In student labs, for instance, the results of several tests on the same soil sample may be surprisingly different. However, many test kits produce results of sufficient accuracy to be useful for quick preliminary results (see Enrichment Activities).

Modern laboratory testing follows a basic two-step procedure of *extraction* and *measurement.* The sample is not tested directly; rather, various liquids extract acidity, potassium, and so on. These extractants might be distilled water, various acids, or various salt solutions. A *saturated media extract*—in which distilled water is added to the sample until it is just saturated, the sample allowed to sit for a while, and then the liquid filtered out—is common for certain measurements.

These extracts are then tested with various pieces of laboratory equipment like the pH meter (Figure 13–9), or a spectrophotometer, which passes a beam of light through a test solution and measures the amount of light absorbed. Even more modern—and expensive—devices are making their way into soil-testing labs.

A few words about extraction procedures are necessary here. Different labs use different extractants, selecting the ones best suited for the region they serve and the situation. No method extracts all of what is being measured; a relative sort of value is obtained. Different extractants displace different percentages of the nutrient being measured. So keep in mind that different labs obtain different values, and results cannot be directly compared. All, however, are equally valid if properly interpreted.

Few testing labs routinely test for all 14 mineral nutrients. Rather, a lab offers tests useful for the region it serves. A *standard series* may include the following or more:

- Texture is determined by feel test or by mechanical analysis.
- Organic matter is measured by comparing soil color to known standards or by heating the sample to high temperatures, reducing organic matter to ash, and weighing the difference.

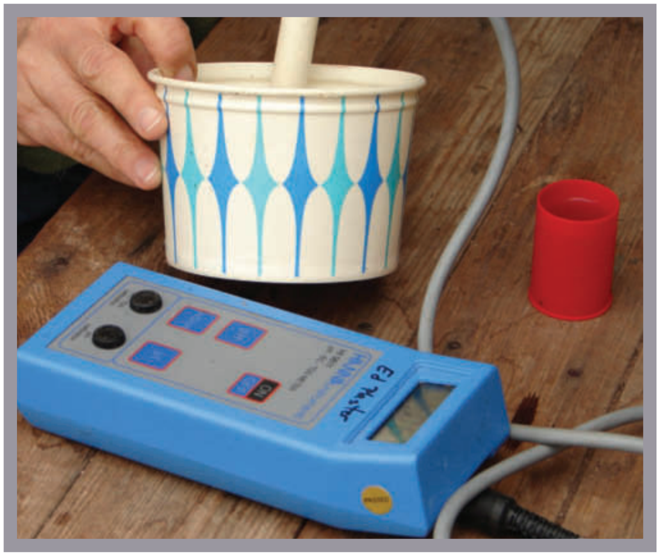


Image courtesy of Ed Plaster

Figure 13–9
This simple pH and electrical conductivity meter can be used for precise measurements of extracts from soil samples.

- pH and buffer pH (if called for) are measured with a pH meter.
- Phosphorus is extracted by a variety of extractants. The resultant number represents *available phosphorus,* not the total of all soil phosphorus. Different tests are selected, depending on the situation. Figure 13–10 shows that this lab offers two different P-tests, and that in this instance, the Bray 1 was selected.
- Potassium is washed from the sample with a solution that replaces it on cation exchange sites. The resultant value represents *exchangeable potassium* that is reasonably available to plants.

The reader will note that nitrogen is missing from this series. Nitrogen changes so quickly in the field that nitrogen tests are not considered useful in many situations. In such cases, nitrogen recommendations are based on the grower's production goals, nitrogen in the soil organic matter, prior application of manure, rotation with legumes, and other considerations. Most turf recommendations the author has seen do not take nitrogen soil tests into account.

However, nitrate tests have value in some settings. Corn, for instance, is a heavy nitrate feeder. Tests can measure nitrates carrying over from the last crop or carried into the subsoil. By taking these into account, nitrogen application can be reduced, saving money and lessening the chance of nitrate pollution. Just reducing the amount of biologically active nitrogen unleashed into the biosphere is a desirable goal (discussed later). Here, corn can also take up remaindered nitrates from the year before.

Laboratories may also test for other nutrients of local concern, such as calcium, sulfur, zinc, or other nutrients. These may be part of a standard series or available on request. Where needed, soil salinity may be routinely tested by measuring electrical conductivity (EC). Labs may also test for toxins or contaminants, such as lead or arsenic.

Greenhouse tests require a very exhaustive list of measurements. All nutrients will be tested, as well as EC, ammonium nitrogen, and nitrate nitrogen. In greenhouse potting soils, texture and organic matter content have little meaning, and are not tested.

Interpretation and Recommendation

The raw numbers obtained by the testing laboratory must now be interpreted. Some numbers, such as percent organic matter, or pH, are fine as is, but the raw numbers for nutrient contents have little meaning until they are tested, or calibrated, against actual crop growth. Prior research will have been done measuring yield against various nutrient levels as measured on the tests, and the amount of fertilizer needed to reach a preferred level. In most public laboratories, that level is sufficiency. The research produces tables that are referred to in interpreting results and making fertilizer recommendations. Many labs make copies of these tables available to the public.

Finally, the lab issues a report (Figure 13–10), which may be delivered to the client by mail, fax, or e-mail. The report contains some variation of results, interpretation, and recommendation. For instance, phosphorus results might be reported as pounds of available phosphorus per acre. This might be interpreted as a low, medium, or high level. Then a recommendation will suggest pounds of phosphate to be added per acre to bring the soil to the preferred level.

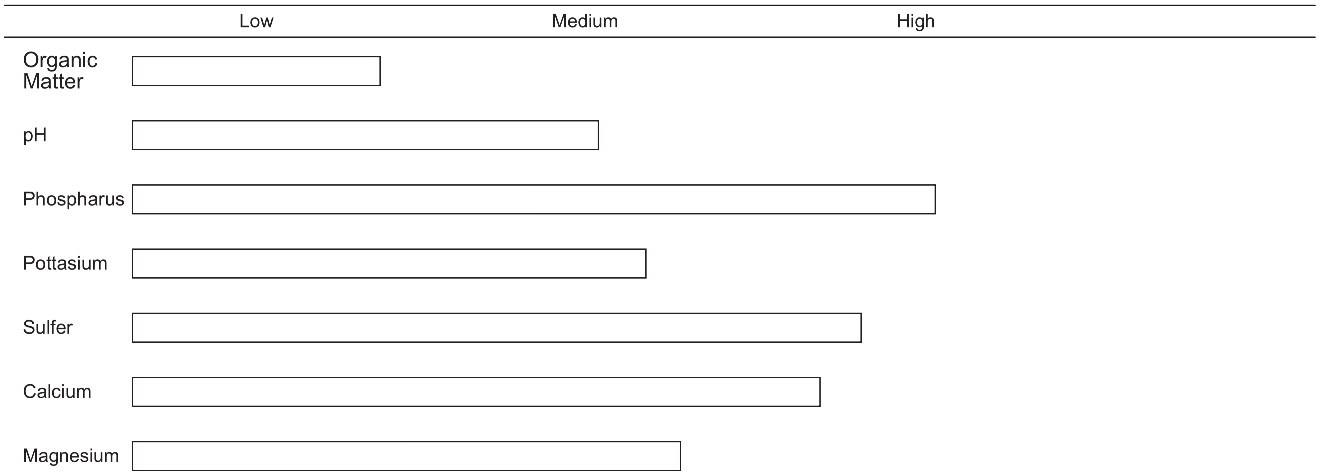
SOIL TEST REPORT
University of Springfield

Grower Michel Smith
Route 1
Strawberry Production

SOIL TEST RESULTS

Sample Number	Texture	Organic Matter %	Soluble Salts mmhos/cm	pH	Buffer Index	Olsen Phosphorus ppm	Bray 1 Phosphorus ppm	Potassium ppm	Sulfer ppm	Calcium ppm	Magnesium ppm
1	**Coarse**	**1.5**		**6.5**			**30**	**90**	**10**	**600**	**110**

INTERPRETATION OF SOIL TEST RESULTS



RECOMMENDATIONS

Lime ENP/Acre	Nitrate lbs/acre	Phosphate lbs/acre	Potash lbs/acre	Sulfur lbs/acre	Calcium lbs/acre	Magnesium lbs/acre
0	**80**	**90**	**140**	**15**	**0**	**0**

Figure 13–10
This soil test report shows raw test results, interpretations of those results, and recommendations for fertilizer and lime.

Different reports may be issued for different types of clients. The homeowner report differs from one issued to a farmer or a greenhouse grower, reflecting their differing needs.

Because different labs use different procedures, and because yield tests that give meaning to raw test results are conducted under local soil and climatic conditions, a grower might best use a local laboratory. Such labs may be associated with a university or state agricultural experiment station. A number of private labs also do soil testing. Some testing labs are geared to production agriculture, and their results may be less valid for horticulturists or other soil users.

GROWER TESTING

Growers may do a certain amount of their own soil testing, a commonplace practice for greenhouse growers. One might use simple color test kits as in Figure 13–8. A number of relatively inexpensive, simple electronic devices such as pH and EC meters are also available, like those being used in Figure 13–11. EC meters measure salinity, but because fertilizers are salts, can also infer fertilizer levels in potting soils. Devices for measuring nitrates, potassium, and phosphorus are also now available. These devices allow inexpensive, frequent, and timely in-house testing for crops that need close monitoring. Other soil users may find the devices useful as well.

Most often, growers mix 1 part medium with 2 parts distilled water (2:1 extract), let it sit for half an hour, and then filter. The liquid is then tested with the devices. The newer "pour-through" method involves pouring a certain volume of distilled water through the soil in a pot, and testing this extract. Either way, raw results have to

Image courtesy of Ed Plaster

Figure 13–11
In-house testing of pH and electrical conductivity is a routine practice in greenhouse production.

be interpreted in light of prior research on what the numbers mean. There are charts available for the purpose. Keep in mind that these procedures are not the same as those used in soil-testing laboratories, and values cannot be directly compared.

TISSUE TESTING

Plant tissue tests in combination with soil tests give the most complete picture of nutrient status in the plant. In **tissue testing**, nutrients in the plant itself, rather than nutrients in the soil, are tested. These tests are useful for "smoking out" trace element problems and may be more reliable than soil tests. Tissue tests may distinguish symptoms of nutrient problems from disease or other problems. Tissue tests may also indicate if some soil condition is hindering nutrient uptake. Some growers employ tissue testing to check the effectiveness of their fertilizer programs.

Plant tissue tests are also very useful for tree and vine crops in nurseries, vineyards, or orchards. Their root systems are much more extensive than those of annual crops. Thus, it is often difficult to determine exactly where feeding roots are and at what depth a soil sample should be taken. For these reasons, tissue tests are useful in monitoring the nutritional status of the crop.

Nutrient levels vary sharply in different plant tissues of different ages. Before sending samples to a laboratory, be sure to determine the plant part used and the growth stage required. For example, soybean samples are collected from fully open leaves at first flowering. Apple samples are taken from leaves in the middle of shoots 8–12 weeks after full bloom. A grower should follow the instructions of the actual laboratory being used. A general method for sampling plants follows:

1. Sample about 10–15 plants using the recommended plant parts. The parts should be clean of soil or dust. Sample only the intended species. Do not, for example, mix both clover and grass samples from a pasture. Do not include dead materials, and avoid damaged parts unless they are the intended sample.
2. If necessary, use water to clean dust or soil from the leaves.
3. Air-dry the samples before shipment.
4. Fill out the information sheet completely. Include any recent soil test results, if suggested by the laboratory.
5. Ship the samples to the laboratory in a heavy paper sample bag. Leaves may mold if shipped in a plastic bag.

Green-Tissue Tests

A simpler form of tissue test is the **green-tissue test** or plant-sap test. In this test, plant sap in the leaf petioles or young stems is tested for nutrient levels. Portable test kits are available that can be used in the field. Some kits use test papers treated with testing reagents. To use these, squeeze plant sap on the test spots. Other test kits use glass vials and spot plates. These tests require bits of leaf petioles to be mixed with a liquid reagent in a vial and the color is noted on a spot plate.

As in tissue testing, several plants should be tested. Best results are obtained by comparing test results from both deficient plants and nearby healthy plants.

SUMMARY

Soil users need to make effective use of fertilizers and avoid exporting nutrients into the environment. Soil testing is the best tool growers have to decide how much fertilizer is needed to avoid both underfertilization and overfertilization.

The first step is to sample the soil. Each area to be sampled should be uniform. Many subsamples are collected and mixed to form a composite sample from which a small amount is removed and sent to a private testing laboratory or university soil-testing center. Sampling areas are much smaller in precision agriculture, and are individual pots in greenhouse and container production. A sampling information sheet accompanies the sample to provide data the laboratory needs to make useful recommendations.

Soil-testing laboratories use modern equipment to measure nutrient levels quickly and precisely. A computer then generates test results, interprets the data, and makes fertilizer and lime recommendations.

Plant tissue tests are used less often, but when added to soil tests, a more complete picture of plant nutrient levels is obtained. Growers who wish to try tissue tests should consult with the testing laboratory for instructions.

Commercial laboratory testing provides more reliable results, but portable test kits and devices are available to growers for both soil and plant-sap tests.

REVIEW

1. Describe the four main steps of soil and testing.
2. Why should a grower not rely on visual symptoms as a way to detect nutrient shortages?
3. When is fertilization most cost-effective?
4. Why do container plants need more frequent testing?
5. How does soil sampling in precision farming differ from that of standard practices?
6. How might a grower best patronize a local testing laboratory?
7. How do we obtain a valid composite sample—that is, one that accurately reflects soil of the field being sampled?
8. What role does soil testing play in protecting the environment?
9. Why should soil be tested before a new crop—or even a new garden in someone's yard—is planted?
10. A case study: A greenhouse grower conducted both a soil test and a tissue test on a potted geranium showing some unknown damage. Because the symptoms did not resemble any known pest problems, a nutrient problem was suspected. The grower sampled both healthy plants and affected plants and compared the results. Most nutrients were within acceptable range in both soil and tissue, but iron was very low in the soil and extremely high in the plant tissue, especially on infected plants. Speculate on an explanation for the difference between the two tests. Why test healthy plants? What might have happened had the grower done only the soil test?

ENRICHMENT ACTIVITIES

1. Sample a test area and send the sample to a local testing lab. Or sample a greenhouse crop, asking for the appropriate greenhouse media test.
2. Use a soil test kit to test the same sample in your school. Compare the results of your test with the lab results.
3. Tour a soil-testing facility.
4. For the procedures used in one soil-testing facility, try the University of Minnesota's Soil Testing Laboratory's web page on "Tests Offered" at http://soiltest.cfans.umn.edu/test.htm. Click on "methods" to learn details of how soil tests are conducted.

5. Enrichment Activity 10 in Chapter 11 lists a Web site devoted to in-house testing for greenhouse operators. It describes various techniques, and provides the charts of numbers needed to interpret the results.
6. With a combination EC/pH meter, like that shown in Figure 13–11, use a 2:1 extraction to measure EC and pH of a sample from your yard, or a houseplant, or a plant in the greenhouse. The pH reading will be a true reading of your soil pH as is. Now compare the EC to the salinity rating system of Figure 11–24. This is not a valid use of the EC number you obtained. Why not?
7. The A&L Great Lakes Laboratories (a private testing facility) Web site at http://www.algreatlakes.com includes a wealth of information, including a number of useful fact sheets.

CHAPTER 14

Fertilizers

TERMS TO KNOW

banding
broadcasting
calcium carbonate equivalent (CCE)
chelate
complete fertilizer
fertigation
fertilizer
fertilizer analysis
fertilizer burn
fertilizer filler
fertilizer grade
fertilizer ratio
fluid fertilizer
foliar feed
fritted trace element (FTE)
granule
mixed fertilizer
nutrient carrier
pop-up fertilizer
pressurized liquid
prill
pulverized fertilizer
salt index
sidedressing
split application
starter fertilizer
topdressing

OBJECTIVES

After completing this chapter, you should be able to:

- distinguish forms of fertilizers
- describe fertilizer sources for each nutrient
- perform important fertilizer calculations
- describe how to use fertilizers
- list two effects fertilizers have on the soil

Before plant nutrients were scientifically identified, growers knew some materials helped plants prosper. Early farmers probably noticed the lush growth of grass around animal droppings and began using them to raise better crops. Lime, ashes, dead fish, ground bones, and seabird and bat guano have all been used. Even human waste ("night soil") has been an important fertilizer in some cultures. Most American growers now use fertilizers to supplement the elements their crops need. Another option is high-nutrient organic amendments, covered in Chapter 15.

FORMS OF FERTILIZER

Fertilizer is material applied to soil or plants to supply essential elements. Some states legally define minimum requirements for a material to be sold as fertilizer. Fertilizers can be grouped into four categories—mineral, organic, synthetic organic, or inorganic (Figure 14–1):

- Mineral fertilizers are ground rocks containing nutrients. Dolomitic lime, for example, is a fine source of calcium and magnesium. We might also call these *rock powders.* Most minerals have low nutrient content and dissolve very slowly, so their usefulness as fertilizers is limited. Mineral fertilizers join the mineral pool of soil nutrients, to be made slowly available by dissolution. Because of low nutrient content and high shipping costs, mineral fertilizers tend to be expensive per unit nutrient, unless an inexpensive local source is available. Such rock powders are acceptable for organic growing.

- Organic fertilizers are organic materials, such as blood meal, that contain nutrients. Many can be considered "slow-release" fertilizers because nutrients are released slowly over the growing season as the organic matter decays. Organic fertilizers join the organic pool of soil nutrients, to be made available by mineralization. Like mineral fertilizers, if organic fertilizers must be purchased, they tend to be expensive per unit nutrient. In some states, "dilute" organic materials may not be legally labeled as fertilizers because their nutrient content is too low. Most such materials are acceptable for organic growing.
- Synthetic organic fertilizers are manufactured by industry but are chemically organic (contain carbon and hydrogen). Urea is readily available to plants, but others, mostly urea derivatives, are made to be slow release. Nutrient content is generally high compared to mineral or natural organic fertilizers.
- Inorganic fertilizers are mined and processed or manufactured and are chemically inorganic. Most dissolve quickly in the soil for rapid growth response, initially joining the nutrient pool in the soil solution. The

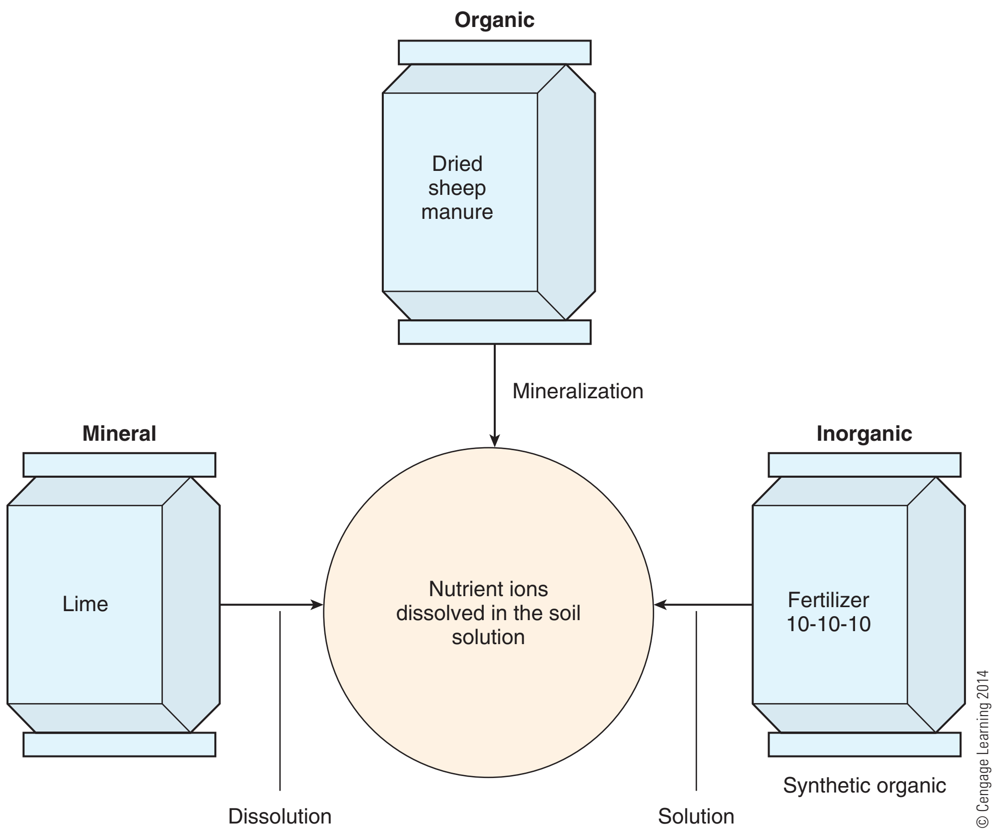


Figure 14–1
Mineral, organic, and inorganic fertilizers undergo dissolution or mineralization to release nutrient ions taken up by plants.

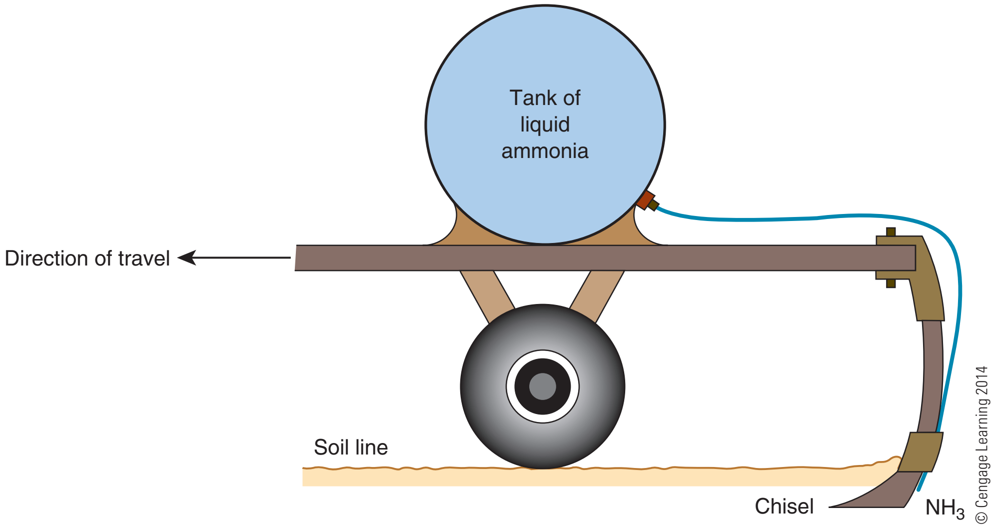


Figure 14–2
Anhydrous ammonia, a pressurized liquid, is injected into the soil through chisels. The ammonia dissolves in soil water to become ammonium ions.

concentrated content of inorganic fertilizers reduces shipping costs, making them generally less expensive per unit nutrient than other sources. Neither synthetic organic nor inorganic fertilizers are allowed in organic production.

Fertilizers are provided or applied in a number of forms, giving growers several choices of application methods. The forms can be divided into four main groups: pressurized liquids, fluids, dry fertilizers, and slow-release fertilizers.

Pressurized Liquids

Anhydrous ammonia is the primary **pressurized liquid**. Ammonia is a gas at normal temperatures and pressure, but changes to a liquid when cooled to −28°F. It can then be stored in large, high-pressure or refrigerated tanks. Smaller, wheeled tanks are filled from the storage tanks and are driven to the field to be fertilized.

The liquid is applied by injecting it into the soil (Figure 14–2). Pressure in the tank forces the liquid through tubes to special chisels that are pulled underground. When it reaches the soil, the liquid evaporates rapidly.

Fluid Fertilizers

Fluid fertilizers are also liquid, but they are not under pressure. In the case of nitrogen, they are often called nonpressure solutions. The most common fluid fertilizers are solutions. In a true solution, fertilizer dissolves in water to form a clear liquid and will not settle out. Solutions can be made only of chemicals that are soluble in water.

Fluid fertilizers are popular because they can be applied in many ways: sprayed on a field or on turf, injected into soil, mixed into irrigation water (Figure 14–3), or sprayed on crop foliage. They can also be mixed with fluid lime, herbicides, and other crop chemicals, with care to ensure that they mix without problems.

Image courtesy of Ed Plaster

Figure 14–3
A small fertilizer injector in a greenhouse. This device injects concentrated fertilizer solution out of a stock tank into the irrigation water, diluting to the level needed. Fertigation is the main way to fertilize greenhouse crops, but can be used in a wide variety of applications in agriculture and horticulture. Chapter 17 includes a sidebar about using this device.

Dry Fertilizers

Dry fertilizers are applied to soil, where they dissolve quickly in soil water to release nutrients. Dry fertilizers are available in three types:

- **Pulverized fertilizers** are made by crushing fertilizer materials into a powder. They are dusty, making them unpleasant to handle or spread evenly, so are not the preferred form. Some pulverized fertilizers absorb moisture from the air, causing them to cake during storage.
- **Granules** are much easier to use. The manufacturer treats the material so it has large, more evenly sized grains. Granules spread evenly and easily, with much less dust. However, some dust, or "fines," still causes problems. Granules are coated to reduce moisture absorption.
- **Prills** are smooth, round, and dust free. Prills (Figure 14–4) have superior flowing and spreading qualities and are free of fines. Growers find them easy to use. Prills are also coated to prevent caking during storage.

Slow-Release Fertilizers

Slow-release fertilizers are also dry. The nutrients they contain dissolve into the soil solution slowly over a period of several weeks up to a few months. Slow-release fertilizers work in one of two ways. Some are made of large nitrogen-containing molecules that break down slowly under the influence of water and microbes. Others are simply small granules of regular fertilizers coated with plastics or sulfur. These

Figure 14–4
Fertilizers are prepared in pulverized, granular, and prilled forms. The prills in this picture are smooth and spherical; granules are rougher and more irregular in shape.

slowly release nutrients as coatings thin, soften, and crack when exposed to water. Products are manufactured to different release rates, but in practice rates vary depending on the temperature, moisture, and biological activity they are exposed to, and tend to release nutrients more rapidly at first. They work best if incorporated into the soil, rather than left lying on top of the soil or potting mix.

Slow-release fertilizers are too costly for common agricultural use, but they are widely used in horticulture; for example, as turf fertilizers. They are often incorporated into potting mixes; the author has even used them in his gardens. While cost is a drawback, they present a number of advantages:

- A reduced need for repeat applications
- Delivery of nutrients at a rate plants can use them, limiting adverse effects on the environment
- Reduced chance of fertilizer burn (see end of chapter), since only a small amount of fertilizer is released at any one time

FERTILIZER MATERIALS

Few fertilizers are pure elements. Rather, most consist of compounds that release nutrients in forms useful to plants. These compounds are called **nutrient carriers**.

Nitrogen Carriers

Organic nitrogen exists in several forms (Figure 14–5). Decay changes the organic nitrogen to ammonia, which, in turn, changes to nitrates. Many organic nitrogen

Organic Material	Percentage, Dry Weight Basis N	P_2O_5	K_2O
Bat guano	10.0	4.0	2.0
Blood meal	12.0	2.0	1.0
Fish meal	10.0	6.0	—
Cotton seed meal	6.0	3.0	1.5
Soybean meal	7.0	1.2	1.5
Bone meal, raw	3.0	22.0	—
Bone meal, steamed	1.0	15.0	—
Wood ashes	—	1.0	4.0

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Figure 14–5
Organic fertilizers do not give a rapid response, but mineralized nutrients become available over time.

sources are too expensive for farmers and are used primarily by home gardeners. However, some sources, such as manure, continue to be used by many farmers.

The first commercial nitrogen fertilizer was actually organic—seabird droppings, or guano, harvested in Peru. Later, deposits of sodium nitrate were mined in Chile. Today fertilizer companies manufacture most nitrogen carriers from ammonia produced by the Haber–Bosch process.

The Haber–Bosch process, one of the more momentous of human inventions, was developed by a pair of German chemists in the early 20th century. For the first time, we could produce usable plant nitrogen on an industrial scale. We all contain substantial amounts of nitrogen in the proteins of our bodies produced by the Haber–Bosch process. Unfortunately, negative environmental impacts occur because of the ready availability of nitrogen, a topic taken up in Chapter 15.

The Haber–Bosch process fixes nitrogen from the air by attaching hydrogen atoms to it from natural gas. This reaction, in the presence of heat, pressure, and an iron catalyst, produces ammonia:

$$3H_2 + N_2 \rightarrow 2NH_3$$

This reaction is costly from an energy standpoint, and the price of natural gas accounts for 70 percent to 90 percent of manufacturing costs. Ammonia can be used as a fertilizer or changed to other forms, as shown in Figure 14–6.

- Anhydrous ammonia, consisting of 82 percent nitrogen, results directly from the Haber–Bosch process. The word *anhydrous* means "without water." It is the main pressurized liquid and is applied as shown in Figures 14–2 and 14–17. Anhydrous ammonia is the cheapest, strongest form of nitrogen. In the soil, ammonia reacts with water to release ammonium ions. If not injected deep enough, especially in sandy soil, it may evaporate and be lost from the soil. Ammonia destroys lung tissue if inhaled, so care should be taken during transport and application to ensure that none escapes.

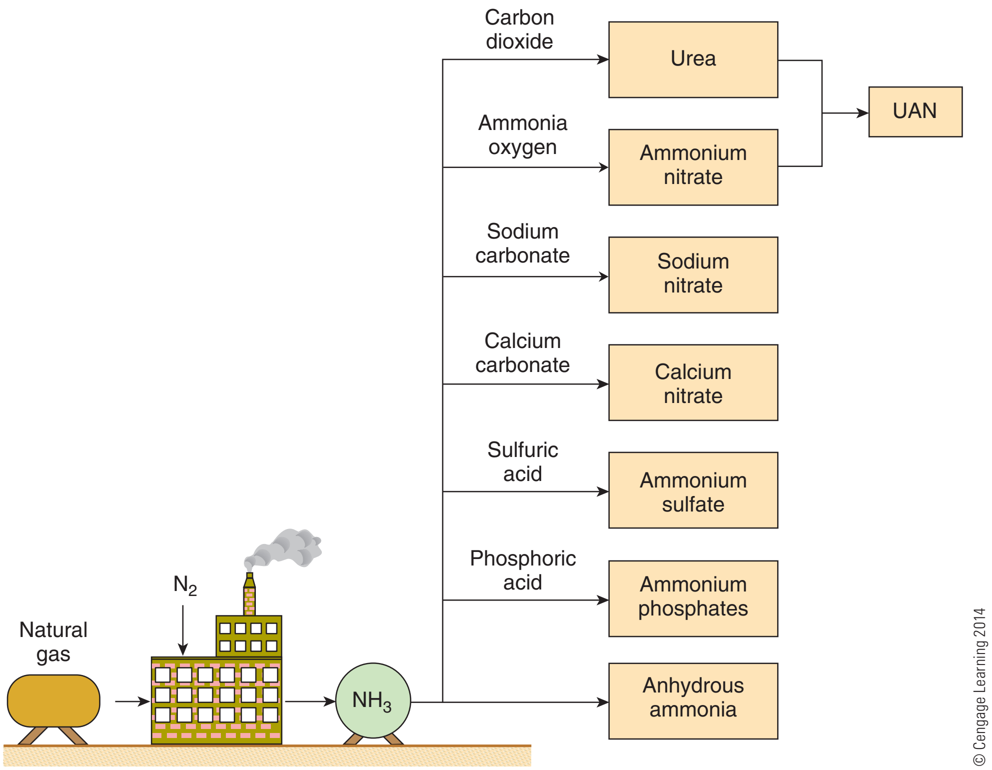

Figure 14–6
The Haber–Bosch process is the source of most chemical nitrogen fertilizers.

- Aqua ammonia, consisting of 20 percent nitrogen, comes from dissolving ammonia in water to form a low-pressure solution. The use of aqua ammonia has declined as growers switch to other fluid fertilizers.
- Ammonium nitrate, containing 33 percent nitrogen, is half ammonium nitrogen and half nitrate. This is a good general-purpose dry material that is easy to handle and apply. It absorbs moisture from the air, causing it to cake.
- Ammonium sulfate, consisting of 21 percent nitrogen, also contains sulfur. It is a dry fertilizer. Ammonium sulfate is very acid forming and is ideal for acid-loving plants. Any ammonium fertilizer, including ammonium nitrate or sulfate, can lose nitrogen by volatilization when spread on recently limed or calcareous soils. To prevent loss of nitrogen, it is best mixed into the soil.
- Nitrate of soda (sodium nitrate, 16 percent nitrogen) is commonly used on tobacco. Unlike most other nitrogen sources, it raises soil pH. Calcium and potassium nitrates are similar but less salty materials, commonly used in greenhouse fertilizers. Both materials are dry but water soluble.
- Urea, containing 46 percent nitrogen, is a synthetic organic material ($CO(NH_2)_2$). In soil, urea rapidly breaks down to ammonium nitrogen. If urea is left on the top of the soil, some ammonia may escape into the air. A popular dry fertilizer, perhaps the most widely used nitrogen fertilizer, it can be produced more cheaply than ammonium nitrate. It is also used to make fluid fertilizer.

Nitrogen Carrier		% Nitrogen	% Ammonium	% Nitrate	Effect on pH
Anhydrous ammonia	NH_3	82.0	82.0	0	Very acid
Ammonium nitrate	NH_4NO_3	33.0	16.7	16.6	Acid
Ammonium sulfate	$(NH_4)_2SO_4$	21.0	21.0	0	Very acid
Aqua ammonia	NH_4OH	24.0	24.0	0	Acid
Nitrate of soda	$NaNO_3$	16.0	0	16.0	Basic
Calcium nitrate	$Ca(NO_3)_2$	15.5	0	15.5	Basic
Urea	$(NH_2)_2CO$	46.0	46.0*	0	Acid
UAN (nitrogen solution)		32.0	22	10.0	Acid
Urea formaldehyde†		37.0	37.0	0	Acid
Sulfur-coated urea†		39.0	39.0*	0	Acid
IBDU†		30.0	—	—	—

*Urea becomes ammonia in the soil.
†Slow-release fertilizers.

Figure 14–7
Some common nitrogen materials. Other sources are listed under potash and phosphate sources.

- Urea–ammonium nitrate (UAN) is a nitrogen solution. UAN is made by mixing liquid urea and ammonium nitrate to make either a 28 percent N solution or a 32 percent N solution.
- Urea–formaldehyde (UF), isobutyldiene urea (IBDU), and sulfur-coated urea (SCU) are slow-release synthetic organic materials. These are used primarily to fertilize turfgrass and potted plants. They are too costly for general agriculture use.

Figure 14–7 summarizes the characteristics of these and other nitrogen forms. Another set of nitrogen carriers, the ammonium phosphates, as well as potassium nitrate, are described next.

Phosphorus Carriers

Phosphorus fertilizers are obtained from surface mining of rock phosphate in Florida and other locations (Figure 14–8). Rock phosphate was deposited during geologic time under shallow seas. Phosphate rock contains various apatite minerals, which are calcium phosphate materials. The ground rock can be applied directly to the soil, but is usually treated with acid to break down the apatite into simpler compounds (Figure 14–9) of higher water solubility. Figure 14–5 lists some organic sources of phosphorus and Figure 14–10 summarizes the following carriers:

- Rock phosphate, a rock powder containing between 25 percent and 35 percent phosphate, and calcium, may be spread on the soil but will dissolve slowly. It is an example of a mineral fertilizer. Rock phosphate works best when finely ground and used on acid soils, and is commonly used in organic growing.
- Superphosphate, $Ca(H_2PO_4)_2 + CaSO_4$, containing 20 percent phosphate, results from the reaction of rock phosphate with sulfuric acid (Figure 14–9). This material is half gypsum (calcium sulfate) and half

Figure 14–8
Rock phosphate mine in Florida. Most phosphorus fertilizers are manufactured from this mined material.

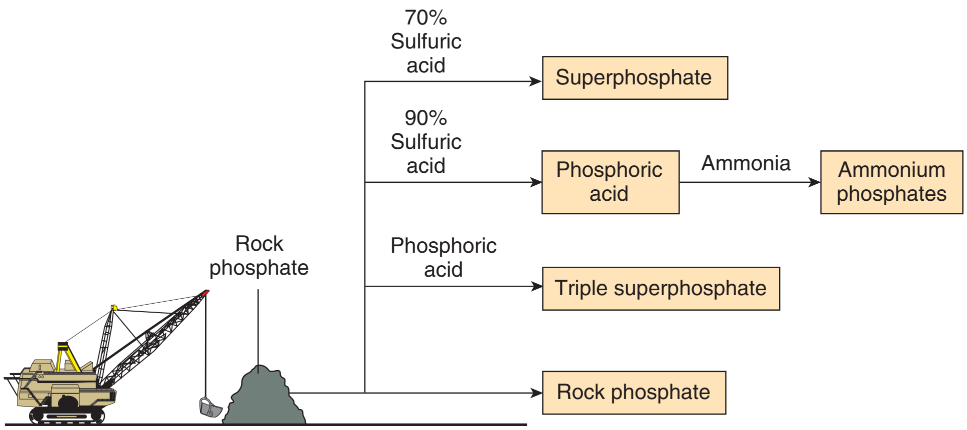

Figure 14–9
Phosphate rock is treated with acids to produce common fertilizers.

calcium phosphate. Being lower in phosphate than other carriers, it is no longer used by most growers. Growers find it most useful when sulfur or calcium is lacking in the soil.

- Triple superphosphate, $Ca(H_2PO_4)_2$, with 46 percent phosphate, is also treated rock phosphate. It is higher in phosphorus than regular superphosphate and contains less sulfur or calcium. Triple superphosphate is a popular fertilizer. Both superphosphates contain small amounts of fluorine, making them unsuitable for the many potted foliage plants highly sensitive to flourine. Neither is water soluble enough to make up a solution.

Phosphate Carrier	Percentage Available P_2O_5	P	N
Rock phosphate	25–35	11–15	—
Superphosphate	20	8.7	—
Triple superphosphate	46	20	—
Monoammonium phosphate	48–55	21–24	11–13
Diammonium phosphate	46–53	20–23	18–21
Ammonium polyphosphate	36–62	16–27	10–15
Phosphoric acid	53	23	—

Figure 14–10
Common phosphate fertilizers.

- Ammonium phosphates are made by mixing phosphoric acid with ammonia. Two similar products result: monoammonium phosphate, $NH_4H_2PO_4$, and diammonium phosphate, $(NH_4)_2HPO_4$. These are referred to as MAP and DAP, respectively. Both are much more water soluble than superphosphate compounds, and are the products of choice in applying phosphorus in fluid form. They are also used in dry fertilizers.
- Bone meal and manure are both organic sources of phosphate. Bone meal is made by grinding bones that are a by-product of the meat-packing industry. Homeowners use bone meal as a phosphate and calcium fertilizer.

Potassium Carriers

Potash is mostly mined in deep mines from deposits laid down in geologic time by evaporating shallow seas (Figure 14–11). Some is harvested in gigantic evaporation pans from evaporating bodies of water such as the Great Salt Lake of Utah and the Dead Sea of the Mideast. Canada supplies the greatest amount of the world's potash.

These deposits are mixtures of various salts, which are processed to separate and purify the potassium. Figure 14–5 lists some organic potassium sources, and Figure 14–12 summarizes primary carriers.

While we speak of potassium as a plant nutrient, when referring to fertilizers the term *potash* is commonly used. This older term derives from an original source of potassium oxide in "pot ashes." No fertilizers actually contain potassium oxide. In the following listing, the reader will notice other archaic terms still in common use, such as *muriate of potash*.

- Muriate of potash (potassium chloride), containing 60 percent potash, accounts for 97 percent of all potassium fertilization. It costs less than other carriers and dissolves readily in water. Because it contains chlorine, other sources may be better for crops sensitive to chlorine. It is also highly saline.

Courtesy of Potash and Phosphate Institute

Figure 14–11

Underground potash mine in Saskatchewan, Canada. Here we see a "continuous boring machine" that digs potash ore.

	Percentage Available	
Potash Carrier	K_2O	Nitrogen
Muriate of potash	60	—
Sulfate of potash	49	—
Potassium nitrate	44	13
Sulfate potash magnesia	22	—

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Figure 14–12

Common potash carriers.

- Sulfate of potash (potassium sulfate) contains 49 percent potash and is used to a minor extent in dry fertilizers for crops sensitive to chlorine or where the saltiness of potassium chloride is a problem.
- Nitrate of potash (potassium nitrate) contains 13 percent nitrogen and 44 percent potash. It is a common fertilizer for container plants. Although it is mostly used in a dry form, it can also be used in solution.
- Sulfate of potash-magnesia is also useful for chlorine-sensitive crops and where soil salinity is a problem. It consists of 22 percent potash, 11 percent magnesium, and 22 percent sulfur. It may be used for soils that lack sufficient amounts of magnesium and sulfur.
- Wood ashes and manure are also good potash sources.
- Granite meal is a rock powder used by some growers who prefer not to use chemical fertilizers. This material is a finely ground, gritty waste product of the monument and building-stone industry. Granite dust

	Percentage Available			
Material	Ca	Mg	S	Effect on pH
Calcitic lime	31.7	—	—	Basic
Dolomitic lime	21.5	11.4	—	Basic
Gypsum	22.5	—	12.0	Neutral
Hydrated lime	46.1	—	—	Basic
Burned lime	60.3	—	—	Basic
Magnesia	—	55.0	—	Basic
Magnesium sulfate (Epsom salts)	—	11.0	14.5	Neutral
Potassium magnesium sulfate	—	11.0	22.0	Neutral
Flowers of sulfur	—	—	30–100	Acidic

Figure 14–13
Common sources of secondary elements.

is too insoluble to be of any immediate use to plants but adds to the "bank" of soil potash. Figure 2–5 lists nutrients in a typical granite.

- Greensand is another rock powder derived from certain sedimentary deposits. The author has no experience with the material, but it is said to be more readily available than granite meal. Both are used in organic growing.

Secondary Elements

Mineral fertilizers supply most of the calcium, magnesium, and sulfur required by plants. The most important fertilizers include lime, dolomitic lime, gypsum, and sulfur. The finer the grind, the more quickly these materials act. Many of the minerals, but not gypsum, affect soil pH. Figure 14–13 lists several sources of secondary elements.

Trace Elements

Each trace element is available in a number of chemical forms. Most trace elements, however, are commonly used in the following forms, which are summarized in Figure 14–14.

- Sulfate salts are inexpensive and dissolve easily in water. They can be used as dry or fluid fertilizers. Trace elements are also available in other types of salts and oxides.
- **Fritted trace elements (FTEs)** are a safe way to apply trace elements. FTEs are made by adding salts to molten glass, which is poured into cold running water. The glass cools and shatters; the pieces are then ground into fine powder. Frits are dry fertilizers that act as a slow-release source of micronutrients.
- **Chelates** are common, useful, water-soluble trace element fertilizers, generally used in fluid form. Chelates, described in Chapter 12, are commercially available as a fertilizer.

Trace Element	FTE	Sulfates	Chelates	Others	Treatment
Boron	X			Borax	BC Borax
Copper	X	X	X	Oxide	BC or B sulfate
Iron	X	X	X		F chelate, acidify soil
Manganese	X	X	X	Oxide	BC or B sulfate
Zinc	X	X	X		B chelate
Molybdenum	X			Sodium molybate, molybdic acid	Mix with NPK, liming soil

Key: FTE = Fritted trace elements; BC = Broadcast; B = Banding; F = Foliar feeding

Figure 14–14
Common sources of trace elements.

MIXED FERTILIZERS

Growers could apply a fertilizer that contains a single nutrient, which would mean a fertilization operation for each nutrient. It is often more convenient to use fertilizers that contain several nutrients. Such fertilizers are made by mixing several of the carriers just described.

Fertilizer Analysis and Grade

The contents of a bag of fertilizer may be listed in two ways. Some bags list **fertilizer analysis**, which lists the fertilizer elements in the bag and their percent content (Figure 14–15), as well as percent nitrogen as nitrate and ammonium.

Such a list could include any of the 14 mineral elements.

All bags of fertilizer should show the **fertilizer grade**, which indicates the primary nutrient content. Grade lists the content as a sequence of three numbers that tell, in order, the percentage of nitrogen (N), phosphoric acid (P_2O_5), and potash (K_2O). Grade is often referred to as "NPK," which stands for nitrogen, phosphorus, and potassium, in that order.

For example, a fertilizer with the grade 0-0-60 is 60 percent potash with no nitrogen or phosphate. To decide how much potash is in the bag or a ton of the fertilizer, multiply the weight times the percentage. Thus, 1 ton of muriate of potash contains the following amount of potash:

$$\text{Potash} = \frac{2{,}000 \times 60 \text{ percent}}{100} = 1{,}200 \text{ pounds}$$

Even more simply, multiply the weight by the decimal equivalent of the percent (which is what the 100 in the above formula does). In the above example, potash = (2,000 pounds) × (0.6) = 1,200 pounds. One might call this a "fertilizer formula" for determining the amount of active ingredient in any quantity of fertilizer.

Fertilizer containing only one element is called a single-grade fertilizer. Many fertilizers contain two or three nutrients and are called **mixed fertilizers**. **Complete**

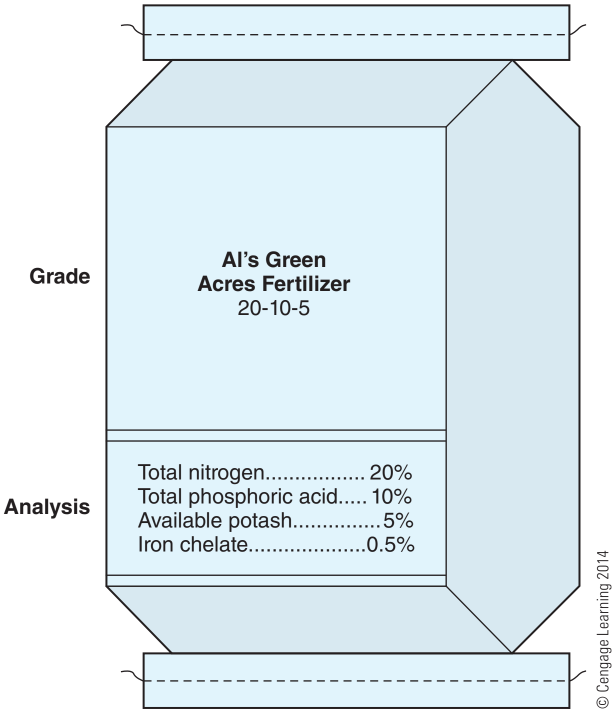

Figure 14–15
Grade is expressed by three numbers: nitrogen, phosphate, potash. All three are present here, so this is a complete fertilizer. Also shown is analysis, a listing of the percentage of all nutrients present.

fertilizers have all three of the primary elements. Note that "complete fertilizer" does not mean that all 14 mineral nutrients are included.

To determine the amount of each nutrient in a complete fertilizer, the percentage of the nutrient is multiplied by the weight of fertilizer. For example, in a 50-pound bag of 20-10-20:

$$\text{Nitrogen} = \frac{50\text{ pounds} \times 20\text{ percent}}{100} = 10\text{ pounds}$$

$$\text{Phosphate} = \frac{50\text{ pounds} \times 10\text{ percent}}{100} = 5\text{ pounds}$$

$$\text{Potash} = \frac{50\text{ pounds} \times 10\text{ percent}}{100} = 10\text{ pounds}$$

Additional information may also be found in the analysis, such as the percentage of nitrogen that is ammoniacal and the percentage that is nitrate. Some fertilizers, especially those blended for turf, contain nitrogen sources that dissolve slowly. These will be identified as water-insoluble nitrogen (WIN) or slow-release nitrogen (SRN).

Grade may also identify a secondary nutrient as a fourth or even fifth number in the traditional nitrogen, phosphorus, and potassium (NPK). For example, calcium nitrate may carry the grade 15-0-0-39Ca, meaning the material is 39 percent calcium. Similarly, sulfur (S) or magnesium (Mg) is found as a fourth number. Fertilizer containers typically also list the carriers used to formulate the product, sort of an ingredient statement.

Contents of Fertilizers

Fertilizer grades never total 100 percent. For example, 10-10-10 fertilizer is 30 percent nutrient and 70 percent other ingredients. What are those other ingredients? Primarily, the remainder of the fertilizer is the weight of the other elements that are part of the carrier, such as hydrogen and oxygen.

A small percentage is **fertilizer filler** and conditioner. Fillers may be sand, clay granules, ground limestone, or ground corncobs. They are used to bring a load of bulk fertilizer to a weight of 1 ton. Conditioners improve the quality of the fertilizer and make it easier to use.

Fertilizer Ratio

Fertilizer ratio states the relative amounts of nitrogen, phosphate, and potash in fertilizers. Ratios are useful when comparing two fertilizers, as shown in the following examples:

	Grade	Ratio
(*a*)	10-10-10	1-1-1
(*b*)	20-20-20	1-1-1
(*c*)	6-12-12	1-2-2
(*d*)	5-15-30	1-3-6

Note that (*a*) and (*b*) have the same ratio. This means that one fertilizer can be used in place of the other. Applying 1 ton of 10-10-10 is the same as applying 0.5 ton of 20-20-20. A grower may select fertilizer with the ratio suggested by soil test reports. For instance, if the report suggested 100 pounds of nitrogen, 50 pounds of phosphate, and 75 pounds of potash per acre, a single fertilizer with the ratio of 4-2-3 would be ideal.

Elements and Oxides

The way fertilizer grade is listed leads to some confusion. Most people think of fertilizer grade as NPK: nitrogen, phosphorus, and potassium. Actually, nitrogen is listed as the element, but the other two nutrients are listed in their oxide forms. The true grade should be listed as N-P_2O_5-K_2O, which is read as nitrogen, phosphoric acid, and potash.

As an example of the confusion, consider the fertilizer 20-10-10. The numbers lead one to expect 200 pounds of phosphorus in a ton of this fertilizer. Actually, 1 ton contains only 88 pounds of phosphorus. The amounts of nutrients in a ton of 20-10-10 can be listed in the elemental and oxide forms:

	Oxide	Element
N	400	400
P	200	88
K	200	166

The oxide form is a fiction, a relic of a much older way of doing things. No fertilizer actually contains the oxides. In scientific publishing, the true elemental content may be listed as grade, true NPK, which leads to very odd numbers: 10-10-10 becomes 10-4.4-8.3. When reading soil test reports or other recommendations, check which form is being used. Generally, labs report soil nutrient levels in the elemental form—P and K—but fertilizer recommendations are expressed as oxides. Therefore, the grower ordinarily need not make a conversion. But to convert between phosphorus/phosphoric acid and potassium/potash, the following formulas are used:

(a) $P \times 2.29 = P_2O_5$

(b) $P_2O_5 \times 0.44 = P$

(c) $K \times 1.2 = K_2O$

(d) $K_2O \times 0.83 = K$

As an example of the use of one of the formulas, determine how much actual potassium is contained in 1 ton of 0-0-60:

$$K = \frac{2{,}000 \times 60 \text{ percent}}{100} \times 0.83 = 996 \text{ pounds}$$

SELECTING FERTILIZER

Growers can choose from an array of fertilizers. Factors influencing the selection include crop, time of year, application method, and cost.

For most crops, the form of the fertilizer is not critical. One choice is between nitrate and ammonium nitrogen. Plants absorb both ions, but the preference for most agricultural crops is for the nitrate form, and a mixture of the two is generally desirable. However, under warm, moist conditions, ammonium nitrogen nitrifies to the nitrate nitrogen in four to six weeks. For that reason, ammonium and nitrate usually have similar effects on crop growth. On the other hand, nitrates are lost more easily from the soil.

In a few cases, either ammonia or nitrates work best. There are a few simple rules to guide the grower in selecting the best form:

- Nitrates are preferred for early-spring planting of cool-season crops.
- Ammonia is better for fall fertilization because less nitrogen will leach out of the soil before spring, applied after soil cools below 50°F, to inhibit nitrification.
- Fertilizers for container plants favor nitrate over ammonium nitrogen. Roots growing in a pot are easily damaged by excess ammonia, especially when nitrification is slowed by cool, cloudy weather. So-called "dark-weather feeds" contain no ammonium nitrogen.
- Many acid-loving plants prefer ammonium nitrogen. Cranberries, for instance, essentially use only ammonium nitrogen.

Some crops, including tobacco, are sensitive to chlorine. For these crops, low-chlorine fertilizers should be chosen. In some applications, growers need to be concerned about how a fertilizer affects soil pH or salinity, as discussed later in this chapter.

Fertilizer Prices

Fertilizer prices, a major cost of agriculture, fluctuate strongly from year to year; Enrichment Activity 3 provides a Web site with data. Prices have risen greatly in recent years owing to rising gas prices and to strongly rising demand. Between 2011 and 2015, global nitrogen fertilizer demand is expected to rise by 1.7%, phosphate demand by 1.9%, and potash demand by 3.1%, with a total demand increase of 2.0%.

Source: Data from Food and Agriculture Organization of the United Nations.

Growers also base their fertilizer selections on the means used to apply fertilizer. For example, fertilizers applied through the irrigation system must be water soluble. Several other recommendations are noted later in the chapter.

Fertilizer selection commonly depends upon price—the least costly fertilizer per pound of plant food is commonly selected. Cost can be calculated as follows, using nitrogen as an example:

$$\text{Price/lb N} = \frac{\text{price per ton}}{2{,}000 \times \%\text{N}} \times 100$$

For instance, the price of nitrogen in a ton of ammonium nitrate (33-0-0) that costs $200 would be:

$$\text{Price/lb N} = \frac{200}{2{,}000 \times 33} \times 100 = \$0.30 \text{ per pound nitrogen}$$

The same calculation can be made for a single bag of fertilizer; just substitute the weight of the bag and the price per bag. Similarly, the cost of potash and phosphate may be computed by substituting their values for nitrogen in the formula. These figures allow a grower to compare the cost of different fertilizer elements.

APPLYING FERTILIZER

Fertilizers can be applied before a crop is planted, during planting, after the crop is growing, or in some combination of the three. Preplant feeding brings the field or garden to a good nutrient level before a crop is planted. On a fine soil with little leaching and a high cation exchange capacity (CEC), this one feeding may supply all the nutrients needed for the season.

While this is the main fertilization for most crops, there are three drawbacks:

- Phosphate is not concentrated near young seedlings. Phosphates do not move much in the soil, and young seedlings are limited in their ability to forage for nutrients. Cold spring soils make uptake even more difficult. The same is true, to a lesser extent, of potash.
- In coarse, low-CEC soils, much of the nitrogen applied in a preplant feeding will leach away before plants can use it.

- Applying fertilizer before planting does not match the needs of the crop. Generally, the crop needs most fertilizer when growing rapidly later in the season. Timing nitrogen application closest to maximum crop use reduces nitrogen losses and chances of environmental contamination.

Fertilizer applied while planting, called **starter fertilizer**, allows phosphate to be placed near the seed. Fertilization after planting solves the other two problems. This is usually done by dividing the year's fertilizer into two or more parts, one applied before planting and the rest used later in the season in one or more applications. For example, corn may be fertilized before planting, then again 30 days after planting. This **split application**, an important Best Management Practice (BMP) of nutrient management, reduces the loss of nitrogen by leaching and allows a grower to apply fertilizer when the crop has the greatest need for it. Fertilization with irrigation allows the grower to make several applications to closely match growth needs. Figure 14–16 presents a model schedule for **fertigation of corn** (fertilizing with irrigation) corn. See extension agents for local recommendations.

For perennial crops such as hay or fruit, later fertilizations must follow a preplant application. A single preplant feeding will not meet the nutrient needs of the crop in later years. Thus, fertilizer is added yearly.

Now let us look at the methods used to apply fertilizers at these different times.

Fertilizing Before Planting

Fertilizing before planting brings soil fertility to a good level to launch the crop, and can supply much of the phosphorus and potash for the season. Preplant fertilization is particularly important for perennial crops, and such materials as turf or fruit, to supply phosphorus and potash that will be less effectively added later. Common methods include broadcasting and injection. Fertilizing before planting could also include incorporation of fertilizer into potting mixes before planting.

Broadcasting

The simplest and most economical way to fertilize before planting is by **broadcasting**. Machinery, and sometimes aircraft, is used to spread dry fertilizers evenly on the soil surface. Fluid fertilizers also can be sprayed on the soil. For phosphate and potash, the material should then be "plowed down," or mixed into the soil, before the crop is planted. This step is important because these nutrients do not move very rapidly into the soil, and, if left on the surface, will not reach the root zone and may run off into surface water. Broadcasting is quite popular because bulk blends can be applied rapidly.

Crop Stage	Fertilization
(1) Preplant	1/6
(2) 8 leaves	1/6
(3) 12–15 leaves	1/2
(4) Early tassel	1/6

Figure 14–16

A model nitrogen schedule for fertigated corn on sandy soils. This schedule reduces nitrogen losses into the environment and supplies nitrogen according to plant needs.

Figure 14–17
Preplant application of anhydrous ammonia on an Iowa no-till corn field.

Soil Injection

This is also known as knifing or chiseling, and can be used before crops are planted. Most commonly, anhydrous ammonia is chiseled into the whole field (Figure 14–17). Fluid fertilizers may also be chiseled into the soil. Chiseling reduces some potential losses of fertilizer by volatilization or erosion.

Fertilizing at Planting

Fertilizing at planting concentrates phosphorus near seedling roots, when the plant has a limited ability to forage for phosphorus. It is, on the whole, the most efficient way to apply phosphorus. It is most recommended when certain soil conditions restrict phosphate uptake, including cold, wet, or compacted soil; acid or alkaline soil; low-phosphate soil; and in conservation tillage.

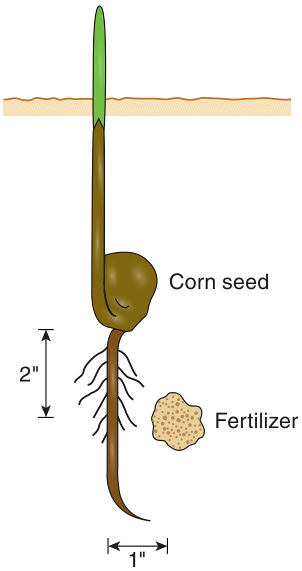

Figure 14–18
In banding, a seed planter places a band of fertilizer below and to the side of the seeds. This placement puts concentrated fertilizer where it will be immediately available to the young seedling without damaging roots.

Banding

The most common method of fertilizing at planting is called **banding**. A seed planter places a band of dry fertilizer 2 inches below and 1 inch to the side of the seeds (Figure 14–18). Banding is the most efficient way to apply phosphate, and sometimes potash. The placement is not close enough to hurt the seed but is close enough that young roots quickly find the band of fertilizer. Because the phosphate fertilizer is packed in a narrow band, there is less soil–fertilizer contact, reducing phosphate fixation. Banding can also be done more deeply to provide P and K throughout the growing season. On the whole, banding provides more growth response with less fertilizer.

Courtesy of USDA Natural Resources Conservation Service

Figure 14–19
Fertilizing pasture in Iowa by topdressing, using a broadcast spreader and dry fertilizer.

Pop-Up Fertilizers

Pop-up fertilizers are placed in the row with the seeds, rather than beside the seed as in banding. These fertilizers are quite effective in cold soils. Generally, only small amounts are applied to prevent damage to the seed. Fertilizers for pop-up use should have a low salt index to reduce injury to the germinating seed.

Transplant Solutions

Dilute fertilizer solutions are often used to water-in newly planted transplants such as tomatoes or bedding plants. Vegetable-transplanting machines are designed to dispense a cup solution to each plant as it is placed in the ground. In smaller transplanting operations, each plant may be similarly treated by hand. Transplant solutions are an excellent way for professional or home gardeners to get transplants off to a fast start. Fertilizer ratios of 1-2-1 are typical.

Fertilizing After Planting

Fertilizing after planting allows for split applications, and is the only way to fertilize perennial crops in the years after planting crops such as turf, orchards, or forages. Most postplant fertilization focuses on renewing nitrogen during the growing season, which is the most efficient time to apply nitrogen to rapidly growing crops. Several methods are in common use.

Topdressing

Topdressing is similar to broadcasting, except that fertilizer is spread over a growing crop and is not mixed into the soil. Either dry or fluid fertilizers can be used. Farmers often topdress perennial crops such as hay to replace lost nutrients. This method is also used to feed grains, pasture (Figure 14–19), and lawns. Topdressing works best for nitrogen because it moves readily into the soil. However, because many crops that might be topdressed have dense, fibrous root systems very near the surface, some potash and phosphate can reach them.

Ammonium and urea fertilizers left on the soil surface can lead to losses by volatilization. Irrigation can help move the nitrogen into the root zone quickly.

Turf managers use these terms differently. Spreading fertilizer on established turf is called broadcasting, while spreading a thin layer of soil, compost, or other amendment over existing turf is topdressing.

Sidedressing

Sidedressing is a way of making postplant applications to row crops. Sidedressing is done by fertilizing along the crop row. Commonly, this is done by knifing ammonia into the soil, "dribbling" fluids, or dropping solids. Sidedressing is the most popular way to make split applications. It concentrates fertilizer near the roots. Corn rows, vegetable rows, nursery rows, and even orchards can be fertilized by sidedressing.

Fertigation

A third way to fertilize a growing crop is to inject fertilizer into irrigation water (Figure 14–3). Fertigation works best in sprinkler or drip irrigation but can be used with surface irrigation. Drip is especially well adapted, because low levels of fertilizer can be virtually spoon-fed to the root system.

In fertigation, a device called an *injector* draws concentrated fertilizer solution out of a stock tank and injects it into the irrigation water, diluting it to the desired rate. Clearly, only very water-soluble fertilizers work. Ammonium phosphates and potassium nitrate can be used to supply phosphate and potash. Chelated trace elements also can be used. Special back-flow prevention devices must be included in the system to prevent fertilizer from being drawn back into the water supply, and because of this hazard, many states require permits.

Greenhouses rely on fertigation as their main way to fertilize their crop (Figure 14–3). Because they grow so many different crops at different stages of growth, they may have multiple injectors and stock solution. Greenhouse growers may also inject acids into their water to neutralize alkaline water (Chapter 17).

Foliar Feeding

Growers sometimes fertilize by spraying dilute fertilizer solutions, or organic preparations such as seaweed extract, directly on crop leaves. Small amounts of nutrients can be quickly and efficiently taken up by plants through tiny nanopores in the leaf cuticle. **Foliar feeding** may be a practical solution to nutrient uptake problems such as high soil pH or dry soil, and is often actually more efficient than soil application. It also delivers a quick response when needed. Spraying nutrients directly on affected tissues—such as calcium-deficient tomatoes—also puts the nutrients immediately where they are needed.

Because only small amounts are absorbed, foliar feed works best for micronutrient deficiencies. For example, pecans growing on alkaline soil may be sprayed with zinc several times a season. Iron chelates are also commonly applied to plants suffering iron chlorosis. Calcium sprays are also common on horticultural crops. The natural immobility of calcium in plants (Chapter 12) favors spraying calcium directly on tissues that need it.

Spraying macronutrients also works for a rapid response, and urea is a form of fertilizer readily absorbed through leaves. However, the large need for these elements makes it difficult to supply enough by foliar feed except by repeated dilute applications. Sprays strong enough to supply high nutrient value can burn foliage. However, foliar feed can be used to "top off" plant needs at strategic times during the crop cycle or under periods of stress. This is a common practice on golf courses. For major nutrients, we must still primarily rely on a proper soil-fertilization program.

Foliar feed works well in the greenhouse. Protected conditions in greenhouses cause thin leaf cuticles, allowing more absorption. In greenhouse culture, where a single missed fertilization can plunge a crop into mild nutrient starvation, a quick foliar feed perks up the crop.

Foliar sprays are always temporary in their effect, and most often need to be repeated. This is particularly true for immobile nutrients; none will be translocated to new leaves as they form. The need for repeated sprays reduces the convenience and cost effectiveness of the practice. Sprays should be spaced properly over time to reduce the chance of leaf burn.

Foliar sprays should be applied in a fine mist to coat the leaves on both sides, and absorption improves under conditions where the leaves stay damp for some time, as under high humidity or in the evening.

FERTILIZER EFFECTS ON SOILS

Fertilizers alter soil chemistry in ways other than increasing nutrient content. These changes include increases in soil salinity and altered soil pH. While these changes are most marked in growing media used for growing potted plants, field soils react as well. Let us look first at soil pH.

Effects on pH

Fertilizers, mainly nitrogen fertilizers, alter soil pH. Ammonium fertilizers depress soil pH by processes that release hydrogen when ammonium nitrogen is added to the soil. First, when roots absorb ammonium ions, they release hydrogen ions into the rhizosphere (Figure 10–15). More important, nitrification of ammonium ions releases hydrogen ions into the soil (Chapter 11, reaction *j*). In potted plants, the effect can be rapid, and greenhouse growers may deliberately use ammonium nitrogen to keep pH down. In field soil, soil acidification creates the need for repeated applications of lime. Fertilizers such as ammonium sulfate are recommended for acid-loving plants such as blueberries and azaleas.

Nitrate fertilizers have the opposite effect: they tend to raise pH. This occurs because roots release basic hydroxide or bicarbonate ions into the rhizosphere when they absorb a nitrate ion (Figure 10–15). The basifying effect of nitrate is much weaker than the acidifying effect of ammonia, so a 50:50 material such as ammonium nitrate is still mildly acidifying. The mild pH-raising effect of nitrate ions concerns field growers little, who mostly use ammonium sources of nitrogen. Container growers use more nitrate fertilizers, and they must be watchful for rising pH in their containers.

How to Fry a Lilac

The old adage that a little bit is good, more is too much applies here. Inspecting a row of new lilac bushes that had died abruptly one summer, the author found absolutely fried foliage and a mound of fertilizer carefully placed around the base of each plant by a homeowner who wanted to give his bushes a big extra boost. Benign neglect would have been preferable to this overeager gardener.


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Figure 14–20
Fertilizer burn on the leaf margins of this maple due to overapplication of fertilizer.

A measure of potential acidity or basicity may be printed on fertilizer labels as a **calcium carbonate equivalent (CCE)**. For "potential acidity," the number represents how many pounds of pure calcium carbonate will be neutralized by the acidity of 1 ton of fertilizer, while "potential basicity" represents pounds of pure calcium carbonate that will have the same basifying effect of 1 ton of fertilizer. In either case, the higher the number, the stronger the reaction.

Effect on Salinity

Fertilizers are salts. They therefore raise soil salinity when applied. In humid areas, where natural soil salinity is low, small increases in soil salts is of little concern except when fertilizers are placed near seeds, as in banding. In arid areas, where natural salinity may be high and is often increased by irrigation, less-saline materials may be recommended on golf courses and other situations. Container plant growers and interior landscapers, even homeowners with potted plants, must be especially mindful of the salt contribution of their fertilizers. Misapplying or spilling fertilizer may damage roots and cause **fertilizer burn** (Figure 14–20), as when a homeowner spills fertilizer on the lawn.

We measure fertilizer salinity as a **salt index**, which compares the salinity of a product to pure sodium nitrate, given the value of 100. For instance, potassium chloride carries a salt index of 116, or is 16 percent more saline than sodium nitrate. Potassium sulfate, with a salt index of 46, is clearly preferable as a potassium source where salinity is a concern. Tables of salt indexes may be readily found on the Internet.

SUMMARY

A fertilizer is a substance used to supply essential elements. Fertilizers may be finely ground minerals, natural or synthetic organic materials, or inorganic chemicals made by industry.

The Haber–Bosch process fixes nitrogen from the air to make ammonia. Ammonia, in turn, is the base for most other nitrogen carriers. Phosphate and potash result from mining. Factories treat rock phosphate to produce superphosphate and purify potash deposits to make potassium fertilizers.

Ground-up minerals supply most of the secondary elements. They may also be obtained from other fertilizers. For instance, superphosphate also contains calcium and sulfur. A wide variety of compounds deliver trace elements, including sulfates, oxides, FTEs, and chelates.

Fertilizers come in a number of physical forms that allow many methods of use. Dry blends come in large grains that can be scattered on the soil, as in broadcasting or topdressing. They can also be banded next to seeds or used as pop-up fertilizers.

Fluid fertilizers, applied as liquids, can be sprayed on the ground for broadcasting or topdressing, injected into the soil, added to irrigation water, or sprayed on plant leaves. The high-pressure liquid, anhydrous ammonia, is used to prepare a field for planting or to sidedress a row crop.

Slow-release fertilizers, unlike other forms, release nutrients slowly. They find their greatest use in turf and in growing potted plants. By releasing nutrients at a rate that matches crop needs, they reduce the chance they will pollute the wider environment.

Mixed fertilizers contain two or three primary elements. The fertilizer grade lists the percentage of each primary element in the form of nitrogen, phosphate, and potash. These numbers can be used to determine how much of each nutrient is contained in a fertilizer, how much they cost, and fertilizer ratios.

Growers have many fertilizers from which to choose. Obviously, the fertilizer should fit the needs of the crop and the method of use, and pH and salinity effects should be considered. Cost is often the most important factor.

REVIEW

1. Why does the price of natural gas affect the price of fertilizers?
3. Explain how large amounts of nitrogen fertilizer can be wasted by volatilization. How can it be prevented?
3. Assume you use a complete fertilizer containing urea, superphosphate, and potassium chloride. Describe what might happen to all the nutrients added. How might they be used, stored, or lost?
4. Figure the cost per pound of nitrogen for each of the following:
   a. Ammonium nitrate at $150 per ton
   b. Anhydrous ammonia at $210 per ton
   c. Urea at $5 per 50-pound bag
5. What fertilizer grade and ratio does one get when mixing 25 pounds of urea, 50 pounds of triple superphosphate, and 25 pounds of potassium nitrate?
6. How many pounds of phosphate is in a ton of triple superphosphate (see Figure 14–10)? How many pounds of actual phosphorus?
7. You work at a golf course and are going to fertilize an 80,000-square-foot fairway with 20-5-20 at the rate of 1 pound nitrogen per 1,000 square feet. How much fertilizer do you need to buy? (*Hint:* The problem is the opposite of the first part of question 6.)
8. You read that bell-pepper plants should be sidedressed with 75 pounds per acre of nitrogen at first blossom. How much nitrogen should be applied to your 10,000-square-foot planting (1 acre = 43,560 square feet)?
9. A soil test report recommends an application of 100 pounds per acre nitrogen, 30 pounds per acre phosphate, and 50 pounds per acre potash. What fertilizer ratio would be most appropriate?
10. Name and describe an organic, a mineral, and an inorganic source of phosphorus. Which of these would be acceptable for an organic operation?
11. Identify whether each of the following has an acidic, basic, or neutral effect on the soil:
    a. Sodium nitrate
    b. Ammonium phosphate
    c. Gypsum
    d. Dolomitic lime
    e. Superphosphate
12. What value is there in split applications of fertilizer?
13. In March 2011, according to the U.S. Department of Agriculture (USDA), anhydrous ammonia was selling for $749 per ton (the author assumes—the table did not state its units) while urea was selling for $526. Which was the cheaper nitrogen source? Show your work.

ENRICHMENT ACTIVITIES

1. Use a soil test of your grounds and local recommendations to develop a fertilizer program for an important crop in your area. If you are a landscape horticulture student, prepare a fertilizer program for high-quality turf.
2. Safety practices are an important issue when working with fertilizers, especially anhydrous ammonia. This article, "Using Anhydrous Ammonia Safely on the Farm," on the University of Minnesota Extension's web page, has a fact sheet on working with anhydrous ammonia: ftp://ftp.fao.org/ag/agp/docs/cwfto15.pdf.
3. This USDA Economic Research Site has tables of fertilizer use and prices over the last four decades. Can you explain why the prices of anhydrous ammonia jumped around in the past decade? The site is http://www.ers.usda.gov/Data/FertilizerUse/.
4. Before the Haber–Bosch process was developed, guano and sodium nitrate deposits were so rare and valuable that they helped spark the War of the Pacific between Chile and Bolivia in 1879. There were also sea battles between Germany and Britain early in World War I over shipments from the same fields. Why would armies fight over fertilizers? Check out the story by typing "War of the Pacific and Chile" or something similar into a Web browser.
5. Use the Internet to learn more about potash or phosphate mining and issues surrounding them. Phosphate mining is a big issue in Florida, and the Internet provides numerous stories about it.
6. For more detail on fertilizer use, go the website http://www.back-to-basics.net and click on Efficient Fertilizer Manual. Keep in mind that this is the site of a major fertilizer manufacturer and distributer.
7. Cornell has a brief summary of the Nutrient Management Planning process at http://nmsp.cals.cornell.edu/publications/factsheets/factsheet33.pdf. This site will be of most value following Chapter 15, but you can check it out now.
8. *Landscape Magazine* (June 2, 2010) printed a story called "Summer fertilizer bans spreading like weeds in Florida" about lawn fertilizer restrictions in some Florida counties to protect Tampa Bay and other locations. This could be an interesting topic for classroom discussion. What is one way to reduce fertilizer runoff during the summer, Florida's rainy season, being explored by one lawn care company? The answer is found in this chapter. The article can be found at http://www.landscapemanagement.net/lawn-care/news/summer-fertilizer-bans-spreading-weeds-florida-9706.

Organic Amendments

TERMS TO KNOW

biosolid
eutrophication
hypoxia
mesophilic
organic amendment
phosphorus index
sewage sludge
thermophilic

OBJECTIVES

After completing this chapter, you should be able to:

- explain the benefits of organic amendments
- describe how to use animal manure
- describe how to use biosolids
- explain composting
- list environmental side effects of fertilizers and amendments

An **organic amendment**, as defined here, contains both plant nutrients and large amounts of organic matter, as in the composted turkey manure in Figure 15–1. Organic amendments are used to both fertilize and amend the soil. In this chapter, we stress their use as fertilizers.

While inorganic fertilizers effectively raise soil nutrient levels, these organic amendments also improve soil health and quality in ways that benefit the soil user:

- Organic amendments contain a combination of nutrients, including secondary and trace elements.
- Organic matter acts as the main soil storehouse of many nutrients, including nitrogen, phosphorus, sulfur, and others.
- Organic amendments contain large amounts of organic matter to improve the physical condition of the soil and increase its cation exchange and water-holding capacities.
- Organic amendments support the growth of beneficial living organisms in the soil, increasing biological activity.

Figure 15–1
Composted turkey manure and wood chips in Arkansas.

- Organic amendments often produce a greater yield than a complete fertilizer applied at the same nutrient rates, especially on sandy soils. Furthermore, improved yields may continue long after organic amendments are applied, unlike the shorter-term benefits of inorganic fertilizers.

Society benefits from a grower's use of these materials because many are waste products, best and most safely utilized as soil amendments. Other options, such as landfilling, incineration, and ocean dumping, carry greater risks to the environment and waste their nutrient and organic matter content.

The organic materials described here act as slow-release fertilizers, and carry their benefits listed in the previous chapter, if used properly. However, if used improperly, in excess of plant needs or in situations that lead to runoff and erosion, they too can cause nutrient loading into the environment, nutrient leaching into groundwater, soil contamination, or other problems. This chapter addresses those issues, and concludes with a discussion of environmental problems of any nutrient use, whether fertilizer or organic amendment.

Of the many organic materials available, three account for the greatest use: animal manures, biosolids, and compost.

ANIMAL MANURE

It is ironic that for many farms today manure has become a waste disposal problem. This is an abrupt change, for throughout history people have long relied on animals as a source of soil nutrients. However, many farms do still use this resource. Properly used, manure offers many benefits; improperly used, it poses many problems.

Benefits of Organic Amendments

A 2009 study illustrated the effects that organic amendments can have on building soil. As part of a larger study, 8 inches of topsoil were removed from a silt loam soil, exposing subsoil to mimic erosion. Manure compost or fertilizers were incorporated into the remaining soil over a three-year period. The soils treated with the organic materials showed decreased bulk density, greater water-holding capacity, increased organic matter content, and improved structure (all indicators of soil quality) compared to the fertilizer plots. These materials have great potential to rehabilitate degraded soils.

Source: Jagadedamma, S. (2009). Effects of topsoil depth and soil amendments on corn yield and properties of two Alfisols in central Ohio. *Journal of Soil and Water Conservation, 64*(2), 70–79.

Benefits of Manure

When handled and applied correctly, manure benefits growers in several ways:

- Manure is a fertilizer with good amounts of nitrogen and potash. Phosphorus and calcium are present, as are lesser amounts of sulfur and magnesium. Manures also have traces of several micronutrients. Figure 15–2 provides examples of the nutrient content of several manures. Keep in mind, nutrient contents vary greatly, especially depending on how the manure is handled.
- Manure adds organic matter to the soil. Organic solids make up 20 percent to 40 percent of manure. This matter decays readily because of its high nitrogen content. Nitrogen tie-up occurs only if the manure includes a lot of straw or wood shavings used as animal bedding.
- Manure has longer-lasting effects than an equivalent amount of chemical fertilizer. Improved yields may continue years after manure stops being added to the soil.

Problems of Manure

Manure can also pose problems for the environment. Recent decades have seen an increasing separation of crop from animal production, with farmers specializing in one or the other. This specialization may also be regional, which means less

	Pounds/Ton					
Animal	N	P_2O_5	K_2O	S	Ca	Mg
Dairy cattle	10	4	8	1	6	2
Beef cattle	11	8	10	1	3	2
Poultry	23	11	10	3	36	6
Swine	10	3	8	3	11	2
Sheep	28	4	20	2	11	4
Horse	13	5	13	—	—	—

Figure 15–2
Sample nutrient composition of several manures, on an as-is basis (not dried or composted) in pounds nutrient per ton. Actual composition of manure varies widely and should be measured.

local recycling of manure and the export of nutrients from crop production areas to animal-raising regions, where manure disposal becomes a problem and its nutrients become a source of water pollution. Water-quality impairment is often associated with regions of high animal populations. Large confined feeding operations in these regions compound the problem (Figure 15–3). Furthermore, global climate models predict intensified rainfall in some areas that will promote runoff from fields treated with manure. Examples of environmental side effects include:

- Excessive application of phosphorus to land. With high soil-phosphate levels, runoff elevates phosphate levels in surface waters, with results detailed later in the chapter.
- Excessive rates of manure application to land. This occurs most commonly where more animals are being raised than there is nearby land available to receive their manure safely.
- Leaching of nitrates under animal-confinement areas or land receiving manures, or into drainage systems, and its transport into rivers.
- Runoff of organic materials into lakes and streams.
- Water transport of human pathogens into surface and groundwater.
- Large spills from manure lagoons.
- Generation of gaseous air pollutants such as hydrogen sulfide (H_2S), which has human health effects; methane (CH_4), a greenhouse gas; and ammonia (NH_3), which can dissolve in local surface waters.
- Salt or ammonia damage to plants or germinating seed if manure is applied raw or applied in excess.

Photo by Jeff Vanuga, USDA Natural Resources Conservation Service

Figure 15–3
A confined cattle feeding operation in Arizona. Concentrations of animals increase the difficulty of safe manure disposal.

Manure and Human Health

Each year we spread more than 300 million tons of animal manure in the United States, and more than 150 pathogens have been found in manure. Most outbreaks of illness from water contamination have been linked to animal sources on farms.

Source: Gerba, C. P., & Smith, J. E. (2005). Sources of pathogenic microorganisms and their fate during land application of wastes. *Journal of Environmental Quality, 34,* 42–48.

Under the Federal Clean Water Act of 1972, large feedlots are considered to be point sources of water pollution (see later sidebar), so their operations can be regulated. For growers today, the goal is to make the most efficient use of manures for profit while minimizing environmental problems.

Content of Manure

Manure includes both solids and liquids, which, for the most part, are feces and urine of animals. The solid part may also include bedding. As Figure 15–4 shows, solids contains most of the phosphate. Most of the potash is in the liquid part. Urine holds about half the nitrogen in manure, primarily in the form of urea and similar compounds. The rest of the nitrogen is contained in animal feces.

Several factors determine nutrient content, including the type of animal. In general, sheep and poultry manure has a high nitrogen content; manure of cattle, pigs, and horses has a lower nitrogen content. All common animal manures contain a much higher proportion of phosphorus to nitrogen than that needed by plants. This is particularly true of poultry, which process phosphorus in their feed less efficiently than ruminant animals like cattle. Therefore, if manure is applied to soil at a rate determined by the nitrogen needs of a crop, phosphorus will be in excess. Recent developments in animal feeding programs can reduce phosphorus levels in manures.

The amount and type of bedding also influences nutrient content because it thins out the manure. If manure contains a large amount of high carbon–nitrogen (C:N) ratio bedding, nitrogen tie-up can even occur in the soil for a time. How manure is handled, described shortly, also affects nutrient content. The amount and type of rations and age and health of the animal are also important factors. Figure 15–2 lists average values of nutrient content for several animal manures.

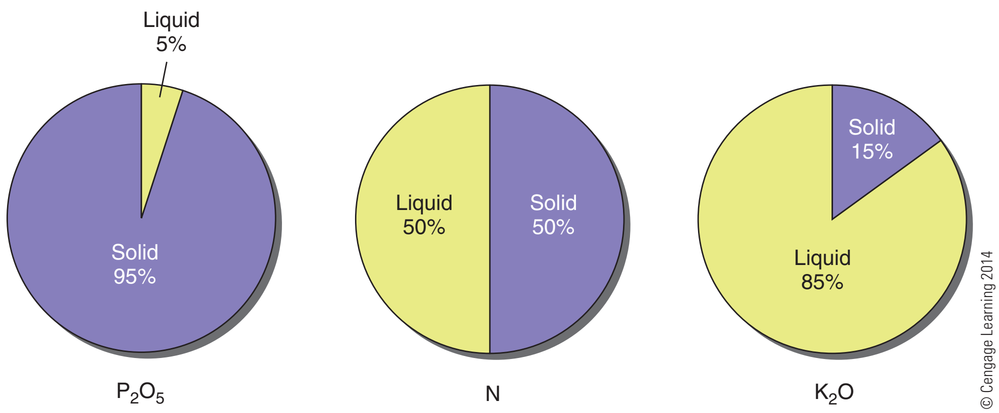

Figure 15–4 Much of the potash in manure is found in the urine, the phosphorus mainly in the feces. Nitrogen is distributed equally between the two parts.

Nutrient Losses from Manure

Manure can lose substantial amounts of nutrients during the several steps of manure management; this is a loss of nutrient value to the user. But also, the lost nutrients become an environmental pollutant. The waste stream from a herd of cattle contains far more phosphorus, for example, than a much larger population of people, yet the treatment of municipal sewage is far more regulated than manure treatment. To make the best and safest use of animal manures, the user must understand losses and how they can be best avoided.

Urine contains about 50 percent of the nutrient value of manure. If this part of the manure is lost, most potassium and much of the nitrogen will also be lost. Urine is lost when it seeps into the ground through barn floors or in feedlots. A great deal of urine simply drains away from manure heaps.

Sharp nitrogen losses occur if manure begins to decay before it is spread. As much as 90 percent of the nitrogen can be lost within three weeks if manure is poorly handled. The losses occur when urea changes to ammonia gas during decay (see the discussion of volatilization in Chapter 12). The loss is most rapid when it is warm and the concentration of urea is highest. Water in the manure dilutes the urea and slows the change. Nutrient losses continue after manure is spread in the field. Ammonia continues to escape unless manure is mixed quickly into the soil. Runoff and leaching increase the loss. Spreading manure on frozen, sloping land increases the chances of manure being lost to runoff. If the soil has become overloaded with phosphorus, some will begin to leach downward toward the water table.

Decay organisms respiring in a manure pile change organic carbon to carbon dioxide gas. Organic matter decay explains why manure piles shrink over time. Because the organic matter would be a desirable addition to the soil, it can be considered a loss as well.

Figure 15–5 summarizes the ways in which nutrients are lost from manure.

Handling Manure

Manure may be handled by solid and liquid systems. Solid manure is best spread immediately on unfrozen ground and quickly plowed into the soil. In this way, nutrients are preserved and are less likely to be carried off the field in runoff during rain events. However, in some regions this technique is not practical in every season.

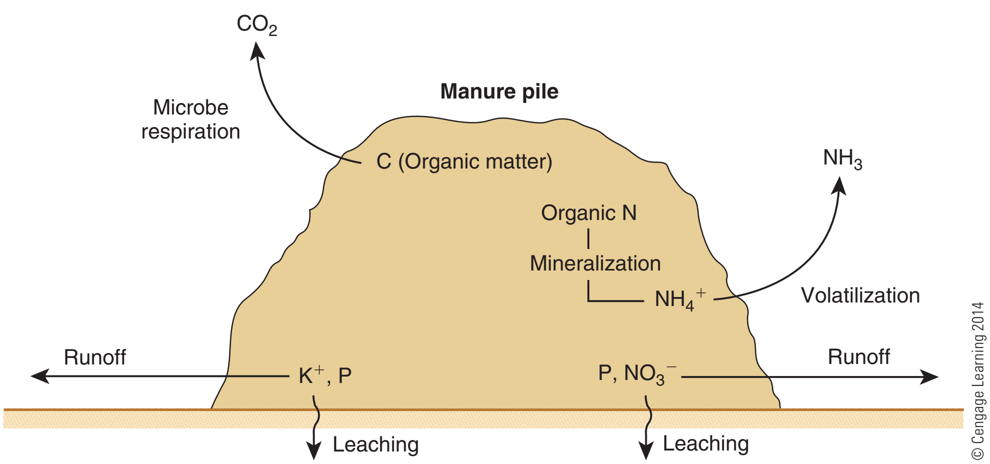

Figure 15–5
Much of the nitrogen and potash, and some of the phosphorus, can be lost during storage.

Incorporation of solid manure does present a problem with reduce tillage systems, especially no-till (Chapter 16). Since tillage increases rates of erosion, it is possible that the tillage needed to incorporate manure will lead to loss of soil particles with phosphorus attached to them.

If solid manure cannot be mixed into the soil immediately, it should be stored properly and then applied when it can be plowed into the soil. The actual loss of nitrogen varies with handling and storage systems. As noted in Figure 15–6, piles in an open lot, exposed to sun, rain, and air movement, will lose about half their nitrogen.

Some liquid storage systems and their potential nitrogen losses are listed in Figure 15–6. Liquid manures can be spread on fields or even run through an irrigation system. By far the best way to reduce nutrient loss and water pollution is to inject liquid manure into the soil (Figure 15–7). While slowing the disposal

Method	Nitrogen Loss (percent)
Solid Systems	
Daily scrape and haul	15–35
Manure pack	20–40
Open lot	40–60
Deep pit (poultry)	15–35
Liquid Systems	
Anaerobic deep pit	15–30
Aboveground storage	15–30
Earthen storage pit	20–40
Lagoon	70–80

Based on data from Utilization of Animal Manures as Fertilizer by Sutton, Nelson, and Jones. Purdue University

Figure 15–6
Nitrogen losses from animal manures as affected by methods of handling and storage.

Courtesy of USDA

Figure 15–7
Liquid manure injection into cropland in Maryland. Injection preserves nutrients and reduces pollution issues, especially of phosphorus.

operation, injection greatly reduces nitrogen losses, and prevents runoff losses that pollute local surface waters. Injection complements conservation tillage systems because injection does not bury crop residues as does incorporation of surface-applied manure.

Best Management Practices

As noted earlier, it is a grower's task to make the most efficient use of animal manures without inflicting damage on the environment. To this end, a number of Best Management Practices (BMPs) have been proposed:

- Test manure and soil for nutrient levels. With tests, the grower can reduce fertilization by an amount equivalent to the nutrients in the manure. Apply manure and fertilizer together at a rate based on crop nutrient needs.
- Base manure application rates on phosphorus needs, especially for chicken and swine, rather than nitrogen. The latter is more commonly done, but in many soils it leads to heavy phosphorus soil loading. For high-phosphorus manures, this may mean augmenting the nitrogen with fertilizers.
- Carefully spread solid manures evenly over the field with calibrated equipment (Figure 15–8).
- Incorporate or inject all manures into the soil as soon as possible.
- Increase time animals spend on pasture rather than on a feeding operation.
- Design the animal feeding program to reduce the phosphorus content of manure.

Photo courtesy of Bob Nichols, USDA Natural Resources Conservation Service

Figure 15–8
Calibrating a manure spreader in Louisiana. Calibration is part of proper manure management for the best use of manure that protects the environment.

Proper composting, as described later in this chapter, is a BMP for manure management. If manure is composted with a high C:N material like wood shavings, nitrogen losses should be minimized because the nitrogen will be immobilized by the decay of the high C:N material. Nutrients are stabilized, most pathogens and weed seeds are killed by heat, and the reduced volume makes transport more practical. Many certified organic programs require manure to be composted before use.

Another more recent option for handling manure is to treat it with *anaerobic digestion*, which is a controlled decomposition inside a structure that produces methane that can be burned as a fuel source and residues that can be spread on land.

Sensitive Areas

The environmental hazards of manure application increase greatly in sensitive areas. Such areas feature nearby waters that receive lost nutrients, and soils or terrains that promote runoff or leaching into groundwater. Examples of receiving waters include nearby streams, lakes, wetlands, drainage ditches and systems, and well heads. Soils prone to loss include sloping land, sandy soils, and soils with shallow bedrock or high water tables. Many states regulate disposal on sensitive areas.

Commonly, states require setbacks from receiving waters—some distance from the water that manure may not be applied. At a further distance, only injection may be used, or sometimes spreading with immediate incorporation. An effective further protection of water is the vegetative buffer—a zone of dense vegetation along the edge of the water (Figure 8–12). A properly constructed buffer slows the flow of water, allowing more to infiltrate the soil, and filters out solids. The vegetation, in turn, takes up the nutrients.

Regulations for CAFOs

The federal Clean Water Act of 1972 listed feedlots as point sources that could be regulated to preserve quality of waters of the United States. In practice, that has meant regulation of Confined Animal Feeding Operations, or CAFOs. A CAFO is an operation with large numbers of animals—1,000 head of beef cattle, 2,500 large swine, and so on—or operations with smaller numbers of animals with potential to impair surface waters. Such operations must obtain a federal or state permit under the National Pollution Discharge Elimination System (NPDES). Requirements include, among other things, filing a nutrient management plan, keeping detailed records, and filing reports. Nutrient management plans must include provisions for such procedures as

- Minimizing of nutrient excretion by animals
- Proper storage of manure
- Land applications at agronomic rates for N and P
- Setbacks and buffers from sensitive areas
- Periodic soil testing

The rules are reasonably complex and a suitable subject for advanced study.

BIOSOLIDS

The spreading of human waste on soil has a long history in many societies. In the United States, **sewage sludge** began to be spread on land in the early 1970s in response to federal clean water and air laws. The Environmental Protection Agency (EPA) estimates that about half the sewage sludge produced in the United States is spread on land.

Three major options exist for handling sewage sludge: incineration, landfilling, and land application. The last method may be safest because the material is diluted by application over large areas, filtered by the soil matrix, and decomposed by soil organisms. It is the least expensive way for cities and towns to dispose of sewage sludge. Landfilled sludge generates methane, a powerful greenhouse gas, and incineration pumps carbon dioxide into the atmosphere. Land application moves the carbon into the soil. Furthermore, it contains nutrients and organic matter useful as a soil amendment but wasted in the other treatments.

Land application is a form of recycling by closing a nutrient loop. Farm fertilizers are absorbed by crops, the crops are eaten by people, and some of the nutrients are flushed into the sewage system. If the sewage is then spread on farm fields, nutrients return to the land and the nutrient loop is closed. In recognition of the value of this material, it is generally now called **biosolids**: the primarily organic solid product yielded by municipal wastewater treatment that can be beneficially recycled.

Biosolids Problems

Biosolids may be a valuable amendment, but they carry potential risks needing regulation. EPA regulations govern proper sludge treatment and application. It is worth noting that biosolids are the most controlled and regulated of all organic amendments. These rules especially concern three hazards that may be present in biosolids: pollutants, human pathogens, and human pest vectors.

Pollutants

Biosolids contain small amounts of such pollutants as heavy metals such as cadmium or lead, and organic pollutants such as pesticides. The EPA currently regulates nine heavy metals that can be toxic to animals—as in lead poisoning—or damaging to plants. Those sludges with the lowest heavy-metal levels may be spread on land with the least regulatory control; those with the highest cannot be used at all. The intermediate group can be spread on land with certain restrictions and monitoring requirements.

Human Pathogens

Biosolids may contain small but detectable levels of human disease organisms and parasites, and while these eventually die in soil, they may present risks in some situations. Biosolids are classified according to their pathogen content. Class A biosolids are essentially free of pathogens and may be safely applied anywhere, including home gardens, with little regulation. Class B biosolids, less treated, may be applied to other lands under certain restrictions.

Pest Vectors

Vectors are insects or rodents that may carry human diseases and that may be attracted to fields treated with biosolids. EPA regulations require sludge treatments that make biosolids less attractive to vectors when spread on land.

Other Problems

Biosolids may also present problems of nutrient pollution (see later in chapter), soluble salts, or odor. Application guidelines are designed to reduce these problems as well as the major issues described earlier.

Application Guidelines

Federal rules set standards for biosolids application to protect public health and the environment; states may set stricter standards. These rules apply to common sites of land application, such as agricultural land, nurseries, or reclamation sites.

The EPA classifies biosolids that can be spread on land as Exceptional Quality (EQ) or High Quality (HQ). EQ biosolids meet all the standards for all three problem areas, while HQ conforms to slightly lower standards. The EPA accepts EQ biosolids for home and garden use, and they can be used like other fertilizers with little restriction. HQ biosolids can be applied to other land categories, with restrictions like setbacks from receiving waters and restrictions on winter application. Federal guidelines specify that biosolids be applied at rates based on nitrogen needs of the crop, but regulations prohibit application of more than meets heavy-metal guidelines.

Biosolids can be handled much like manure: injected into the soil, irrigated, or spread on the ground. Because injection reduces odors, discourages vermin, and lessens runoff losses, the EPA prefers such application. Surface-applied biosolids should be tilled into the soil within 72 hours.

It should be pointed out that some object to land spreading of biosolids, for a number of reasons. Organic certification programs do not permit biosolids on organically grown crops.

COMPOST

Composting piles organic materials above ground to stimulate decay and create a useful soil amendment. Many commercial greenhouses and nurseries compost their own organic wastes and mix the results into their potting soils. Homeowners often compost yard and kitchen wastes, but it presents large-scale commercial uses as well. Examples of important composting operations include composting of yard wastes by cities and landscape companies (Figure 15–9): the EPA says 16 million metric tons of yard wastes were recovered for composting in 2000. Materials also include other municipal solid wastes, food processing wastes, or sewage sludge. Composting manure reduces many of the hazards of manure and the product can be more easily sold and transported than raw manure.

Compost that results from these operations may be used as a soil amendment by the operator, given away to homeowners for their gardens, or sold as a commercial product. In the process, a variety of wastes are put to good use. Done properly, composting is a BMP for disposal of many organic wastes.

Some nutrient losses during composting are unavoidable, such as loss of gaseous nitrogen. On the other hand, nutrients are stabilized and protected in the process. Composting offers several benefits:

- Composting reduces the C:N ratio of materials such as leaves or wood chips, eliminating nitrogen tie-up when it is turned into the soil.

Figure 15–9

A windrow of yard wastes composting at a resort in Hawaii. Such composting disposes of wastes while providing a useful soil amendment.

- Composting reduces the weight and volume of organic wastes, making them easier to handle and ship.
- Having already lost labile materials during decay, stable compost mineralizes slowly and better enhances soil carbon long term than other methods like green manures.
- Heat generated in the pile kills many weed seeds and plant and animal pathogens.
- Organisms that colonize stable compost can suppress root pathogens—a trait greatly appreciated by container nursery growers.
- Incorporation of compost into contaminated soils reduces a number of pollutant problems.

People practice a number of composting methods, even using earthworms as composting agents, called *vermicomposting*. Here we will focus on the primary composting methodology, the aerated pile.

A properly prepared compost pile mixes carbonaceous and nitrogenous materials to achieve a C:N ratio of about 30:1. At this ratio, nitrogen is preserved because it remains immobilized; at a lower ratio, much will be free to leach or volatilize. At much higher ratios, the process is very slow.

A compost pile is kept moist but not wet, at a moisture level of about 50 percent. The pile must be moist to permit rapid decay, but excess moisture creates anaerobic conditions. Anaerobic piles decay very slowly, generate unpleasant odors, and produce "sour compost" containing organic acids and other chemicals that damage plants.

Component	Pounds/Ton
Total nitrogen	44.00
Phosphate (P_2O_5)	68.00
Potash (K_2O)	38.00
Calcium carbonate	160.00
Magnesium	8.00
Sulfur	12.50
Sodium	5.56
Iron	6.80
Aluminium	4.24
Manganese	0.73
Copper	0.59
Zinc	0.50
Organic matter	1,000.00

Based on data from Agri-Brand Compost, Holden Farms, Inc.

Figure 15–10
Average analysis of one wood shaving–turkey manure compost product.

In commercial composting, waste may be shredded before it is piled in long windrows and moistened. The composting process now follows three stages. In the first, **mesophilic** stage, organisms that prefer moderate temperatures begin the decay process, and temperature begins to rise. In the second, **thermophilic** stage, heat-loving microbes replace mesophilic ones, and temperature rises to around 150°F. During this stage temperatures are monitored and whenever they begin to drop, the pile is turned with front loaders or specialized machines to bring in fresh oxygen and organic matter, and temperatures rise again. The bulk of decay occurs during the thermophilic stage. When temperatures drop for good, a second mesophilic "curing" stage takes a month or two, during which stabilization of the compost occurs. Mesophilic organisms, particularly actinomycetes and fungi, recolonize the pile; a number of these organisms are beneficial in being antagonistic to root pathogens.

Hobby farmers, urban farmers, and gardeners compost yard and kitchen wastes on a smaller scale, but follow the same process. Small-scale compost piles are usually confined to bins, which are tidier and easier to manage with hand tools.

Well-prepared compost is well decayed and stabilized. It is low in heavy metals and soluble salts, with a pH between 5.0 and 8.0. Particle size should be around a millimeter in size, with little or no foreign matter, such as pop-can tabs. The C:N ratio should be between 15:1 and 25:1, and it should be free of the toxic residues of anaerobic decay. It should also be mostly organic matter, with little soil mixed in. Figure 15–10 shows the nutrient analysis of a turkey manure–bedding compost from one composting operation.

FERTILIZER AND THE ENVIRONMENT

Fertilizers aid the productivity of American farms, but they have not been without their problems. Fertilizers, manures, and sludges all can cause pollution and human health problems. The grower who is environmentally aware acts to keep these problems to a minimum by practicing proper nutrient management.

Animal and Human Health

The main health problem is the effect of nitrates on animal and human infants, and ruminant animals like cattle. Small amounts of nitrates in drinking water cause an infant anemia called "blue-baby disease" (methemoglobinemia), in which the ability of the blood to carry oxygen is reduced. In some rural parts of the United States, water is no longer fully safe for human or animal infants (Figure 15–11).

A certain amount of natural nitrate leaches into groundwater from normal mineralization of organic matter and other natural nitrogen inputs. Grower additions such as fertilization or manuring can greatly increase the nitrate load. Thus, groundwater may be contaminated by nitrates from water percolating through fertilized soil. This has occurred most often on irrigated outwash sands with water tables near the

Nitrates and Well Water in Minnesota

In a study of nitrate pollution of wells on outwash sands of central Minnesota, well owners were provided nitrate test kits. Where the well was surrounded mainly by agricultural land, 10 percent of the wells exceeded EPA standards. Where other land uses predominated, only 3 percent tested higher than EPA standards. Water treatment systems to remove the nitrates averaged about $800 to install and $100 per year to maintain.

Source: Lewandouski, A. M. et al. (2008). Groundwater nitrate contamination costs: A survey of private well owners. *Journal of Soil and Water Conservation, 63*(3), 153–161.

Image courtesy of Ed Plaster

Figure 15–11
For a summer, the public was warned not to drink the water in this freeway rest stop in Minnesota because of nitrate contamination.

surface. These soils, naturally droughty and infertile, tend to be heavily irrigated and fertilized. Biopores and other soil channels can also rapidly transport nitrates into groundwater. Some regions also feature a geology (*Karst topography*) with sinkholes that provide a direct route to the water table by pollutants.

Eutrophication and Hypoxia

Nutrient losses from farms and landscapes cause **eutrophication**, an increase of algae growth in water bodies. In many ecosystems this is a slow, long-term but natural process. However, fertilizer inputs dramatically speed up the process. The EPA rates eutrophication as the most widespread water-quality problem in the United States.

In freshwater systems, while nitrogen contributes to the problem, phosphorus is the major cause of eutrophication in lakes and streams. It leads to loss of water clarity, less dissolved oxygen in the water, damaged aquatic ecosystems, and reduced value for swimming or fishing (Figure 15–12). When algal growth explodes, algae begin to die and are attacked by bacteria that use up the oxygen in the water. The resulting low-oxygen conditions, called **hypoxia,** result in major losses of aquatic life such as fish. Phosphorus also contributes to toxic algal blooms, where exploding algae populations generate toxins that kill fish or even animals like pets swimming in the water.

Phosphorus discharges from point sources such as sewage-treatment plants and industry have been greatly, though not completely, reduced by government regulations, leaving agriculture as the major contributor. Phosphorus enters surface waters primarily in runoff from fertilized or manured fields, either in solution or attached to soil particles. For instance, failure to incorporate manure leaves phosphorus to accumulate in the top couple of inches of soil, where it can be removed by running water and transported into streams. In many locations, years of fertilizing and manuring have resulted in soils with surplus phosphorus, raising the hazard of loss.

Photo courtesy of Lynn Betts, USDA, Natural Resources Conservation Service

Figure 15–12
Algae growth makes this Iowa lake less suitable for recreation, a consequence of nutrient runoff.

One effort to reduce the problem is the **phosphorus index**, an effort to quantify potential phosphorus hazards on lands, to identify sites with a higher risk of phosphorus movement, and to help devise corrective plans. Researchers have devised various indices around the nation. They have also been used in regulations.

In coastal marine ecosystems nitrogen tends to be the major contributor to hypoxic conditions. The largest areas of low-oxygen conditions occur in hypoxic zones of the coastal oceans of United States, Europe, and Japan. These areas of severe hypoxia have grown in recent decades where river systems enter the ocean. Here nutrient inputs, particularly nitrates, cause an offshore growth of algae. These settle to the bottom, and their decay reduces oxygen levels in subsurface water. The effects of this hypoxia can seriously damage commercial and recreational fisheries.

The Gulf of Mexico hypoxia zone ranks as the largest in the United States. This zone along the coast of Louisiana and Texas can reach an area about the size of New Jersey during the summer. It is fed by an average annual input from the Mississippi River of some 1.5 million metric tons of nitrates, mostly from the Corn Belt but also from other croplands of the river basin. The Council for Agricultural Science and Technology (CAST) reports that an estimated 55 percent of this input comes from fertilizers and another 25 percent from legume crops.

Large areas of artificially drained soils in the Mississippi River basin are a major contributor to the Gulf hypoxic zone. Drain tiles readily transport leached nitrates into streams that eventually feed the Mississippi River. Reducing the severity of coastal hypoxia means reducing nitrate leaching and transport in drainage systems through such methods as Agriculture Drainage Management Systems (Chapter 9).

Energy Costs

Fertilizers have a high energy cost, particularly nitrogen fertilizers. Each ton of industrially fixed nitrogen consumes 1.5 tons of natural gas, and several percent of the nation's yearly fuel bill goes to making fertilizer. This high energy bill raises the cost for farming and even threatens farms if supplies become limited. Organic farmers cite this factor as one reason for avoiding chemical fertilizers.

Human Changes in Global Nitrogen Cycles

Ecologist Peter Vitousek and others have argued that humans have greatly altered the global nitrogen cycle. Most of the world's nitrogen pool (N_2 gas) is useless to most organisms. Humans now create as much biologically active nitrogen like nitrates or ammonia as all the natural processes combined, by fertilizing and cultivating legumes. Figure 15–13 shows a piece of how much we have altered the natural nitrogen cycle. In 1890, before invention of the Haber–Bosch process, there was very little nitrogen applied as fertilizer and bacterial fixation by growing legumes dominated. Most of the nitrogen fixed on the planet appeared in natural ecosystems. A hundred years later, nitrogen fertilization explodes and dramatically alters the nitrogen cycles, and fixation in agricultural systems overtakes that of natural ecosystems.

Much of the nitrogen eventually moves elsewhere in water or in the atmosphere. The Gulf of Mexico hypoxic zone is one consequence.

Some results are well known, such as those just described. Others remain unclear. Nitrogen oxides, released from fertilized soil by denitrification, act as strong

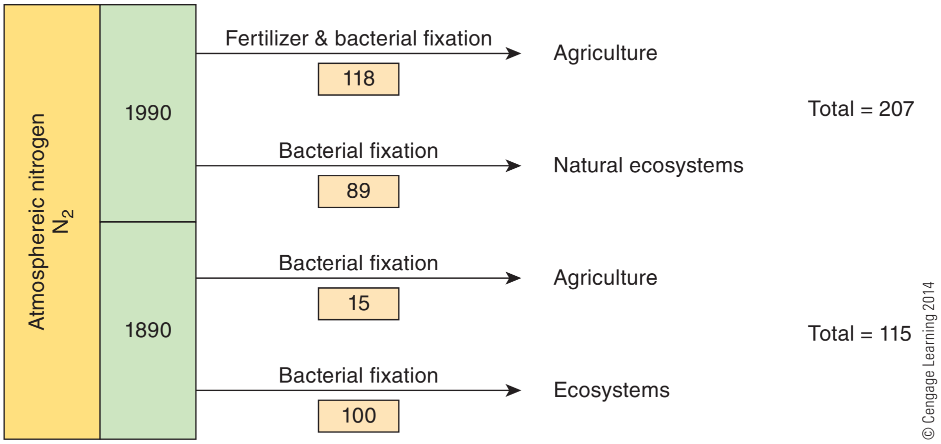

Figure 15–13
This figures portrays part of the alteration of the natural nitrogen cycle. In 1890, nitrogen entered farm soils and natural ecosystems by biological fixation. By 1990, bacterial fixation in natural ecosystems had declined while fertilizers from the Haber–Bosch process caused an explosion of nitrogen application to agricultural land.

greenhouse gases, add to smog, and acidify soils and waters. Nitrogen enrichment is also changing the nature and health of natural ecosystems. Enrichment Activity 7 cites a Web site where one article on the subject can be found.

Best Management Practices

Growing the crops needed by humanity requires plant nutrients in some form, but we can use cropping systems that make the most efficient use of them. Best Management Practices, or BMPs, are practical cropping systems that reduce environmental impacts of practices such as fertilization. The BMPs that we use to maximize benefits of nutrients while minimizing their environmental impact, including not just fertilization and manuring but irrigation and other practices, are included under the umbrella term *nutrient management.*

It is estimated, for example, that only half the nitrogen applied to crops actually ends up in those crops—the rest is lost to water or the atmosphere. This not only creates nutrient problems, but also costs growers money: the CAST report suggests that $410 million worth of nitrogen fertilizers is annually lost down the Mississippi River.

Nitrogen Deposition and Species Diversity

The results of a 23-year-long study of low chronic rates of human-induced nitrogen deposition, similar to those common to many parts of the globe, on experimental prairie plots were published in 2008. Results showed that treated plots lost 17 percent of their species compared to control plots. A follow-up study showed that some species diversity could recover if nitrogen deposition ceased. The study indicates nitrogen deposited from the atmosphere from industrial, transportation, and agricultural sources is reducing species diversity in nature, and that the loss can be at least somewhat reversible if we can strongly reduce those sources.

Source: Clark, C., & Tilman, D. (2008). Loss of plant species after chronic low-level nitrogen deposition to prairie grasslands. *Nature, 451,* 712–715.

Efficient and environmentally sound fertilizer and amendment use dictates using the right *amount* of fertilizer applied at the right *time* by the right *method*. For instance the general rule for the right time is when plants are growing actively. In the author's home state, a late fall application to turf is no longer recommended because the grass is no longer growing actively and the chance of loss is high.

Many of the practices described elsewhere in this text are BMPs that improve nutrient use. Examples include:

- Thorough and timely soil testing.
- Practices such as conservation tillage that reduce erosion and runoff.
- Efficient irrigation practices that reduce nitrate leaching and denitrification on irrigated lands.
- Proper manure handling to increase nutrient retention and decrease such losses as leaching and runoff from feedlots and fields.
- Fertilization practices that deliver fertilizers at times and rates best suited to plant growth, such as split applications.
- Precise fertilizer applications resulting from good soil testing with credits taken for manure and legumes. Precision agriculture is a good tool.
- Careful use of fertilizers on lawns and golf courses, such as sweeping up granules and clippings from sidewalks.
- Use of slow-release fertilizers and recycling of all irrigation water in container-growing nurseries and greenhouses.
- Controlled drainage systems.
- Vegetative buffers along sensitive areas.
- Cover cropping to "sop up" excess nitrates before they can leach.
- Budgeting nutrient inputs so they equal nutrients removed by harvest and avoiding application greater than crop needs.
- Many of the practices of organic and sustainable agriculture.

SUMMARY

Manure, biosolids, and compost provide a double benefit to growers—they contain nutrients to promote plant growth and organic matter to improve the soil. Applying these materials to land is a good alternative to other disposal methods.

Manure is highest in carbon, nitrogen, and potash. However, the phosphorus level is usually in excess of plant needs, so phosphorus loading often occurs when manures are applied to fields. Proper handling of manure reduces nutrient losses and lowers the chance of

polluting surface or groundwater. Manure is best injected or spread on unfrozen land as soon as possible after collection and then tilled into the soil.

Biosolids are recycled "human manure" and can be handled much like animal manure. However, possible health problems from heavy metals and human pathogens mean that they must be used according to strict state and federal EPA guidelines. Biosolids are applied according to the nitrogen rate to a variety of crops and sites.

Composting is a way to reduce the C:N ratio of organic materials and to kill harmful organisms. For example, composting sludge with wood chips stops nitrogen tie-up from the chips while killing pathogens in the sludge. Composting followed by land application to gardens, lawns, farm fields, degraded soil, and other locations is an excellent way to handle a wide variety of organic wastes.

Any nutrient source—fertilizer, biosolids, or manure—can harm the environment if used improperly. Nutrients and pathogens can wash into surface waters or leach into groundwater, causing pollution and human and animal health problems. Using inorganic and organic fertilizers in the suggested ways and rates and avoiding erosion are important ways to reduce these problems.

Farm fertilizers increase national energy use and force agriculture to rely heavily on fossil fuels. For most growers, making the most efficient use of fertilizer, biosolids, manure, compost, and legumes is the best answer.

REVIEW

1. Assume you are advised by a soil test recommendation to apply 150 pounds of nitrogen per acre to a crop. How much dairy cattle manure would you apply if half the nitrogen becomes available that first season (using numbers from Figure 15–2)? You will incorporate immediately and we will assume no nitrogen loss by volatilization.
2. In question 1, Figure 15–2 provides an average nutrient content. Is it proper to use these in calculating manure application rates for your fields? If not, what should you do instead?
3. In the manure application of question 1, how much phosphorus would you be adding? What might be the consequences if this rate is higher than that recommended on the soil test report?
4. Garden centers offer lawn fertilizers manufactured from municipal sewage-treatment systems. What must be true of such products, and what must be their biosolids rating?
5. Explain why nitrogen losses in compost piles can be high if the pH is too high. Review Chapter 12 if necessary.
6. Occasionally large manure lagoons spill their contents into local surface waters. Based on this chapter, what effects would this have on those waters?
7. Manure injection reduces the loss of phosphorus from fields over surface application. Explain why.
8. Looking at Figure 9–8, what potential pollution problem should come to mind after reading this chapter? Can there be a consequence far from this field? Suggest a couple of actions one might take to reduce the problem.
9. For the homeowner, which product would be most suitable for amending soil in a garden, raw or composted manure? Why?
10. Describe policies and regulations about manure or biosolid application to land in your state. Information can be obtained by entering "manure" and the name of your state into a Web browser.

ENRICHMENT ACTIVITIES

1. Visit a facility that works with one of the amendments described here, such as a composting facility, sewage-treatment plant, or manure storage facility.
2. Build and manage a compost pile.
3. For further details on manure handling, read the CAST 1996 report “Integrated Animal Waste Management.”
4. Through the website http://www1.extension.umn.edu/agriculture/ you can find extension bulletins on manure usage and nutrient management.
5. Numerous fact sheets on anaerobic digestion can be found on the Internet. Select one to learn more about it.
6. Search the Gulf of Mexico hypoxia zone on the Internet.
7. The Ecological Society of America offers an article in its journal *Issues in Ecology* by P. M. Vitousek et al., “Human Alteration of the Global Nitrogen Cycle: Causes and Consequences,” at http://cfpub.epa.gov/watertrain/pdf/issue1.pdf.
8. Check out George Washington’s composting operations at Mount Vernon at http://www.cityfarmer.org/washington.html.
9. Find the EPA’s page on biosolids by typing “biosolids EPA” into a Web browser.
10. Virginia Cooperative Extension at Virginia Tech offers several nutrient management publications for different settings such as small farms, turf, and environmental horticulture. Go to http://pubs.ext.vt.edu and type “nutrient management” into the custom search box.
11. Several states offer financial aid and matching services to help animal operations with too much manure to ship it to crop growers who can use it. Maryland has such a service; an online pamphlet is at http://www.mda.state.md.us/pdf/manurematching.pdf.

CHAPTER 16

Tillage and Cropping Systems

TERMS TO KNOW

allelopathy
conservation tillage
conventional tillage
cover cropping
crop rotation
double cropping
dryland farming
fallow
lister plow
moldboard plow
no-till
organic farming
primary tillage
rangeland
reduced tillage
row crop
saline seep
secondary tillage
small grain
sustainable agriculture
tillage

OBJECTIVES

After completing this chapter, you should be able to:

- explain the reasons for and effects of tillage
- describe conventional and conservation tillage
- list several cropping systems
- briefly describe organic and sustainable agriculture

To produce crops, a grower places seeds or plants in contact with the soil, provides nutrients, controls pests, and manages soil water. These activities usually involve some form of tillage. There are many ways to work the soil—including no tillage at all—and different situations require different methods. Each method has an effect on the crops and the soil. Early in this text, the author stressed the coming role of growers to sequester carbon in their soils—one tactic in efforts to reduce global climate change. Carbon storage in soils can be quite sensitive to tillage and cropping systems. This chapter looks at some standard tillage and cropping systems.

USES OF TILLAGE

Tillage is working the soil to provide a favorable environment for seed placement and germination and crop growth. In the United States, mechanization and research have led to a variety of tillage systems. Regardless of the method of tillage used, a grower has three basic goals: (1) weed control, (2) alteration of physical soil conditions, and (3) management of crop residues.

Weed Control

Tillage for weed control can be divided into two time periods: before crop planting and after crop planting. Before planting, tillage prepares a weed-free seedbed that greatly simplifies weed control during the growing season. Tillage destroys young seedlings, and repeated tillage operations may also weaken perennial weeds. After planting, cultivation continues to destroy or bury emerging seedlings. However, deep cultivation or cultivation late in the season may sever crop roots and reduce yields.

The importance of tillage for weed control has declined with increases in both herbicide use and tillage systems designed around herbicide use. Some herbicides require incorporation into the soil by shallow tillage.

Physical Soil Conditions

Tillage alters physical soil properties such as structure, moisture, and temperature. Tillage during seedbed preparation stirs and loosens soil, improves aeration, and creates a suitable medium for growth. Deep tillage and subsoiling may temporarily break up subsoil compaction.

However, tillage causes a long-term decline in physical structure. The decline is partly due to losses of soil organic matter that result from tillage. Repeated tillage operations crush some soil aggregates. Wheel traffic compacts the soil, especially wet soils, and tillage pans may form. Soil aggregates on the surface of bare soil shatter from raindrop impact, causing crusts that hinder seed germination and shed water. Bare soil resulting from many forms of tillage erodes easily. Recent changes in tillage aim to reduce these adverse side effects.

Tillage also affects the moisture level and temperature of soil. Tilled soil usually warms and dries earlier in the spring, allowing earlier seeding and better germination.

In areas where soil tends to be wet or cold in the spring, crops may be planted on ridges created by tillage. The ridges warm and dry faster than the rest of the soil.

Shallow cultivation of crust-forming soils may improve crop yield even where herbicides are used to control weeds. By breaking up crusts, cultivation improves water infiltration and reduces runoff. Such cultivation should be just deep enough to break the crust.

Crop Residue Management

After most crops are harvested, residues such as stalks or leaves remain in the field. The amount of residue depends on the type of crop, how well it grew, and how it is harvested. For example, corn leaves about 8,500 pounds of residue per acre for a 150-bushel crop, and about 5,600 pounds of residue for a 100-bushel crop. If corn is harvested for silage rather than grain, little residue is left in the field. Notice that a vigorous, productive crop produces more mass of organic matter that can be managed to reduce erosion and improve soil quality. Figure 16–1 lists residues for several crops.

There are several ways growers manage crop residues, depending on objectives. Moldboard plowing buries crop residues, resulting in a clean field that is easy to plant and cultivate. In semiarid grain-growing areas, special tillage tools, including rodweeders and sweeps, till under the surface to kill weeds but leave residues on the surface to protect against wind erosion. Conservation tillage in more humid climates leaves residues on the surface to protect against water erosion. Broadly speaking,

Crop	Approximate Residue per Bushel Grain (lb/acre)	×	Sample Yield (bu/acre)	=	Sample Residue (lb/acre)
Barley	80		50		4,000
Corn	56		125		7,000
Flax	80		15		1,200
Oats	60		32		4,300
Rye	100		30		3,000
Sorghum	60		50		3,000
Soybeans	50		40		2,000
Wheat	100		40		4,000

Figure 16–1
Crop residues in pounds per acre for several crops. To obtain these values, the number of pounds residue per bushel of grain is multiplied by the per-acre yield. Sample yields may not represent yields in your area. Note that the higher the yield, the greater the crop residues available to protect soil or add organic matter to the soil.

Implement	Estimated Percentage of Residue Remaining After Each Operation
Inverting Tools	
Moldboard plow	5
Lister plow	20
Mixing Tools	
Field cultivator	80
Chisel plow, spear point	80
Chisel plow, twisted point	50
Rototill to 6 inches	25
Rototill to 3 inches	50
Tandem disc to 6 inches	25
Tandem disc to 3 inches	50
Spring-tooth harrow	60
Spike-tooth harrow	70
Subsurface Tools	
Blades or sweeps	90
Rodweeders	90

Figure 16–2
Percentage residues remaining after one pass over the field. If two or more tillage operations are practiced, each operation after the first uncovers about half the amount it covers.

for soil quality and carbon sequestration, the best way to manage crop residues is to leave them on the soil surface. Figure 16–2 lists the amounts of residue left on the soil surface from various tillage tools.

In addition to crop residues, tillage may also incorporate phosphate, potash, and lime into the root zone. Tillage also incorporates sewage sludge, manures, and nitrogen sources such as urea that volatilize if left on the soil surface.

Seedbed Preparation

The three reasons for tillage come together in preparing a seedbed to ensure that the soil meets the needs of germinating seeds. Seeds need a moist soil at the right temperature with sufficient air for seed respiration. The soil should be loose enough for good aeration, but compact enough around the seed for good soil–seed contact. It should be free of clods that prevent proper seed–soil contact and seedling emergence.

A seedbed free of crop residue is easiest to plant in, but conservation tillage demands that crop residues be left on the surface to control erosion. Specialized modern planters can plant through crop residues and clods, preparing correct soil conditions near the seed.

CONVENTIONAL TILLAGE

Conventional tillage, the primary form of tillage since invention of the moldboard plow, involves two stages. First, **primary tillage** breaks up the soil and usually buries crop residues. Primary tillage is often accomplished with an inverting implement, like the moldboard plow or lister plow, that inverts or tips over the top few inches of soil. **Secondary tillage** produces a fine seedbed by a series of operations that break up the soil into smaller and smaller chunks. Secondary tillage involves mixing implements like harrows. The following discussion describes these operations in more detail.

Primary Tillage

The traditional primary plowing tool is the **moldboard plow**. The moldboard shears off a section of soil, tips it upside down, and fractures it along several planes (Figure 16–3). In the process, any organic material on the soil surface is buried. The

Courtesy of John Deere Company

Figure 16–3
The moldboard plow shears off a section of soil and inverts it, loosening the soil and burying crop residues. It is a traditional tool of primary tillage.

moldboard plow leaves the surface very rough with a series of ridges and furrows. Moldboard plows work best in moist soil; in wet or dry soil the operation uses more power and the results are poor. On slopes, repeated moldboard plowing slowly shifts soil downhill, accelerating soil loss.

An alternative to the moldboard plow is the chisel plow (Figure 16–4), a set of long, curved teeth that are dragged through the soil. Chisel plows fracture and loosen the soil without inverting it or burying most of the crop residue. A disc harrow can also be used as a primary tillage tool in some situations, described shortly (Figure 16–5).

Subsoilers and rippers (Figure 16–6) feature even larger, stouter teeth pulled deeply through the soil to shatter tillage or natural soil pans. Subsoiling should be done when the soil is dry because if pans are moist, they do not shatter. Deep plowing can temporarily help water infiltration and root penetration into the subsoil. Usually, however, compacted layers re-form as soil is exposed to further wheel traffic and tillage.

Secondary Tillage

Secondary tillage often involves a two-step harrowing process. In the first stage, ridges left from plowing are smoothed out and large clods broken up. Then smaller lumps are pulverized and a fine seedbed is produced.

Growers commonly begin the operation with a disc harrow (Figure 16–5). The typical tandem disc has four gangs of discs set like the four arms of an X. The front two gangs turn the soil outward, and the back two turn it back in. A disc tends to compound compaction problems because it shatters soil aggregates but does not dig deep enough to loosen compaction. Some crop residue is covered in the process. Other secondary tillage tools are also used, including spring-tooth harrows that resemble lighter chisel plows.

Photo by Tim McCabe, USDA Natural Resources Conservation Service

Figure 16–4
This chisel plow loosens soil without inverting it or burying all crop residues.

Courtesy of John Deere Company

Figure 16–5
The disc harrow, a common secondary and sometimes primary tillage tool.

Courtesy of John Deere Company

Figure 16–6
A ripper for breaking up subsoil compaction. The large, heavy-duty teeth are dragged deeply through the soil. This one is adapted for conservation tillage and leaves crop residues uncovered.

Lister Plowing

Lister plows are equipped with two moldboards mounted back to back, resulting in a pattern of 10-inch-high ridges and furrows across the field. In humid regions, crops may be planted on the warmer, drier ridges. In arid areas, they may be planted in the moist soil of the lister furrow. Listing can also help protect the soil from wind erosion. Listing on the contour captures water to improve water use and reduce water erosion.

Preparation of Furrow-Irrigated Fields

Additional steps are needed to prepare furrow-irrigated fields. After standard primary and secondary tillage, the grower carefully levels the field with a blade to ensure proper grade for flow of surface-applied water. Then the field is listed with a special tool to create ridges and furrows.

Timing and Depth of Plowing

Farmers in the eastern United States can plow in either fall or spring. Fall plowing gives the farmer a head start on spring planting by warming and drying the soil. Freezing and thawing on fine-textured soil breaks up large lumps, making it easier to develop a good seedbed. The benefits of fall plowing are especially important with fine-textured soils with somewhat poor drainage.

Spring plowing leaves crop stubble in the field over winter to capture snow and reduce erosion. To conserve soil, one plows in the spring unless there are overriding reasons for fall plowing.

In the western United States, where moisture preservation is critical, plowing immediately after harvest gives more time for the soil to store moisture if weeds are controlled. However, leaving soil bare increases the risk of erosion.

Unfortunately, conventional tillage entails a series of undesirable side effects that harm soil quality, including increased erosion. These problems are answered by conservation tillage.

CONSERVATION TILLAGE

Conservation tillage is a program of crop residue management aimed at reducing erosion. Rather than plowing under crop residues, some or all residue is left on the soil surface. The working definition of conservation tillage requires that 30 percent or more of the soil surface be covered with crop residues. Conservation tillage may also be known as **reduced tillage** or minimum tillage, though these terms may also be applied to systems that reduce tillage and leave lesser amounts of surface residues than conservation.

Conservation tillage reduces water and wind erosion by at least 50 percent to 60 percent. In areas where moisture can be limiting, conservation tillage increases soil moisture by improving infiltration and reducing runoff, reducing evaporation, and trapping snow. Because of reduced runoff, fewer pesticides and nutrients leave the field. Conservation tillage also improves organic matter content near the soil surface, as described in Chapter 6. Conservation tillage, therefore, is one of the most important Best Management Practices (BMPs) for soil and water conservation.

Conservation-tilled soil tends to be cooler than clean-tilled soil because of light reflection off the mulch and increased soil moisture. In warm climates, cooler soil benefits production but may hinder early growth and planting in northern states. Diffusion and mass flow of nutrients improves in the moister soil, increasing nutrient uptake.

Other benefits of conservation tillage are obtained from fewer trips across the field. These benefits include less time in field work and lower fuel costs. At times, compaction is reduced because of less wheel traffic. Conservation tillage may also require fewer implements, thus reducing equipment costs per acre. Fewer and quicker tillage operations also speed planting of a second crop in the field, allowing increased use of double-cropping systems (discussed later in chapter).

Conservation tillage increases biological diversity in the field, an important consideration for soil quality. This means a more diverse soil microflora and more diverse insect populations, as well as higher numbers of earthworms. Conservation tillage disrupts fungal networks less, improving habitat for fungus and especially for mycorrhizae fungus. Conservation tillage provides better habitat for pheasants and other wildlife. For instance, no-till fields have been shown to provide habitat for nesting ducks in North Dakota and nesting bobwhite quail in Tennessee.

Increasing carbon sequestration in farm fields also calls for conservation tillage. Conservation tillage reduces total greenhouse gas emissions from farm fields and farm operations compared to conventional tillage, and increases soil carbon storage.[1] This means a higher organic matter content in the top few inches of soil. No-till functions best from this perspective.

Conservation tillage, of course, presents its own set of challenges. For instance, a greater challenge of weed control follows less tillage, with greater reliance on herbicides. Fertilization practices must be adapted to the system. Nevertheless, because of soil conservation, water quality, and economic benefits, its use continues to grow. The U.S. Department of Agriculture (USDA) reports that in 2004 about 38 percent of U.S. agricultural land was under conservation tillage.

Conservation tillage covers several different tillage methods.

Mulch-Till or Chisel-Plow

A chisel plow (Figure 16–4), which loosens the soil but does not invert it, is used for primary tillage. Chisel plowing to 8 inches leaves the soil rough with about 50 percent to 80 percent residue cover. A subsequent light discing reduces residues to between 30 percent and 50 percent. Seeds are then planted through the remaining residues. After planting, light cultivation and herbicides control weeds. Mulch-till can be worked into an organic growing system, which does not permit herbicide to substitute for cultivation, though it may take some change in tools and techniques to maintain sufficient residue cover.

Strip-Till

With no primary tillage, a specialized implement tills a band of soil and plants seeds into the band. A different type of implement simply sweeps residues off a strip into the middle of the rows as the seed is planted. The planting operation bares about one-fourth of the soil surface, leaving about 50 percent of crop residues.

[1]Robertson, G., et al. (2000). Greenhouse gases in intensive agriculture: Contributions of individual gases to the radiative forcing of the atmosphere. *Science, 289,* 1922–1925.

Ridge-Till

The ridge-till system excels in cool, moist conditions. Seed is planted on 6-inch ridges (Figure 16–7) with crop residues swept into the shallow furrows. About two-thirds of crop residues remain after planting. Cultivation with special tools minimizes residue burial and rebuilds ridges for the coming year.

The ridges in this system warm up and dry more quickly than soil in other tillage systems. In addition, if oriented across the slope, they further reduce runoff and erosion. Or, if oriented perpendicular to prevailing winds, they reduce wind erosion and help to trap snow. The roots of plants on the ridges also grow separated from the compacted zone between the ridges where wheel traffic occurs. Ridge-till, like mulch-till, can also becompatible with organic agriculture.

No-Till

In the **no-tillage** method soil is barely disturbed (Figure 16–8). Specialized planters cut a slot through residues, insert the seed and fertilizer, and close the slot. About 90 percent of the soil surface is untouched. Contact, systemic, and preemergent herbicides are needed to control weeds with no cultivation, though the heavy cover of dead vegetation may reduce weed competition. The reliance on herbicides makes no-till a challenge for organic producers.

Because no-till involves the least soil disturbance, it maximizes the benefits of conservation tillage. By not disturbing the soil surface, it preserves the tops of earthworm and other channels at the surface, greatly improving water infiltration. No-till best preserves soil organic matter, and organic matter content actually rises in the soil near the surface. Of all the tillage systems, no-till most reduces greenhouse gas production and stores the most soil carbon. However, the greater number of

Photo by Lynn Betts, USDA Natural Resources Conservation Service

Figure 16–7

Soybeans planted ridge-till in corn residues on an Iowa farm. Corn residues are swept into the row middles and shallow ridges formed by tillage. Planting is done on the ridges, where soil will be warmer and drier.

Figure 16–8
No-till planting of corn into a barley cover crop in Virginia. Seeds are planted into barely disturbed residues for maximum soil cover.

biopores open to the surface can increase downward movement of nutrients and pesticides, such as might happen if rain falls heavily soon after surface application of liquid manure.

Residue levels can be predicted from data on crop residues left by crops (Figure 16–1) and the amount of residue remaining from each pass with an implement (Figure 16–2). It can also be measured directly in the field (Chapter 18).

DIFFERENCES BETWEEN CONVENTIONAL AND CONSERVATION TILLAGE

Conventional and conservation tillage differ in more than the obvious ways. Most growers ask first about yields. Current research shows equivalent yields from conventional and conservation tillage if known technology is applied to each tillage system and the systems are matched to crops and soil types. Shifting from one tillage system to another demands shifts in other management practices that can challenge the grower. For instance, even spreading of residues during the harvest process is key to success in conservation tillage.

Equipment

Conservation tillage places some requirements on equipment. For example, residues should be spread evenly behind harvest equipment. Planters must penetrate the residues, place and cover seed, and ensure seed–soil contact in a rough seedbed. Tillage and cultivation equipment must be designed to operate in heavy residues without clogging and minimal burial of residues.

Fertility

Because there is less soil mixing in conservation tillage (especially in no-till), the form and placement of fertilizers are affected. Lime, phosphates, and potash tend to stay near the soil surface. However, because residues provide a mulch, soil near the surface tends to remain moist, promoting root growth near the surface and improving uptake from that layer. Conservation tillage, especially no-till, can reduce nitrogen availability by increasing nitrogen tie-up in surface layers, increasing leaching and volatization, and reducing average soil temperatures. The injection of nitrogen deeper into the soil and nitrification inhibitors will reduce these problems.

Matching Tillage to Soil Type

Soils tend to be cooler and wetter in conservation tillage, especially with the no-till method. On fine-textured soils in northern states, cooler soil may delay planting and hamper seed germination. No-till is a poor choice on cold, poorly drained fine-textured soils; for these conditions, the ridge-till method is a better choice. Nor does no-till work well in highly compactable soils. On excessively drained coarse soils, no-till can improve yields by preserving moisture. Local extension agents can provide advice on the best system for each grower.

CROPPING SYSTEMS

Growers employ a number of cropping systems; several are described here. A grower's choice depends on climate, economics and market demand, government programs, and grower preference. Each system requires different soil management techniques and has different effects on the soil.

Continuous Cropping

In continuous cropping, a farmer grows the same crop each year. Continuous cropping is favored by many farmers because they can grow the most profitable crop. This method also allows the grower to specialize in the crop best suited to local soil or climate conditions. In general, however, yields inevitably decline with continuous cropping. At the same time, expenses for fertilizer, herbicides, and pesticides tend to rise compared with expenses for a crop-rotation system. Depending on the crop, repeated growing of the same crop can increase soil erosion and harm soil quality as well.

Crop Rotation

Crop rotation means that a series of different crops is planted on the same piece of ground in a repeating system. Many farmers do not rotate because it means planting some less profitable crops. Often a farmer has no use for certain crops in common rotations. For instance, a farmer who feeds no animals has little use for hay unless a buyer can be found for it.

However, crop rotation has important benefits for those who practice it. Crop rotation:

- Aids the control of diseases and insects that rely on one plant host, reducing a grower's pesticide bill.
- Helps control weeds. Many weed species grow best in certain crop types, so alternating crops suppresses the weeds. Some rotations suppress weeds by **allelopathy**, where one plant emits chemicals from the roots that suppress growth of other plants. For instance, soybeans planted into wheat residues suffer fewer weed problems because of the allelopathic effects of wheat.
- Supplies nitrogen if certain legumes such as alfalfa are in the rotation. This can lower a farmer's fertilizer bill.
- Improves soil organic matter and tilth. Deep-rooted crops such as alfalfa also improve subsoil conditions.
- Reduces erosion compared with continuous row crops, as long as the rotation includes small grains or hay. This topic is covered in more detail in Chapter 18.

Generally, crop rotations involve some combination of three kinds of crops: row crops, small grains, and forages. The specific crops and crop sequence vary from place to place. In the author's home state, farmers commonly rotate corn and soybeans; such a rotation of two row crops does not offer all the benefits of other rotations.

Row Crops

Row crops, where adapted, are usually most profitable. Row crops are planted in wide rows and under conventional tillage are cultivated for weed control, with the help of herbicides. Row crops usually leave soil bare, making it erosion-prone, so are best suited to fairly level ground. In general, continuous row cropping diminishes soil quality. Conservation tillage, crop rotation, and other conservation practices greatly reduce erosion from row crops (see Chapter 18). Common row crops include corn, sorghum, soybeans, and cotton.

Small Grains

Small grains, such as oats or wheat, are planted in closely spaced rows, so quickly cover the soil surface. Land planted to small grains loses less soil to erosion. Small grains also leave a large amount of residue that controls erosion in conservation-tillage systems. The dense growth of small grains competes with weeds that infest row crops, and several suppress weeds by allelopathy. As grasses, they improve soil structure and tilth.

Perennial Forage

Forages are harvested for their green matter and fed to animals. They may be harvested as hay or used for grazing in pasture or range. Forages improve soil tilth, add organic matter, and control erosion. Tap-rooted plants, such as alfalfa, help break up soil pans. Legume forages also fix nitrogen that can be used by later crops, reducing the need for later fertilization. Examples include legumes such as alfalfa and a wide array of forage grasses.

Double Cropping

Double cropping is the practice of harvesting two crops from the same piece of ground in one year. A common example is planting soybeans into winter wheat stubble. Double cropping is easiest in warm climates with long growing seasons. The use of double cropping has grown with the use of no-till systems. The second crop can be planted right behind harvest of the first crop, omitting time-consuming seedbed preparations.

Multiple cropping keeps the soil covered with vegetation for a larger part of the year. Better erosion control results. Two crops grow more green matter than one, so the practice helps maintain organic matter in the soil. Where one crop is a legume, the nitrogen addition is welcome.

Cover Cropping

Like double cropping, **cover cropping** involves two crops in one year on the same piece of ground. However, the cover crop is grown as a conservation tool and is usually not harvested. Several cover-cropping methods exist. In one variation, a cover crop is interseeded between rows of a taller row crop that is already growing. In a second variation, a cover crop is grown until it covers the ground, then the main crop is planted right into that first crop. The cover crop may be killed (Figure 16–8) or treated in some way to reduce competition. Cover crops may consist of grasses such as rye grass or legumes such as various vetches. The cover crop is sometimes termed a “living mulch.”

Cover crops may be grown and then simply plowed down, mowed, or rolled down to add organic matter to the soil. In this application, the crop is a *green manure.*

Cover cropping is a potent BMP for a number of problems. The thick cover reduces runoff and erosion and loss of chemicals in that runoff. The cover crop “sops up” nitrate left over from the last crop to lessen nitrate seepage into groundwater. Cover cropping increases soil organic matter content, lessens weed growth, and suppresses some crop pests. In some areas, the standing mulch protects seedlings from blowing sand, and if a legume, adds nitrogen to the soil.

Intercropping

Intercropping means growing more than one crop at one time in the field for harvest. This was a common traditional practice. The classic Native American example was a field intercropped with corn, beans, and squash. Intercropping systems create diversity in the field and can be quite stable, with crops complementing each other, and a greater guarantee of at least one crop producing if conditions are bad for the others. Intercropping has potential for small-scale agriculture and gardeners—it is a common practice in urban agriculture with a system called Small Plot Intensive (SPIN). One reviewer reported a growing interest in intercropping wheat and soybeans under center pivots in Nebraska. Winter wheat is planted in the fall, followed by soybeans in strips between wheat rows in the spring. The wheat comes off in July, followed in the fall by the beans.

DRYLAND FARMING

The term **dryland farming** is applied to farming in low-rainfall areas without irrigation. In the United States, dryland farming is practiced in states west of a line from western Minnesota to eastern Texas, following the 96th meridian. We will discuss two characteristic dryland farming systems: small grain–summer fallow rotation and rangeland grazing.

Summer Fallow

Many dry areas lack enough water to produce good crops each year. As a result, crop rotation of small grain–summer fallow is commonly used. In the crop year of the rotation, small grains are grown because they are relatively tolerant of low-moisture conditions. After the grain is harvested, soil is left fallow for the next year. More complex systems include a three-year rotation of winter wheat–fallow–sorghum, common on the southern Great Plains.

Summer **fallow** is the practice of leaving the soil crop- and weed-free to store moisture. During the fallow period, weeds are controlled by cultivation or herbicides. By controlling weeds, no moisture is lost from the soil because of transpiration. Some water is lost by evaporation, but not all. After a rain, water seeps into the soil. As soil dries, some moisture moves to the surface by capillary rise, where it evaporates. However, after the surface dries, it seals the rest of the water in the soil. After the next rain, more water is sealed in the soil. Generally about 25 percent of the rainfall on a fallow field will be stored for the following crop. The effectiveness of summer fallow can be improved by reducing runoff (Chapter 8).

Three problems arise from the practice of summer fallow. First, during the fallow year, wind erosion can be quite serious. This problem will be discussed in detail in Chapter 18. Second, crop-fallow rotations lead to a long-term decline in soil organic matter and stress on microbial populations and mycorrhizae, leading to a decline in soil quality. The third problem is the development of **saline seeps**.

Saline seeps appear in almost 2 million acres of the Great Plains of the United States and Canada. Saline seeps appear where glacial till overlays an impermeable layer. During fallow, increased percolation picks up salts and carries them deeper into the soil. When salty water reaches the tight layer, it spreads out sideways, flowing downslope underground. Finally, the salty water seeps to the surface on a lower field. The water evaporates, leaving salt on the soil surface.

Researchers have studied ways to reduce fallow problems by devising annual cropping systems. For instance, in the northern Great Plains about a quarter of the annual precipitation falls as snow—if all this were captured rather than allowed to blow off, it could equal the moisture saved during a fallow year. Studies using tall wheatgrass strips to capture snow have shown improved profitability for annual wheat cropping with reduced problems such as wind erosion.

Rangeland

Range is an uncultivated area used for livestock grazing, particularly in the western United States. **Rangeland** is particularly important because it occupies such a large proportion of the land surface of the United States: up to half may be rangeland ecosystems. Of federally owned lands in the western United States, 85 percent are grazed by livestock. This land provides food and important wildlife habitat.

Grazing is the best agricultural use of range because it is too dry, too rocky, or too infertile for other agricultural uses. Most rangeland, if cultivated, would erode badly. Generally, little is done with rangeland because water shortages make improvement unprofitable.

Care is needed, however, to keep range healthy, profitable, and acceptable as wildlife habitat. A 1994 report by the National Academy of Sciences[2] noted that because range receives few inputs such as irrigation or fertilizer, the health and productivity of rangeland rely heavily on natural processes. That report goes on to say that "Rangeland health should be defined as the degree to which the integrity of the soil and ecological processes of rangeland are sustained." It also defines soil stability and natural nutrient cycles as one of the prime criteria for rangeland health.

Grazing patterns strongly affect soil properties and cover on rangeland (Figure 16–9). Overgrazing leads to degradation of soil quality and numerous environmental problems like pollution-laden runoff.

A North Dakota study compared long-term effects of no, moderate, and heavy grazing on a native mixed-grass range and a fertilized crested wheatgrass plot.[3] The study found that soil was most compacted in the heavily grazed site, and diversity of plant cover was best maintained by moderate grazing. The authors concluded that

Photo by Tim McCabe, USDA Natural Resources Conservation Service

Figure 16–9
Overgrazed range on left in South Dakota suffers soil damage.

[2]National Academy of Sciences. (1994). *Rangeland health: New methods to classify, inventory, and monitor rangelands.* Washington, DC: National Academy Press.

[3]Wienhold, B., Hendrickson, J., & Karn, J. (2001). Pasture management influences on soil properties in the northern Great Plains. *Journal of Soil and Water Conservation, 56*(1), 27–31.

heavy grazing degraded the soil and plant cover resource, while both moderate grazing of native grasses and wheatgrass plots could sustain grazing long term.

SUSTAINABLE AGRICULTURE

Increasing concern for long-term farm productivity and the effect of agricultural practices on the environment led to the concept of **sustainable agriculture**. The American Society of Agronomy in 1989 declared that "a sustainable agriculture is one that, over the long-term, enhances environmental quality and the resource base on which agriculture depends; provides for basic human food and fiber needs; is economically viable; and enhances the quality of life for farmers and society as a whole."

Those who research or practice sustainable agriculture have several concerns. There is concern that agriculture's resource base is being depleted: declining soil productivity due to erosion and loss of organic matter and nutrients; depletion of fertilizer sources such as phosphate rock; and cost and availability of energy. A feared consequence of agriculture is a degraded environment: pollution of water by agricultural chemicals, nutrients, and siltation of waterways. Stability of the farm economy and community further motivates sustainable agriculture.

Sustainable agriculture, then, is a philosophy and collection of practices that seek to protect resources while ensuring adequate productivity. It strives to minimize off-farm inputs such as fertilizers and pesticides and to maximize on-farm resources such as nitrogen fixation by legumes. Top yields are less of a goal than profitable yields based on reduced input costs.

Soil and water management are central components of sustainable agriculture. Techniques include crop rotation, conservation tillage, cover cropping, nutrient management, and others.

Organic Farming

Organic farming is a type of sustainable agriculture that prohibits the use of synthetic substances, including inorganic fertilizers, synthetic pesticides, and biosolids. Organic agriculture stresses managing soil organic matter and soil organisms as a primary goal. By keeping organic matter high, most notably particulate organic matter, soil quality is high and fewer outside inputs are required.

In 1995 the USDA's National Organic Standards Board provided a definition as: "Organic agriculture is an ecological production management system that promotes and enhances biodiversity, biological cycles, and soil biological activity. It is based on minimal use of off-farm inputs and on management practices that restore, maintain and enhance ecological harmony." Buyers of organic products, a rapidly growing market, believe them to be safer or more nutritious or flavorful, or simply support the process of organic growing. Sixty-two million acres of land worldwide are estimated to be under organic production.

Organic growers add nitrogen by the use of manures, composts, legumes, and organic nitrogen fertilizers. Phosphorus and potassium come from manures and mineral fertilizers such as rock phosphate. Organic farms tend to rely more on natural nutrient cycles than do conventional farms. Crop rotations figure centrally in many organic operations. Weed control tends to rely on crop rotation, cultivation, and sometimes flaming or mulches, but remains a challenge for organic growing.

The reliance of organic agriculture on tillage for weed control poses a conundrum. Leaving soil bare is not a good thing for soil quality or preventing erosion. However, mulch-till and ridge-till can allow a certain amount of high-residue cultivation, and are practiced by some organic growers. Other growers employ cover crops to suppress weeds. Efforts are being made to adapt conservation tillage practices, even no-till, to organic growing.

According to a 1980 USDA study, successful organic farms come in all sizes and crops. This and other studies point to soil benefits including reduced erosion, increased soil organic matter content, higher populations of earthworms, richer soil flora, and others. In a 2000 review of studies comparing conventional, sustainable, and organic systems in horticultural crops, their comparative production and profit were highly variable; results depended greatly on the specific sites and practices.[4] Studies comparing product quality of organic versus nonorganic growing, such as nutrient content, antioxidant content, or taste, have been wildly variable. Profitability for organic production tends to rely on the higher prices offered for organic produce.[4] Organic farming may also effectively sequester carbon (see sidebar).

State-sponsored programs to certify organic production have grown in recent years, and in 1990 the Organic Foods Production Act directed the USDA to set up a federal program. The rules set certain production standards; prohibit the use of many substances on organic land, including sewage sludge; and provide a list of allowed and disallowed synthetic materials. The act also sets labeling requirements. These and state standards define what can be sold as certified organic and help the consumer purchase organically grown foods.

Comparing No-Till and Organic Production

A nine-year study by the USDA Agricultural Research Service comparing a minimum-tillage organic system to several standard no-till systems, with or without cover crops, found that the organic system had higher soil carbon and nitrogen than the no-till systems, in spite of tillage. The organic system suffered yield losses due to weed control challenges. Then three years of standard no-till corn followed on all plots, and production was highest in the formerly organic plots, due to a carryover of improved soil quality and higher soil nitrogen. One can conclude that in this study, organic practices were better than standard no-till at sequestering carbon and improving soil quality, but that weed problems limited production. Or one might simply conclude that importing tons of biomass as manure (the organic treatment) raises soil carbon and organic nitrogen over a treatment (the no-till) that received none. This study illustrates the difficulty of crafting and interpreting studies of the organic method.

Source: Teasdale, J., Coffman, C., & Mangum, R. (2007). Potential long-term benefits of no-tillage and organic cropping systems for grain production and soil improvement. *Agronomy Journal, 99,* 1297–1305.

[4]Brumfield, R. (2000). An examination of the economics of sustainable and conventional horticulture. *Hort-Technology, 20,* 687–691.

SUMMARY

Tillage has three goals: weed control, alteration of physical soil conditions, and management of crop residues. Tillage also has a number of side effects, however, especially an increase in erosion, compaction, and reduced soil permeability.

Conventional tillage buries crop residues to produce a smooth, residue-free seedbed. Conservation tillage leaves residues on the soil surface to prevent erosion and preserve soil water. Conservation tillage, particularly no-till, also offers greater potential for storing carbon in the soil as a strategy to reduce greenhouse gases in the atmosphere.

Three cropping systems are used by growers: continuous cropping, crop rotation, and multiple cropping. Continuous cropping (or a simple corn–soybean rotation) allows a farmer to grow the most profitable crops yearly. Crop rotation, on the other hand, is better for the soil and helps control erosion.

In low-rainfall areas, small grains are grown in rotation with summer fallow. During fallow, weeds are controlled by cultivation or weed killers to store moisture for the following crop. Problems with summer fallow include erosion and saline seeps.

Animal grazing is the most practical agricultural use of dry, steep, or rocky land in the West. Controlled grazing, seeding of improved grasses, and sometimes fertilization and water management keep range in good condition.

Organic farming replaces chemical fertilizers and pesticides with crop rotation, manuring, cultivation, mineral fertilizers, and other practices. Organic farmers focus on having a "healthy" soil, and may sequester carbon in their soils. Sustainable agriculture aims to reduce some of the problems of standard agriculture by using techniques that lower off-farm inputs and increase use of resources found on the farm, and the use of BMPs.

REVIEW

1. What is conservation tillage, and what are the criteria for determining whether a practice qualifies as conservation tillage?
2. Compare conservation tillage methods most suitable for areas with soils that tend to be cold and damp in the spring to those that would be warmer and drier.
3. Worldwide, about 95 percent of agricultural ground is still tilled conventionally. What influence do you think widespread adoption of conservation tillage could have on global climate change?
4. Describe the purposes of tillage.
5. After the last cultivation, we plant a fast-growing legume between the rows of a corn crop. What do we call this practice? What might be benefits and drawbacks?
6. Why does summer fallow store some water in the soil for next year's crop? Review the discussion of capillary water movement in Chapter 7 if necessary. How efficient is this practice?
7. Discuss the degree to which rangeland grazing, conventional row-crop agriculture, and organic farming utilize natural nutrient cycles.
8. Would you guess that organic farms consume directly and indirectly less or more energy than conventional ones? Think about fertilizer sources as well as other factors.
9. Using charts in this chapter, estimate the amount of residue left on the soil surface in these three practices:
   a. 150 bushel per acre corn after moldboard plow and discing to 6 inches
   b. 150 bushel per acre corn after a single chisel plow with spear point
   c. 50 bushel per acre soybeans treated as in a and b above

   Which crop leaves the most residue? Which system is likely to have the least erosion?
10. If there came to be widespread removal of crop residues from farm fields as biomass for energy production or other uses, what might be consequences for soil quality and erosion?
11. A number of systems and practices besides conservation tillage were mentioned that increase soil organic matter content and thus improve soil quality and store soil carbon. List them.
12. Nitrate leaching was described in Chapter 15 as a human health problem. This chapter mentioned practices that could decrease or increase nitrate leaching. List them here.

ENRICHMENT ACTIVITIES

1. If you are not already familiar with the tillage tools described in this chapter, visit an equipment dealer to look at them. If you live in an area with different practices than those described here, find materials to study them.
2. Survey and visit local farms to find out what tillage and cropping systems they use.
3. Study organic production certification rules for your state or the rules for the federal program (*Federal Register,* 7 CFR Part 205: National Organic Program; Final Rule. December 21, 2000). Typing "organic certification" and the name of your state into your browser should find information.
4. An organization that promotes sustainable and organic agriculture is the National Sustainable Agriculture Information Service, or ATTRA. Its Web site contains a wealth of information at http://www.attra.ncat.org. For instance, there is an excellent overview of cover crops and green manures at the site.
5. An interesting article on cover crop practices on one research farm can be found in the *Journal of Soil and Water Conservation* (downloadable for a fee at its Web site, http://www.jswconline.org/): Goff, S. (2008). Mixtures and cocktails: Soil is meant to be covered. *Journal of Soil and Water Conservation, 63*(4), 110A–111A.

CHAPTER 17

Horticultural Uses of Soil

TERMS TO KNOW

alkalinity
conductivity meter
media
perched water table
perforation
perlite
stem-girdling root
vermiculite
vertical mulching
xeriscaping

OBJECTIVES

After completing this chapter, you should be able to:

- state how to select soils for horticultural crops
- describe fertilization practices for horticultural crops
- describe how growers manage their soils
- solve the special problems of container soils
- describe how soil influences landscaping

Merriam-Webster's Collegiate Dictionary (11th edition, 2006) defines horticulture as the "science and art of growing fruits, vegetables, flowers, or ornamental plants." While more acreage is devoted to agronomic crops, far more people use soil for horticulture; in fact, almost every citizen does some horticulture, even if only a potted geranium on a balcony. In aggregate, the value of horticultural crops is a major component of the agriculture economy.

The information presented so far in this text about using soils applies to horticultural crops as well as other crops. Let us see how soil is used by growers of different crops, starting with vegetable growers.

VEGETABLE CULTURE

Vegetables are the most important horticultural crop in terms of total value. They make an important contribution to the human diet, supplying starch, fiber, and minerals and vitamins missing in grains and meats. There is also increasing interest in vegetables as a source of antioxidants shown to be important for human health.

Vegetables are grown throughout the United States, but growing areas are concentrated in regions best suited to the economic production of vegetables, such as California.

Soil Selection

Vegetable growers often select a specific soil type that suits the needs of the crop to be grown and the market. Many growers in northern areas choose coarse soils because they warm up rapidly in the spring, allowing early planting and early harvest when prices are best. In general, vegetable growers favor coarser soils than do other farmers. Following are the soil types and their uses:

- Coarse-textured soils are best for early crop growth, especially for cool-season crops such as lettuce or carrots. Several crops, such as melons, grow best on sandy loams. For best yields, these soils are usually irrigated.
- Medium-textured soils are good for all crops. Where yields are more important than early harvest, medium soils are better than coarse ones.
- Fine-textured soils are less desirable for vegetables. They tend to stay wet too long, hampering field operations, and crusting can inhibit germination of fine seeds. Heavy soils are very poor for root crops.
- Organic soils, especially mucks, are favorites for cool-season and root crops such as carrots, onions, and celery.

Soils selected for growing vegetables should be loose, friable, and high in humus. For most crops, a slightly acid soil is best (except for potatoes, which suffer less disease between pH 4.8 and 5.4). Many vegetables are also sensitive to high soil salts.

The most essential factor for success is good drainage. Poorly drained soil warms up slowly and cannot be planted early. Vegetable crops keep their quality for a very short time after they are ready for harvest. Thus, they must be picked regardless of soil conditions. In this case, growers cannot afford a muddy soil. Vegetable growing also calls for relatively flat land because the soil can be unprotected from erosion, for reasons described below.

Soil Management

Growers of agronomic crops such as corn seek to maximize *productivity* by covering the soil with as many light-energy-gathering plants as possible. A dense plant cover (at least later in the season) protects soil from erosion and produces crop residues to maintain soil organic matter and reduce erosion by conservation tillage. Growers of vegetable crops seek product *quality* by spacing plants further apart. Soil is less protected by plant canopy, fewer residues remain after harvest, and there is less filling of the soil volume with dense root systems that can absorb excess nitrates. Thus vegetable growing presents challenges for protecting the soil, maintaining organic matter content, and controlling nitrate leaching.

Vegetable growers could alleviate these problems by using conservation tillage. However, many vegetable seed and transplant planters do not handle high residue levels well. Furthermore, vegetable growers often strive for early harvest when prices are most favorable. Cooler, moister soils of conservation tillage delay planting and slow crop development. While vegetable growers have been slow to adopt conservation tillage, its use has been increasing with such practices as chisel plowing. Cover cropping also offers potential, and its use has grown widely. Cover crops are an important Best Management Practice (BMP) for reducing nitrate leaching and enhancing soil quality.

Most commonly, vegetable growers moldboard plow and harrow their fields to plant. Commonly, growers plant on raised beds. Such beds improve drainage and, because the soil is warmer, promote rapid early growth. The loosened, deeper rooting zone that beds provide is also ideal for a well-formed root crop.

Another common practice is growing warm-season vegetables such as tomato or cantaloupe on black plastic mulch (Figure 4–17). This warms the soil, which speeds growth and increases production for warmth-loving crops. This may be accompanied by the use of soil sterilization chemicals (see Chapter 5) to control nematodes, root rots, and weeds.

Fertilization

Vegetable growers experience a wide range of nutrient problems unfamiliar to most farmers. Plant nutrition presents problems because of the unusual needs of many vegetables and the sandy and muck soils they are often grown in. Calcium deficiencies are common because the immobile element fails to reach the edible part in sufficient amounts. Tip burn on cauliflower (Figure 17–1), blossom end rot on tomatoes, cracked stems in celery, and others result. Thus fertilization with secondary and trace elements is common in vegetable production.

In general, growers feed vegetable crops by the same methods as those described in Chapter 14. One difference is the use of starter solutions on vegetable transplants. Crops such as tomatoes and peppers are transplanted into the field rather than seeded. Transplanting equipment has a tank to hold a weak fertilizer solution that soaks the planting hole of each plant as it is transplanted. Starter solutions are high in phosphate in order to overcome phosphate immobility and stimulate rapid rooting. Starter fertilizers typically have ratios of 1-2-1.

Courtesy of Carl Rosen, University of Minnesota

Figure 17–1
Tip burn on cauliflower resulting from a calcium deficiency. Vegetables are prone to a variety of nutritional problems less common on agronomic crops, and product quality in an overriding concern.

FRUIT CULTURE

Fruits are important in the human diet because they are rich in vitamins, particularly ones missing from many other foods, and because they are a rich source of antioxidants.

Unlike most crops, fruits are usually long-lived woody plants that remain in place for many years; this influences their soil management.

Soil Selection

Fruit trees require a deep, well-drained soil to thrive at all. Shallow soils cannot support a tree crop during dry periods, unless irrigation is provided. Soils with a high water table also restrict the deep rooting of fruit trees. In poorly drained soils, fruit trees may experience a serious health decline as soil-borne fungi attack weakened roots.

Fruit plants tolerate a wide pH range. The recommended pH range is 6.0–6.5, because it suits both the fruit plant and any cover crops that may be grown with the fruit. Blueberries, however, need a pH of 4.3–4.8.

Some fruits are clean-cultivated to remove competition from weeds and sod. These crops must be grown on fairly level ground that is unlikely to erode, unless a slope is terraced. Others, such as apples, may be grown on sod, and can be grown on steeper land.

Fruits also tolerate a wide range of soil textures. Apples and pears do best on moderately fine-textured soils, whereas stone fruits, such as plums and peaches, prefer a coarser texture. Grapes grow on any soil, but the sweetest grapes are grown on sandy or gravelly soil. Berry plants do best on moderately coarse soil.

Soil Management

All fruit crops are perennials and occupy the same ground for many years. Therefore, the soil must be properly prepared before planting—there is no way to try again without a major financial loss. The site should be carefully selected. Any major soil changes such as terracing, drainage, or leveling should be completed. On the basis of soil test results, potash, phosphate, and lime are broadcast and plowed into the soil.

A common soil management tool is the use of permanent sod or cover crops in row middles (Figure 17–2). Frequent clean cultivation of some crops means a loss of organic matter and tilth, diminished soil quality, and erosion. Leaving soil bare under the plants by cultivation or herbicides reduces competition from sod and weeds, while sodded middles protect soil from erosion and preserve the soil quality of most of the land. Growers also often mulch under or between rows of many crops such as strawberries, blueberries, and dwarf apples.

In some crops, long-term presence of the same plants can cause a buildup of soil pests such as nematodes or other problems. This can cause a decline of the crop or problems replanting when the orchard is renovated. Various solutions may be available, such as pest-resistant rootstocks.

Photo by Gary Kramer, USDA Natural Resources Conservation Service

Figure 17–2

Cover cropping in a California orchard. In the row, vegetation is controlled to reduce competition with the trees, but covering the row middles with sod or cover crops reduces erosion and preserves soil quality.

Fertilization

Nitrogen is the most important nutrient for the established fruit crop. However, excess nitrogen compared to potassium and others can cause poor fruiting, poor fruit quality, and late ripening. In addition, many fruits are sensitive to low levels of trace elements. Soil testing avoids these difficulties. Because of the deep rooting of many fruit crops, soils must be tested deeper than in common farm crops. In addition, tissue testing is a particularly valuable practice in fruit growing.

Established fruit plantings are typically fertilized by topdressing in the fall or early spring, depending on the crop and the region. Trace elements may be mixed into the base fertilizer, or in many cases are applied by foliar feeding with chelated elements. In some cases, liming or acidifying the soil solves micronutrient problems.

NURSERY FIELD CULTURE

Soil management is a constant challenge for the nursery grower. The very process of growing nursery stock is very hard on the soil. Soil is usually clean-cultivated, and the only crop residues are a few leaves. Topsoil itself is dug up and hauled away when trees and evergreens are balled and burlapped. For example, using figures for root ball sizes from the American Standards for Nursery Stock and average soil bulk densities, it can be determined that digging up an acre of five-year-old evergreens removes 165 tons of soil.

Site Selection

Soil is one of several factors to consider in selecting a nursery site. The land should be level, so that erosion can be controlled. Sloping land may be used if it is terraced and rows are planted across the slope. It should be well drained because wet soils seriously hamper nursery operations; indeed, wet soil can mean a major loss during the short digging season. A pH between 5.5 and 6.5 is preferred for most nursery crops.

Soil texture is an important concern for nursery crops. Plants to be harvested bare root (soil shaken off the roots) should be grown on sandy or sandy loam soil. Coarse soils most easily shake off plant roots without damaging them. In nurseries where stock is balled and burlapped by hand (soil ball stays on roots), finer-textured soils are better. Soils high in sand do not stick together, so it is hard to dig up an intact soil ball in sandy soils. Silt loam or clay loam soils are best for balling and burlapping. Using machines to dig soil balls allows a wider range of soil textures.

Soil Management

Nurseries, perhaps more than any other operation, need to make a serious effort to maintain organic matter levels. It is typical to rotate nursery crops with green manure. Hybrid sorghum–sudan grass, alfalfa, or other vegetation is used to build the soil. Many growers apply animal manures, composts, and/or sewage sludge. A few growers plant cover crops between nursery rows or mulch in the rows with chopped hay or wood chips. Some growers are beginning to sod row middles (Figure 17–3); interestingly, the sod provides just enough competition to moderate growth on some trees that tend to grow uncontrollably in clean-cultivated nurseries. Cover crops can

Image courtesy of Ed Plaster

Figure 17–3
Nursery soils are usually bare and exposed to rainfall. Little organic matter returns to the soil from the crop. Here, in this Minnesota nursery, sodded row middles help preserve soil quality and reduce erosion. Growers usually also rotate nursery crops and cover crops to build the soil.

Crop	lb N/1000 Ft^2	lb N/acre
Deciduous plants	5	225
Narrowleaf evergreens	4	175
Broadleaf evergreens	3	125

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Figure 17–4
Sample guidelines for fertilizing nursery stock. One should follow local guidelines.

also be used as a "living mulch," such as by planting winter rye in early fall, then killing it with herbicides the following spring as trees begin to grow.

Fertilization

Before planting nursery stock, a soil sample should be taken from the top 2 feet of soil. On the basis of soil test results, the correct amount of potash, phosphate, and lime (or sulfur if the soil pH is too high for acid-loving crops) is mixed into the soil. Each year thereafter, high-nitrogen fertilizers with ratios of 4-1-2 or 3-1-1 may be top-dressed in fall or spring. Figure 17–4 suggest how much nitrogen should be applied.

CONTAINER GROWING

One of the most demanding ways to grow a plant is to grow it in a pot. A containerized plant requires constant attention to watering, fertilizing, and other practices. Despite this, more and more plants are being grown in containers. Not only are greenhouse growers growing flowers in pots (Figure 17–5), more and more nurseries grow shrubs, evergreens, and trees in containers. Landscaping the interiors of buildings means potted plants, and increasingly cities adorn their streets with large

Image courtesy of Ed Plaster

Figure 17–5
A school greenhouse in Minnesota. Growing plants in containers, like the hanging baskets and pots here, challenges the grower.

hanging baskets and container gardens. Apartment dwellers and even homeowners now garden in containers.

The container grower has complete control over soil conditions, making it easier to grow a large, uniform crop of quality plants. Growing plants in containers differs from growing plants in the ground in one key way: the plant's root system is confined to a small soil volume that must supply all the plant's water and nutrient needs. This means the container grower waters and fertilizes far more than those who till the ground.

This section examines four major topics: the special nature of potting mixes, the related practices of fertilization and irrigation, soil temperature in potted plants, and water pollution issues. While many potting mixes, called **media**, contain no soil at all, they still answer to the same chemical and physical properties of regular soil, even if special challenges are presented.

Potting Mixes

A pot of soil is by nature poorly drained because of the shallow soil profile and its lack of capillary connection to lower layers of soil. That is, compared to soil in the field, there is a very short column of water to "push" water further down by gravity, and no connection to deeper soil to "pull" water down by capillarity. In spite of drainage holes, a layer of soil in the bottom of the pot remains saturated after drainage ceases, which keeps soil in the rest of the pot wet and oxygen availability low. This layer is a **perched water table** (Figure 17–6). Because the effect relates to water column depth, the shallower the pot, the more severe the problem. A 6-inch pot may have an air-filled porosity of 20 percent, while a 2-inch pot might have only 2 percent after watering.

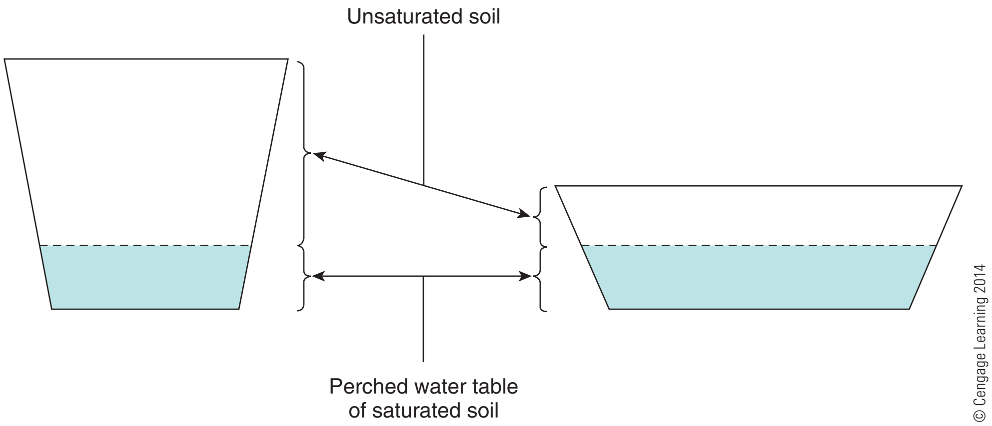

Figure 17–6
A perched water table in a pot causes drainage problems, especially in shallow pots. Highly porous amended potting mixes are needed.

The key to making well-aerated potting mixes is to use large particles to create large pore space. Large pores will be less able to hold water against gravity, improving drainage. This may involve amending regular soil with large amounts of amendment or omitting soil to create a soilless potting mix. These amendments include inorganic materials such as coarse sand, **perlite** (large granules of light weight expanded volcanic glass), **vermiculite** (expanded mica), shredded plastics, or other materials.

Organic amendments also occur in most potting mixes, most commonly shredded sphagnum peat. However, peat harvest involves mining Histosols (Figure 6–12) and damaging the ecosystems growing on them, as well as releasing carbon dioxide into the atmosphere. Peat shortages have also plagued the greenhouse industry. Increasingly, growers replace peat with organic waste products such as composted rice hulls, fine coconut fiber (*coir*), composted bark chips, or composted municipal waste. Many of these materials confer desirable physical properties on the mix while reducing harvest pressure on peat bogs and consuming what is otherwise waste. Many greenhouses also compost their own organic waste stream and use the resulting product in their potting mixes.

In general, a suitable potting mix has a total porosity of 50 percent to 80 percent, much higher than field soils; an air-filled porosity of 10 percent to 30 percent; an available water-holding capacity of 25 percent to 35 percent; and a bulk density of only 0.19–0.7 gram per cubic centimeter. These mixes are far less heavy than field soil.

If a soil mix contains true soil, soil-inhabiting organisms can threaten the life of a container plant. These include several types of seed- and root-rotting fungi. For that reason, greenhouse growers sterilize or pasteurize soil-based mixes using heat, steam, or chemicals. To pasteurize soil means to heat it enough to kill pathogens but not destroy all organisms. Growers also use strict sanitation and fungicides to prevent infections by soil organisms. The industry now also makes use of beneficial organisms that suppress disease organisms, and there are potting mixes commercially available that contain such beneficial fungi and bacteria.

Watering and Fertilizing

The above discussion of potting mixes concentrated on *physical properties.* While *chemical properties* of a potting mix have a starting point depending on components of the mix, they change rapidly in response to watering and fertilization. Again, this change is far more rapid and marked than in field soils. Potting mixes lack colloids such as clay, so are poorly buffered against chemical change. Furthermore, large quantities of water and fertilizer are poured through small soil volumes, exaggerating their chemical effects.

Two chemical traits of water can be of concern. Water contains soluble salts, which build up to high levels in the mix. Growers must be aware of the salt content of their water, and in extreme cases, treat water to remove salts. Growers commonly water with a bit of excess water, about 15 percent, to leach out salt buildup.

Water may also contain high levels of dissolved lime, in particular, bicarbonates (HCO_3^-). While most folks call this sort of water "hard water," growers say it has high **alkalinity**. In this usage of the word, we speak not of high pH, but of high bicarbonate content. Bicarbonate, as a base, reacts with hydrogen ions, removing them from the soil (reverse reaction *b,* Chapter 11), and rapidly raising soil pH. Growers using alkaline water customarily inject acid into the water supply to neutralize the bicarbonate ion. Other growers may have water of such low alkalinity ("soft water") that it leaches lime out of the mix and drops the pH. Such growers counteract with suspensions of lime or dissolved potassium bicarbonate.

Fertilizers themselves are salts, so fertilization also raises soil salinity. High rates of fertilization with inadequate leaching easily damage plant roots. Fertilization mistakes appear rapidly: a malfunctioning fertilizer injector can quickly cause nutrient starvation because of underfertilization or damage because of high soluble salts. In addition, rising ammonium levels become toxic to plant roots when cool, low-light conditions reduce conversion of ammonium to nitrate by nitrification.

Nitrogen fertilizers also change pH. Ammonium fertilizers depress soil pH, while nitrate fertilizers slowly raise soil pH. These effects may counteract or augment pH effects of the grower's water. Thus, soil pH results from complex interactions of the potting mix itself, the fertilizer used, and the water supply.

Crops grown in containers are fussy about pH. For most crops, a pH of around 6.0–6.2 works well, though some prefer lower pH, and others higher. A simple rule deserves to be memorized: low pH creates micronutrient toxicities, most often iron, while high pH creates micronutrient deficiencies.

Needless to say, all this means that container growers must constantly monitor their soil chemistry and adjust. Many growers perform weekly in-house testing of pH and electrical conductivity (Figure 13–11) with pH and **conductivity meters**. Electrical conductivity (EC) measures the soil salinity to reveal salinity problems and to infer fertilizer levels. In-house testing is augmented with frequent complete lab tests of all nutrients, nitrates, ammonium, and pH. Some growers also test plant tissue for additional information.

Fertilizers formulated for container use differ from field fertilizers. Generally they contain a more complete list of macro- and micronutrients. Container mixes favor nitrogen in the nitrate form, unlike field fertilizers, which tend to contain more ammonium nitrogen. Particularly in the winter in northern climates, ammonium becomes toxic because conditions slow nitrification; very low ammonium feeds are required. Most greenhouse growers follow a low-phosphorus regimen to reduce the stretching that phosphorus causes. Many feeds use a ratio like 4-1-4 so potash is roughly equivalent to nitrogen and phosphorus is much lower.

Container fertilizers must also be highly water soluble, which excludes some common materials such as superphosphate. Container fertilization relies on fertigation during regular watering. There has been an increasing trend toward incorporating slow-release fertilizers, especially in container nurseries, to control losses of nutrients into the environment.

Soil Temperature

Plants growing above the ground in dark-colored containers, especially when exposed to hot sunlight, suffer large swings in soil temperature that can damage roots.

More severe is the difficulty of overwintering containerized plants in cold climates. Plant roots are less hardy than plant tops, and a potted root system exposed to

Fertilizer Injectors and Greenhouse Fertilization

Most greenhouses fertilize using water-soluble fertilizers injected into the irrigation water. Fertilization rates in fertigation are measured as parts per million (ppm) of nutrient. Most commonly we measure nitrogen, and use fertilizers that have ratios that will bring along the desired levels of P and K. Fertilization rates range from a low of about 50 ppm N for tender, sensitive seedlings to as high as 400 ppm for heavy feeders. Actual rates depend on the crop, the stage of growth, and the frequency of fertilization. Commonly, growers fertilize lightly with every watering, a practice called *continuous feed*. Greenhouse growers may also inject acids to neutralize water alkalinity.

A device called a fertilizer injector (Figure 14–3) pulls concentrated fertilizer out of a stock tank and mixes it into the irrigation water. Injectors dilute at different rates; 1:100 is common. This would dilute stock solution by a factor of 100, so the stock solution must be 100 times more concentrated than the recommended fertilization rate. Put another way, 1 gallon of stock would be injected into 100 gallons of water as it passes through the hose or irrigation system.

If one uses a bag of premade fertilizer product from a manufacturer, the label may tell you how much to use. Lacking that, the amount of fertilizer can be calculated. If one is measuring for nitrogen, one can calculate ounces of fertilizer per gallon of stock by multiplying the desired concentration of nitrogen in ppm times the injection ratio of the injector, then dividing that by the product of 75 times the percent nitrogen in the raw fertilizer. If we want 150 ppm N from a 20-5-20 run through a 1:100 injector, then

$$\textbf{Ounces fertilizer} = (150 \times 100)/(75 \times 20) = \textbf{10 ounces per gallon stock}$$

The accuracy of the injector—as well as calculations and measurements—should be determined by collecting a sample of the resulting irrigation water and testing it for electrical conductivity (EC). Measure EC with an EC meter (Figure 13–9), then subtract the EC of the clear, plain water (measured separately). Each fertilizer product has an expected conductivity for different concentrations; this number may be on the bag or can be obtained from the manufacturer. Compare the expected EC with the actual EC and adjust the meter or the stock solution as needed.

Most states regulate fertigation. Make sure you know and follow regulations concerning back-flow prevention devices, licensure, inspections, and the like.

subzero temperatures will be damaged. Northern nurseries must protect container plants over winter by covering them with straw or some protective structure. Similarly, landscape plants in containers, such as urns by the doorstep or trees in planters on city streets, experience the same freezing. Northern gardeners and landscapers should use only the root-hardiest plants for this purpose or plant only annuals that do not need to survive the winter. Insulating a container may also be helpful.

Water Pollution

The public is concerned about water pollution; this issue strongly affects container nurseries and greenhouses. For example, many container nurseries have pots sitting on the ground fertilized through overhead sprinklers. Most of this water—as much as 70 percent—lands between, rather than in, the pots. Because a container field is watered and fertilized daily, the potential for water pollution is great.

One answer, where feasible, is to use drip or microspray irrigation (Figure 17–7). Little water or nutrients are wasted this way. Second, greater use of slow-release fertilizers added to the pots reduces or even replaces the amounts added to irrigation water. Third, pots should be set on a sealed surface that stops leaching into the soil and the land surface graded so that water runs off into sealed holding ponds, from where it can be pumped for reuse.

Greenhouses also face issues with nutrient pollution, compounded by the need to leach salts when watering. One solution developed in recent years is flood irrigation, when benches are flooded, the plants watered from below by capillarity, then the water is captured and recycled for further use. No water lands on the greenhouse floor, nor does it splash on leaves, reducing disease problems. Careful water and nutrient management can also reduce the need for heavy leaching.

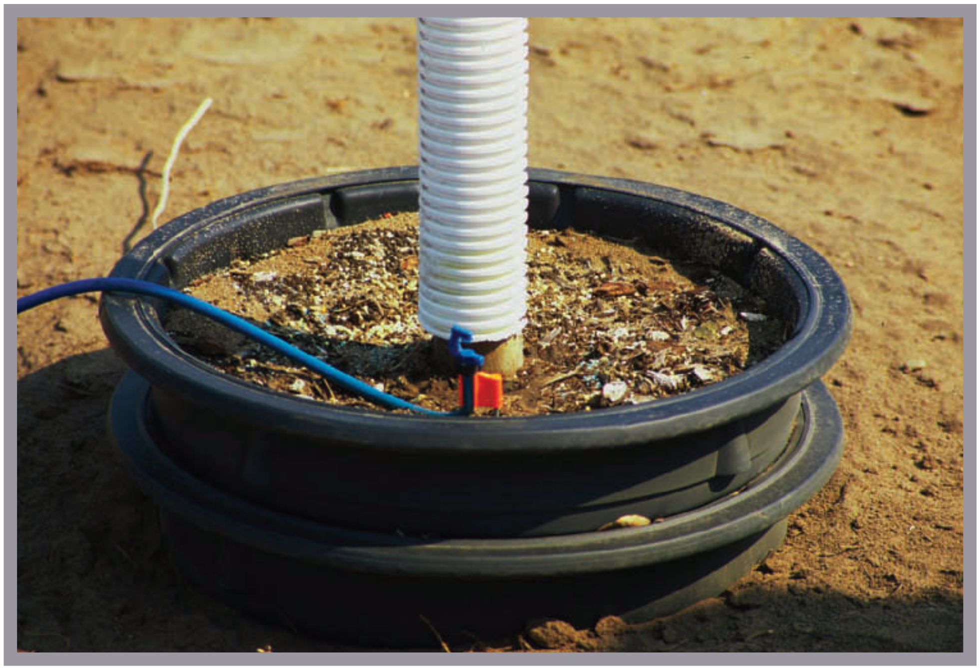

Image courtesy of Ed Plaster

Figure 17–7

Microirrigation on pot-in-pot tree production in a Minnesota nursery. Notice this irrigation puts water only in the pot and does not water nearby soil or weeds.

LANDSCAPING

Landscaping, like the grounds in Tucson shown in Figure 17–8, makes our surroundings more beautiful and more livable. Landscapers must know about soil so that landscape plants will remain healthy, attractive, and easy to care for. But most of all, they should consider landscaping as the set of tools we use to sustain soil and water resources in urban areas.

Most transplanted shrubs and trees survive—yet many fail to thrive, and too many actually die. Some have estimated that the average life of a new urban tree is less than 10 years (Figure 17–9). These failures cost money in replacements and damaged customer relations. Often building contractors are responsible, sometimes homeowners fail to provide proper care, and other times a landscape professional is at fault.

When plants fail to thrive, more often than not, roots hold the answer. More than most, landscapers must understand how soils, roots, and water interact. Landscape soils are complex compared to field soils because they are radically altered by construction and landscaping. Soils of different textures are placed together, and as Chapter 7 points out, that affects water movement.

A *sustainable* landscape is one that thrives for long periods of time without excessive water or fertilizer inputs, that protects soil and water, that is gentle to its surroundings, and that requires minimal maintenance. Now let us see how our knowledge of soil can help us understand proper landscape practices.

Site and Plant Selection

Mismatches between plants and site lead to unhealthy plants and endless maintenance. Landscape designers should know which plants grow well in their area and

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Figure 17–8
A landscape near Tucson, Arizona. This attractive landscape illustrates several of the practices of xeriscaping.

Image courtesy of Ed Plaster

Figure 17–9

Die-back on a downtown tree in St. Paul, Minnesota. Soil problems contribute to the problems of such trees.

select plants that match soil drainage, pH, salinity, and degree of compaction on the landscape site. Appendix 5 lists soil preferences for selected trees.

A thorough designer will take the trouble to examine the soil on a site. A soil survey can provide preliminary data. Salinity and pH can be checked with a soil test or portable testing device. Compaction can be checked with a penetrometer or by seeing how hard it is to shove a screwdriver into the ground, taking soil type and moisture into account. Soil color provides guidance on drainage, or a very simple, crude percolation test can be done. A foot-deep hole is filled with water, and after it drains empty, filled again. Drainage can be inferred from the amount of water that drains in an hour. Experience makes these simple tests most valid.

Avoiding Compaction

Most landscape sites are slightly to severely compacted during construction. Compaction causes shallow root systems. Often, roots from deep in the planting hole actually grow upward along the sides of the hole toward the surface, rather than outward into the surrounding soil. Failure to explore the native soil results in drought damage, nutrient shortages, and poor anchorage.

Ideally, after construction (Figure 4–14) the soil should be ripped deeply to break up compaction, large amounts of compost incorporated, and tilled to prepare a yard

Image courtesy of Ed Plaster

Figure 17–10
Stem girdling roots in a tree in the author's yard from being planted too deep (not by the author!). The large crossing root and lack of any natural flare at the base of the trunk are sure signs. The tree is under stress, but has value in its location so is pampered to keep it going.

for planting. In practice, a yard is rarely so thoroughly prepared, and landscapers often work in yards that have been compacted for some time. Where possible, landscapers should complete the work of preparing the soil, or at least avoid adding to compaction while working. Landscapers who drive on a site with trucks full of rock mulch only compound the problem. Landscapers should especially take care with wet, fine-textured soils.

While no method exists to completely relieve compaction in established landscapes, techniques are available that can be helpful. In **vertical mulching**, many holes are drilled in the ground and filled with organic matter or coarse material like sand. This allows some movement of air and moisture into the root zone of trees. Devices have also been developed to inject air or water into the soil under very high pressure, fracturing compacted soil. The fractures are then filled with a coarse material. The long-term effectiveness of these treatments has not yet been fully determined, though a tree-care firm known to the author reports good results.

Deep Planting

Work at the University of Minnesota has uncovered long-term problems associated with deeply planted trees. Trees planted too deep often fail because roots are deprived of oxygen, but those that survive face a longer-term problem called **stem-girdling r oots**. When planted too deep, even by a few inches, tree roots often develop in ways that cause some to grow across the stem (Figure 17–10). As the tree ages, those roots prevent proper development of the trunk and compress the tree's vascular system. Eventually the tree begins to weaken and die. More dramatically, the tree may snap off at the soil line in high winds. Stem-girdling roots can be avoided by planting trees at the proper depth, and ensuring that planting stock does not come out of the nursery already too deep in a soil ball or pot.

Transplanting

The key to successful transplanting is rapid root growth. After all, for plants dug out of a field nursery, most of the root system is lost. Even containerized stock must grow new roots quickly because it cannot survive on just the soil mass it was planted with. How do landscapers ensure that the roots of newly planted trees and shrubs will grow quickly?

For a start, the best practice is to dig a hole three times as wide as the root system with sloping sides. This provides loose soil the roots can easily grow into initially, especially in clay or compacted soils. The hole should be dug no deeper than the depth of the root system to avoid settling and consequent deep planting.

Research shows that plastic mulch, formerly used in shrub beds to keep out weeds, restricts root growth by keeping oxygen out of the soil. Organic mulches, such as wood chips or pine straw (Figure 5–13), keep down weeds and conserve moisture without robbing the soil of oxygen. Below the wood chips, one could place landscape fabric rather than plastic sheeting. This woven material is porous, allowing movement of air and moisture but restricting weed growth. The mulch should never be piled too deeply; 3 or 4 inches is adequate without restricting aeration.

There is disagreement over the need for fertilization of newly planted trees and shrubs. Some experts claim little need; the author, however, has observed that plants being held for sale often appear depleted by frequent watering without fertilization. The author supports light fertilization with a complete slow-release fertilizer at the time of planting if the soil tests low in nutrients.

There has been increasing interest in inoculating plants with mycorrhizae before planting them. This may improve transplant success and later plant growth. Preparations of inoculum are now available, but experimental results are mixed.

Amending Soil pH

All too often, the native pH of a soil is not proper for every plant one wants to use. Obviously, this calls for designers and others to check for pH, an easy enough task with a soil test or even a piece of pH paper. Once the pH is known, a designer can make informed plant selections.

Nevertheless, there are times when soil pH should be altered. Because many landscape plants prefer acid soil, acidification is common. One common suggestion for acid-loving plants is to dig an especially large planting hole and then put sphagnum peat moss (half by volume) into the backfill. This helps temporarily, but as the peat decays, the pH returns to normal. The author generally recommends sulfur in addition to the peat, as in Figure 11–19. While these procedures work well for small areas like a shrub bed, one is rather challenged to amend the whole root zone of a long-lived tree permanently, and one best selects a tree proper to the native pH.

Landscapers should be aware of the many sources of lime that can raise pH in a landscape site, including lime in a concrete foundation, limestone rock mulches, and alkaline irrigation water. Annual use of acid-forming fertilizers such as ammonium sulfate or special acid preparations may maintain acidity. Sulfur-coated urea, a slow-release fertilizer, will also enhance soil acidity.

Trees that do begin to suffer chlorosis may be treated by sulfur spread over the soil surface. While this changes the pH of only the top inch or so (and that slowly), there may be enough roots there to provide adequate iron for the whole tree. Sulfur may also be placed deeper into soil using a system similar to that shown in Figure 17–12 for fertilizer. However, this and other treatments do not always work well. Foliar feeding with chelated trace elements can provide a temporary green-up in some cases. One may also use devices that inject trace elements into the trunk or root flare, but drilling holes in the trunk may be risky to tree health.

Fertilizing Trees

Experts disagree on the value of fertilizing landscape trees and shrubs, because there is so much variation between different trees and sites that experimental evidence is mixed. It is generally agreed that young, growing trees benefit from fertilization. Some feel that older, established trees benefit little except to relieve an actual deficiency, and that, in fact, fertilizing mature trees might create its own stresses. Stressed trees should be fertilized only lightly because fertilizers may add to stress by increasing soil salinity or by supplying nitrogen the tree cannot handle. Nevertheless, fertilizing trees remains a common practice.

Timing strongly affects landscape plant response to fertilization. Traditionally, fall fertilization has been held to be ideal because nutrients would be absorbed by roots and available in the plant for growth the following spring. Some research indicates trees absorb nutrients more efficiently when in leaf, favoring fertilization early in the growing season. Since plants take up nutrients best when growing actively, this seems sensible.

Nitrogen is the most important element for trees. To understand how to fertilize trees, one must first know where tree roots are (Figure 17–11). Trees may root deeply, but 80 percent of a tree's feeder roots are in the top foot of soil. These feeder roots reach far from the trunk of the tree.

Trees may be fertilized by broadcasting a high-nitrogen fertilizer (e.g., a ratio of 2-1-1) over the root system (though recent research suggests fertilization to the drip line should be adequate) at a rate of about 3 pounds nitrogen per 1,000 square feet.

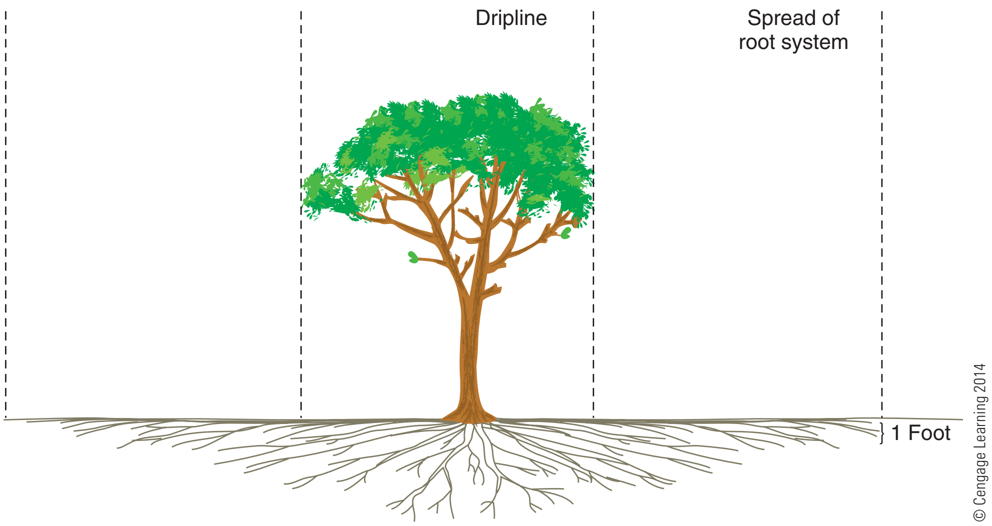


Figure 17–11
Tree roots cover a very large area and extend well beyond the dripline of the tree. Most feeder roots grow in the top foot of soil.

If the shade trees grow in the lawn, split the fertilizer into a fall and spring application. While this works fine for nitrogen, another method called **perforation** inserts phosphorus and potassium into the root zone. The fertilizer is split among many 8- to 12-inch-deep holes drilled into the rooting zone of the tree on 24-inch centers, as shown in Figure 17–12. Liquid fertilizer can also be injected into the soil with special devices in a similar pattern. Details on these practices are available from numerous sources.

Turf

Except in arid regions, turf is the most common element of a landscape. Turf not only looks nice, but also protects the ground from erosion and provides a playing surface. Turf may be planted by seed, sod, or, in some cases, sprigs and plugs. Whatever method, good soil preparation is important to success.

Many turf specialists no longer recommend covering the existing soil with "black dirt" before planting turf because the interface is a problem. If any is added, it should be tilled into the existing soil to avoid the sharp interface. It is highly beneficial to till a 2-inch or deeper layer of compost into the soil.

Chemical amendments should be tilled into the soil before planting, based on good soil tests. Phosphorus should be added now because of its immobility and importance for good root growth and turf spread. Potassium, which promotes good wear tolerance and resistance to disease, drought, and cold, also would be best incorporated now. Lime or sulfur may also be incorporated to adjust pH to 6–7. After

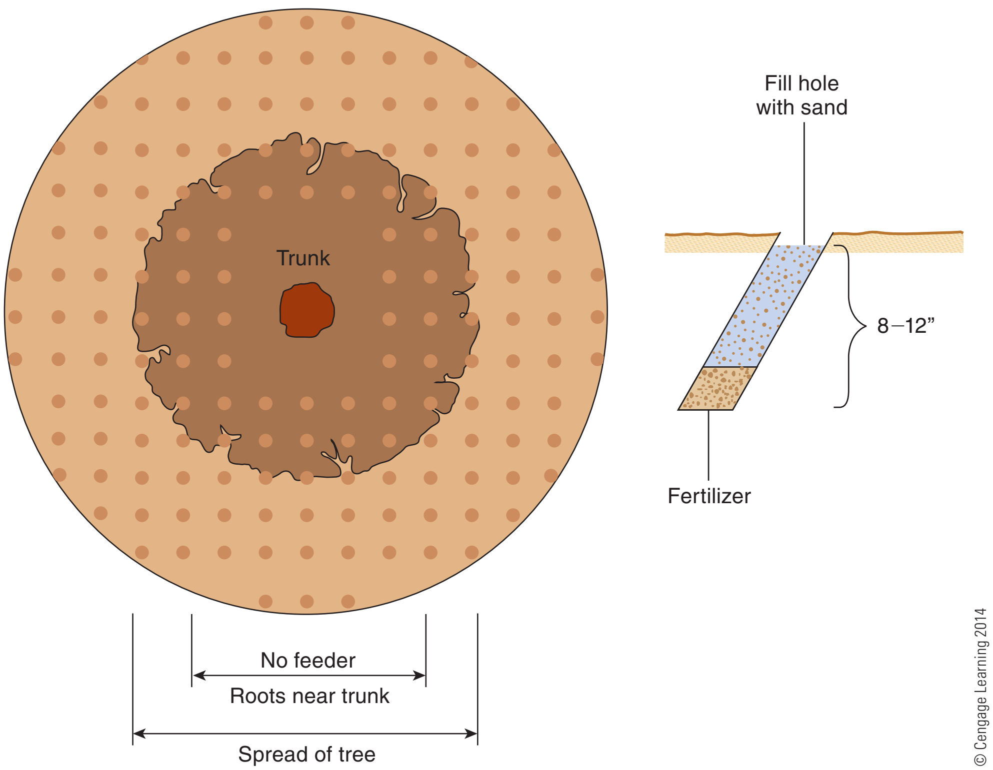


Figure 17–12
Fertilizing trees by perforation. The recommended amount of fertilizer is divided between a number of holes drilled in a grid pattern. Perforation is useful for getting phosphate and potash into the root zone. Recent work has suggested that fertilizing to the dripline may be satisfactory.

soil is tilled to incorporate amendments and to loosen the soil, it is carefully raked or harrowed to make a fine seedbed free of bumps or pits. Turf may then be planted by seed, sod, or sprigs, according to local practice. Frequent irrigation is needed while the turf is being established.

Turf is fed by broadcasting a high-nitrogen fertilizer. Often a fertilizer with a ratio of 20-1-3 is suggested, but seek out local recommendations. Fertilizers with high water-insoluble nitrogen (WIN) content are best. In areas where soil salinity is a problem, turf fertilizers should be of low salinity, and care must be taken to avoid overfertilization.

Fertilizer recommendations vary widely depending on the region of the country, the type of turfgrass, the level of maintenance, and the use of the turf. The annual rate of nitrogen application varies from as little as 1 pound nitrogen per 1,000 square feet for low-input, low-maintenance turf with tolerant turf types to as much as 6 pounds. The larger amounts are split into several applications—often spring, early fall, and late fall. Fertilizer will be taken up most efficiently when the turf is growing actively.

There has been concern that nitrates may leach into the groundwater below turf, or that phosphates will run off into surface waters and induce eutrophication. There is good evidence that turf roots are very efficient at scavenging nitrates out of the soil, and phosphates tend to tie up in the thatch. Properly applied fertilizers at moderate rates, following soil testing, should not create serious problems, but one cannot assume no problems. In the author's home state, lake homes with turf planted to the shore have been implicated in declining water quality. Because of concern over phosphorus pollution, the state now bans phosphorus in lawn fertilizers except in starter fertilizers or with a soil test indicating need. This trend is spreading to other states as well. One should take care to sweep up fertilizers and clippings that fall on surfaces such as sidewalks.

Core aeration (Figures 17–13 and 17–14) is a most useful turf soil management practice. To aerate, a machine, preferably one with hollow tines, creates small pits in the lawn. This breaks up compaction, increases aeration, and improves water infiltration. Aerate when the soil is moist and turf is growing actively. While this aeration is shallow, it improves that all-important top 3 inches.

Image courtesy of Ed Plaster

Figure 17–14
More golf course aeration. This type removes soil cores and leaves them on the surface. They may be raked into the sod as a topdressing. This type is preferred for many applications.

Courtesy of Deep Tine, LLC

Figure 17–13
Aerating turf on a golf course. This type punches holes in the sod, and here, sand is raked into the holes to modify the root zone. Aeration relieves compaction and improves aeration and water infiltration.

For season-long green color, irrigation of turf is usually needed. One expert suggests adding about an inch of water when 30 percent to 50 percent of the lawn shows signs of water stress—a slight rolling of the older leaf blades. Some grasses can be allowed to go dormant in a dry season, but excessive dryness can damage turf.

Some landowners prefer to reduce or even eliminate turf as being unecological and polluting, replacing it with native vegetation like prairies. LEED certification favors replacing turf with native plants. This is a topic beyond the scope of this text, but a couple of words are worthwhile. The nutrient and watering needs of wild native plants differ from those of turf. For instance, fertilization of prairie plants only encourages weeds, since they respond more to nitrogen than do prairie plants. Students interested in such an approach to landscaping should study the topic carefully.

Xeriscaping

Landscapers—and their customers—of the more arid regions of the United States face the problem of water shortages. The problem has been dramatically compounded by the planting of landscapes adapted to the more moist eastern and northern states and high population growth in arid parts of the country. Climate models suggest many of these areas will become even drier (at the time of this writing, Texas and some other states were suffering a record extended drought). An answer to excess water use is xeriscaping (from the Greek word *xeros,* or dry). **Xeriscaping** is landscaping adapted to dry climates. Some of its methods can also be adapted to less arid places to reduce water use.

A major component of xeriscaping is plant selection. A wide range of plants are available that thrive under low-moisture conditions. The most dramatic of these include cacti, succulents, and yuccas (Figure 17–8). However, xeriscaping need not mean only a mixture of sand and cacti. A number of shrubs, trees, and flowers can tolerate dryness, such as palo verde (*Cercidium* sp.) and several salvias (*Salvia* sp.). Some short-grass prairie grasses can be grown for lawn with minimal watering, such as blue gramma grass, the state grass of Colorado.

Wide spacing of the plants is a second component. By spacing plants farther apart, they compete less for water and each plant has a larger water collection area devoted to its use. In this, xeriscaping mimics natural plant distribution in desert areas.

Last, the xeric landscape strives to conserve irrigation water. Precision landscape irrigation—precisely designed and managed irrigation systems—can reduce water usage. Replacing turf, which must be uniformly irrigated, with woody and herbaceous plants that can be watered with microirrigation lowers water usage, as does reducing plant populations. Nonpotable water sources such as sewage effluent or home “greywater” from appliances are also being adopted in some uses. Care must be taken with the elevated salinity and other chemicals such water contains. Finally, some plants can be replaced with paving, boulders, or other hard features that use no water.

Xeriscapes may not always function as planned. In 16 months of monitoring water use in Phoenix, Arizona, one study found that homeowner study subjects applied *more* water to xeriscapes than to conventional landscapes.[1] These results suggest that there may be some challenge to making xeriscapes successful.

[1]Peterson, K., Stabler, L., & Martin, C. (2000, January). *Irrigation application volumes in urban residential landscapes.* Symposium on Central Arizona–Phoenix Long Term Ecological Research, Arizona State University, Phoenix, AZ.

SUMMARY

This chapter discussed how soils are managed to grow fruits, vegetables, ornamentals, and landscape plants. An irrigated, coarse soil allows early production of vegetables, while a medium soil gives the best production. Vegetable soils must be well drained. Many growers make good use of animal and green manures to make up for the small amount of organic matter most vegetable crops produce.

Fruits and field nurseries need a deep, well-drained soil. Clean-cultivated fruits and nurseries need level land and close attention to erosion control. Because crops stay in the ground for many years, land must be carefully prepared before planting, including drainage, terracing, irrigation installation, leveling, and plowing lime and nutrients into the soil. In the years after planting, nitrogen is the most important nutrient. Maintenance of soil organic matter is a challenge for these growers.

Pots drain poorly because the soil column ends at the bottom of the pot. To overcome this, potting mixes are very porous and consist of coarse aggregates such as sand, an organic material such as peat moss, and sometimes soil. Soil-based mixes must be sterilized by heat or chemicals to kill weed seeds and soil pathogens.

For landscape plantings to grow well, the soil must be handled properly. Plants are chosen that will thrive in the soil on a landscape site. Landscapers must be aware of the effects that textural interfaces have on the movement of water and the growth of roots. Proper soil preparation for planting turf and good transplant practices are needed for healthy plants. Fertilizing established turf and trees also keeps them growing well. Xeriscaping is landscaping adapted to dry climates.

Chapter 19 of this text contains information related to this chapter.

REVIEW

1. Why is preliminary soil testing and preparation even more important for fruit crops than for most other crops? What are examples of preparations?
2. Why are vegetables often grown on sandier soils in northern states? Provide a full explanation.
3. Why is nursery culture hard on soil? What practices do nurseries use to compensate?
4. Gardeners often put a layer of gravel in the bottom of a pot to improve drainage. Does it? Explain your answer. *Hint:* Keep the problem of interfaces and soil column depth in mind.
5. Why is it critical for health of plants growing in containers that there be drain holes in the pots?
6. We plant a tree in heavy clay soil. To make sure it does not fall over, we bury a few inches of the stem. To make it easier to water, we leave a deep depression under the tree. What are possible consequences of such actions?
7. As a landscape designer, you like balsam fir (*Abies balsamea*). What kind of soils should be avoided? What soil tests might you ask for to evaluate a yard for suitability for balsam fir? See Appendix 5.
8. Describe a soil we would consider good for both a home landscape and a nursery. See Appendix 4.
9. What are elements of a xeriscape that help save water?
10. It is generally held that when watering a houseplant, one waters until about 15 percent of the water runs out the drain holes at the bottom of the pot. If there is a tray under the pot, the excess should be disposed of. Explain why. Would it matter if distilled water were used?
11. A case study: In 2002, the author's home state (the Land of 10,000 Lakes) passed a law restricting phosphorus in lawn fertilizers to preserve water quality. Describe the problem of phosphorus in surface water. Knowing what you have learned in your soils class, and following an Internet search on "lawn fertilizer and phosphorus," write a paragraph about your reaction to this ordinance.
12. You want to mix 20 gallons of fertilizer stock solution for a 1:100 injector to fertilize greenhouse chrysanthemums at the rate of 300 ppm. You are using a 17-5-17 fertilizer. How much fertilizer will you add to the stock tank? How would you check that your results are correct?

ENRICHMENT ACTIVITIES

1. This little experiment demonstrates the effect of the depth of a soil column on drainage. Soak a common rectangular kitchen sponge until it is saturated. Hold it in the air horizontally (shortest dimension vertical) and watch it drain. Now hold it with the second longest dimension vertical. Observe further drainage. Then hold the longest dimension vertical. What happens? One might quantify this experiment by taking weight measurements.
2. Check out numerous sites about xeriscaping on the Internet. Compare several sites and judge them on reliability. Are they from a knowledgeable source? What is the authority or what are the credentials of each source? Do they seem to have a biased viewpoint? How old is each site?
3. Repeat Chapter 3, Enrichment Activity 6. This time, using charts in the soil survey, create a color-coded map of soil suitability for purposes of landscaping, nursery culture, or other horticultural use.
4. Using a county soil survey, select a soil you think would be excellent for growing vegetable crops. Explain your reasoning.
5. The University of Tennessee has a fact sheet on lawn fertilization at https://utextension.tennessee.edu/publications/documents/PB1038.pdf. Tennessee is in the transition between the turf zones of the northern states and the southern states, and its fertilization information reflects that.

CHAPTER 18

Soil Conservation

TERMS TO KNOW

concentrated flow
conservation buffer
contour buffer strip
contour tillage
cross-wind ridge
cross-wind trap strip
diversion
ephemeral gully
erosion index (EI)
filter strip
grassed waterway
gully erosion
Revised Universal Soil Loss Equation (RUSLE)
rill erosion
riparian buffer
saltation
sheet erosion
splash erosion
strip-cropping
surface creep
suspension
Universal Soil Loss Equation (USLE)
Wind Erosion Equation (WEQ)

OBJECTIVES

After completing this chapter, you should be able to:

- list the effects of soil erosion
- describe how soil erosion occurs
- list the types of water and wind erosion
- calculate soil loss from water erosion on a field
- describe ways to prevent erosion
- discuss climate change and erosion

Natural erosion has always shaped the earth's surface (Figure 2–10). However, human-induced erosion created by agriculture far exceeds geologic rates. Data published in early 2007 revealed that worldwide, humans cause erosion at a rate 10 to 15 times faster than natural geologic processes, and estimated global erosion at 75 *billion* tons of soil per year.

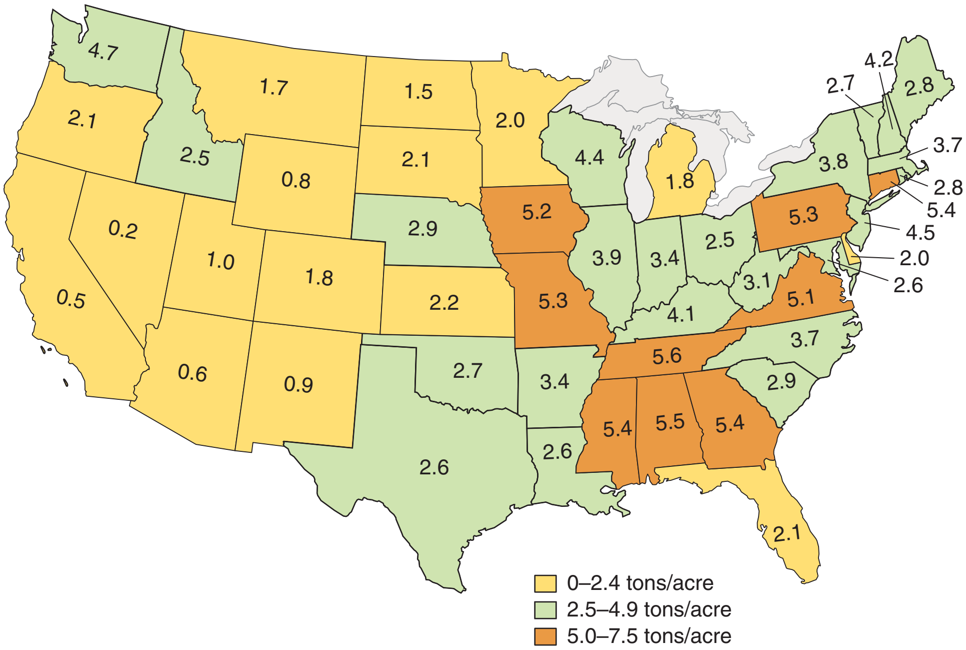
Each year about 1.7 billion tons of soil wash or blow from farmlands of the United States. This quantity is equivalent to losing the full plow layer from 2 million acres of farmland. Most of the loss—almost a billion tons—results from water erosion. The remaining 0.7 billion ton is lost to wind erosion. These numbers actually reveal progress in combating erosion: Total erosion in 1982 was over 3 billion tons, and prior to the conservation efforts that began in the 1930s, erosion was far worse than that.

Soil scientists follow the rule of thumb that 1 acre of land can afford to lose at most 1–5 tons of soil each year. The average soil loss to water erosion on cropland is thought be about 3.8 tons per acre per year, close to the limit. Added to this amount, however, is an average soil loss of 2.5 tons per acre per year to wind erosion (Figure 18–1). About 21 percent of American cultivated cropland suffers soil losses greater than the acceptable limit for water erosion. Figure 18–2 shows where water erosion takes place in the United States.

	Sheet and Rill Erosion 1982	Sheet and Rill Erosion 2007	Wind Erosion (tons/acre/yr) 1982	Wind Erosion (tons/acre/yr) 2007
Cultivated cropland	4.4	3.8	3.6	2.5
Pastureland	1.0	0.8	0.1	0.1

Based on data from USDA, 2007 National Resource Inventory

Figure 18–1
Estimated average annual loss of topsoil in tons per acre to erosion in nonfederal lands of the United States.



Based on data from USDA, 2007 National Resource Inventory

Figure 18–2
Average annual sheet and rill erosion by state on nonfederal cultivated land in tons per acre.

Erosion data are from the National Resources Inventories (NRIs) conducted by the United States Department of Agriculture (USDA) in 1982, 1987, 1992, 1997, 2003, and 2007. As shown in Figure 18–1, erosion has slowed somewhat during those years.

Some decline in erosion rates was certainly due to a voluntary increase in erosion control practices, especially conservation tillage. Some was due to conservation compliance measures required of growers by recent farm bills for participation in other USDA programs. Much improvement is attributed to removal of over 33 million acres of highly erodible land from cultivation, entered into the Conservation Reserve Program begun in 1985. Chapter 20 describes these programs in greater detail.

CONSEQUENCES OF EROSION

What damage is caused by this amount of erosion? Some of the damage occurs on a grower's fields; this is considered on-site damage. Some occurs elsewhere; this is off-site damage. Examples of on-site damage include these:

- Erosion removes topsoil. Topsoil affords the best root environment by providing the best structure, the most air, and an active population of organisms. Once topsoil is lost, only the less productive subsoil remains.

- Topsoil contains most of the soil's organic matter and plant nutrients. Erosion carries away nitrogen, phosphorus, and any nutrient stored mostly in organic matter. Large amounts of fertilizer paid for and applied by the grower are wasted.
- Erosion selectively removes organic matter and the finer soil particles responsible for cation exchange.
- Erosion thins the soil profile, decreasing the root zone. This is a particular problem on already shallow soils.
- Thinning topsoil and declining organic matter greatly reduces total plant-available water in the root zone. This has been considered the most serious effect of erosion on productivity.
- Decline in soil structure stability and increased compaction.
- Gullies cut up fields into odd-shaped pieces and make it very difficult to operate farm equipment.

Examples of off-site problems include these:

- Eroded soil contains nutrients and pesticides that pollute lakes and streams. For instance, large fish kills have occurred in streams fed by runoff water from fields treated with soil insecticides.
- Soil particles entering bodies of water reduce water clarity (Figure 18–3), impairing habitat quality for aquatic organisms and recreational value.
- Soil washed away by erosion settles in streams, lakes, harbors, and reservoirs. The sediment fills in lakes and reservoirs (Figure 18–4), creating a need for expensive dredging. It reduces the ability of streams to carry water, resulting in an increase in flooding.

In some places, progress in controlling sedimentation losses from fields has been sufficient that much of the sediment carried by rivers comes from the river itself. That is, the rivers, free of the heavy sediment load coming off the land, are downcutting into the sediments deposited earlier by poor agricultural practices and carrying it away. Riverbank erosion has also increased in some instances. Until the rivers clear their channels of earlier sediments, we may continue to experience sedimentation in some reservoirs.

Cost of Erosion

It is only fairly recently that data have become available (such as NRIs) to attach values to the cost of erosion. There are actually two separate sets of costs: (1) costs to the farmer and consumer of production losses, and (2) costs to the public and environment of pollution and sedimentation.

Productivity losses to the grower remain difficult to pin down precisely and are not usually severe in the short term but accumulate over time. In a 1994 Indiana study[1] of soybeans, yield losses varied between 17 percent and 24 percent on a severely eroded soil phase compared to a slightly eroded phase of the same soil. The authors impute this loss primarily to loss of available water and nutrients.

[1]Weesies, G., et al. (1994). Effect of soil erosion on crop yield in Indiana: Results of a 10-year study. *Journal of Soil and Water Conservation, 49,* 597–600.

Figure 18–3

Sediment-laden runoff flows into a Tennessee lake. Water quality is seriously impaired.

Figure 18–4

Sediments flowing into lakes and reservoirs can fill them in. One end of this lake in Iowa shows the effects.

Estimates of total productivity losses in the United States vary widely. Crosson[2] estimated a value of $40 million per year; other estimates vary between $83 million[3] all the way up to a value of $27 billion.[4]

Off-site damage estimates for the nation as a whole also vary widely and may be greater than for on-site values. Estimates range from $3.1 billion[2] to $17 billion[4] per year. Dredging costs alone were estimated in 2002 to be about $257 million per year in the United States.[5]

The nation has been battling erosion since the 1930s, and progress has been made in recent years. Yet it remains a major problem, and climate change promises to challenge the progress we have made. It is important for all soil users to understand erosion and the technologies for reducing it. We begin with water erosion.

WATER EROSION

On cultivated land, water erodes more soil than wind. Even in dry climates, occasional high-intensity storms can move a lot of soil off land thinly protected by vegetation. To understand how to protect soil, we need to understand the process of water erosion and the factors involved.

The Process of Water Erosion

Erosion follows three steps. First, the impact of raindrops shatters surface aggregates and loosens soil particles (Figure 18–5). Some of these particles float into soil voids, sealing the soil surface so that water cannot readily infiltrate the soil. Water ponds on the soil surface, then begins to move, flowing over the soil surface down any slope. The scouring action of running water also detaches some soil particles. Second, detached soil grains move in flowing water and are carried down slopes. As it flows downslope, water may collect in channels, increasing its erosive power. Finally, soil is deposited when the water slows down. These three steps are known as detachment, transport, and deposition (Figure 18–6). Detachment is the main task of raindrop impact, and transport primarily of flowing water, especially in channels.

Erosion occurs when the precipitation rate exceeds soil's infiltration rate. Water then ponds on the soil surface and is free to run downslope when there are no obstacles to overland flow.

Erosion is a form of work, and work takes energy. The energy for water erosion comes from the energy of a falling raindrops or running water. The amount of energy in a moving object is the product of the mass of the object and its velocity (speed) squared. Expressed as an equation

$$E = \frac{1}{2}mv^2$$

[2]Crosson, P. (1994). New perspectives on soil conservation policy. *Journal of Soil and Water Conservation, 39,* 222–225.

[3]Den Biggelar, C., et al. (2001). Impact of soil erosion on crop yields in North America. *Advances in Agronomy, 72*(1), 1–52.

[4]Pimental, D., et al. (1995). Environmental and economic costs of soil erosion and conservation benefits. *Science, 267,* 1117–1123.

[5]Hansen, L., et al. (2002). The cost of soil erosion to downstream navigation. *Journal of Soil and Water Conservation, 54,* 205–212.

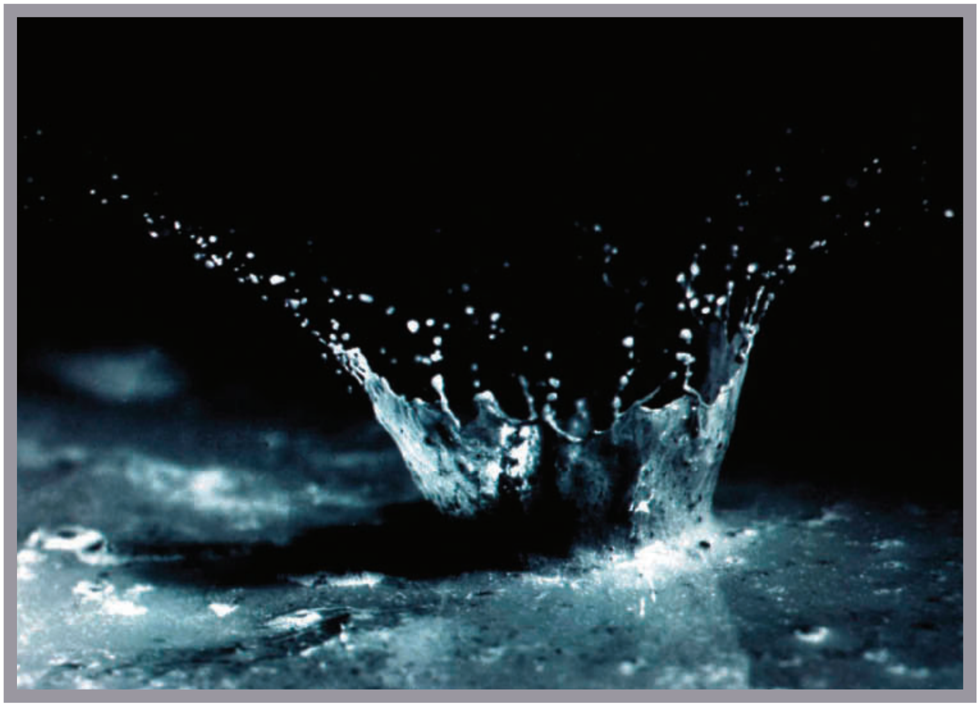


Photo courtesy of USDA Natural Resources Conservation Service

Figure 18–5

Soil erosion begins when raindrops dislodge soil particles.

Photo by Lynn Betts, USDA Natural Resources Conservation Service

Figure 18–6

Erosion, transport, and sedimentation are visible in this Iowa field. Sheet erosion is visible in the background.

The energy of a falling raindrop relates to its size and especially to its speed. A 2-inch-per-hour rainfall has the same energy as a 1-pound object falling 47 feet onto 1 square foot of soil. The erosive energy of running water depends on its volume and speed of flow.

With high erosive energy, water can detach and move more and larger soil particles. Thus, erosive energy relates directly to the amount of soil carried off a field. Deposition occurs when the energy of running water decreases—such as when it slows down at the foot of a slope. This energy concept will help in the understanding of five erosion factors: (1) rainfall erosivity, (2) soil texture and structure, (3) slope, (4) soil cover, and (5) roughness of soil surface.

Rainfall Erosivity

The erosive potential of a rainfall event is a function of rainfall volume and intensity. Volume is the total rainfall that lands in a single event, measured in total millimeters. Intensity is a measure of how fast rain falls, usually in units of millimeters per hour. The faster the rain falls and the longer the rain lasts, the greater will be the erosive potential of the rainfall, and the greater will be the erosion. In many locations, most erosion occurs during occasional severe rainfall events. Readers may have noticed an increased frequency of such events as climate changes.

Texture and Structure

Texture has two effects on soil erosion. First, texture influences the infiltration rate of water. If rainwater infiltrates soil quickly, there is less ponding and less water runoff. With a lower volume of running water, less soil can be transported. Second, particles of different sizes vary in how easily they can be detached. Silt particles are most easily detached, so silty soils are liable to water erosion.

Structure also influences infiltration—good structural grades like granules reduce runoff. The strength and stability of soil aggregates is important too, because strong peds better resist raindrop impact. Because of the importance of organic matter to structure, soil organic matter content has a strong bearing on erodibility. Compaction, loss of organic matter, and destruction of soil peds by tillage all reduce infiltration and increase the volume of water available to transport eroded soil. The combined effects of organic matter content, texture, and structure are called the erodibility of a soil.

Slope

Slope has two components—length and grade. On a steep slope, water achieves a high runoff velocity, increasing its erosive energy. On a long slope, a greater surface area is collecting water, increasing flow volume. On a longer slope, running water can also pick up speed. Figure 18–7 shows that long, gentle slopes can have the same erosive potential as short, steep slopes.

Surface Roughness

A rough soil surface impedes downhill flow of water, slowing its velocity. If roughness takes the form of ridges across a slope, water ponds behind the ridges, decreasing the volume of runoff water. However, if enough water collects behind a ridge, it overflows and wears it away. Thus, roughness can fail to stop erosion during very heavy rains, on long slopes, or if sealing of the soil surface stops infiltration.

Slope (percent)	Slope Length (feet)
4	1,000
6	200
8	100
10	50
12	30
14	20

Figure 18–7
Both slope grade and length affect soil loss. All slopes listed here have equivalent soil loss.

Figure 18–8
Tillage can create surface roughness that impedes downhill flow of water, but tillage up and down the slope creates channels for accelerated water flow, as in this Iowa field.

Surface roughness depends largely on tillage practices. The seedbed resulting from conventional tillage is smooth, while that from chisel plowing is rough. Tillage across slopes acts to impede downhill flow; tillage up and down the slope promotes downhill flow (Figure 18–8).

Soil Cover

Bare soil is fully exposed to the erosive forces of raindrop impact and the scouring of running water. Soil cover reduces energy available to cause erosion. A mulch or cover of crop residues absorbs the energy of a falling raindrop, lessens detachment, and reduces sealing of the soil surface. Mulches also slow down runoff water. A complete crop cover such as turf or hay has the same effect, plus plant roots hold soil in place (Figure 18–9).

Crops that are less close growing, such as row crops or nursery stock, have a different effect. As these crops close in between the rows, they form a canopy over the

Photo by Lynn Betts, USDA Natural Resources Conservation Service

Figure 18–9

Slope planted to native switchgrass (*Panicum virgatum*) on an Iowa field. Highly erodible land is most safely protected by permanent vegetation. It also creates wildlife habitat.

soil. This canopy intercepts rainfall and absorbs much of its impact. When water drips off plant leaves, it again gains velocity and thus energy. The energy of these drops depends on the height of the crop canopy but is not as great as free-falling raindrops. Thus, it is important for erosion control that crops cover the soil surface as quickly and completely as possible. Unlike mulches, crop canopies have no effect on runoff speed or volume, so have a less protective effect.

Types of Water Erosion

A raindrop strikes the soil surface forcefully. The impact shatters soil aggregates and throws soil grains into the air. On a slope, water begins to flow downhill, carrying detached soil grains with it. This water joins other flowing water, increasing in speed, volume, and soil-carrying capacity. This order of events leads to five types of erosion. All five types can occur at the same time on any given slope.

- **Splash erosion** is the direct movement of soil by splashing. A soil grain can be thrown as far as 5 feet by raindrop splash.
- **Sheet erosion** is the removal of a thin layer of soil in a sheet. On gentle slopes, or near the tops of steeper slopes, water moves in tiny streams too small to be noticed. This gives the impression of losing soil in a thin sheet. Sheet erosion appears in the background of Figure 18–6. Sheet erosion may go unnoticed until the subsoil appears.
- **Rill erosion** is visible as a series of many small channels on a slope. Water tends to collect in channels, picking up energy as it runs down the slope. As a result, running water carves out small but visible channels called *rills.* A rill is small enough to be filled in by tillage. Figure 18–10 shows rill erosion in the background.

Figure 18–10
Severe soil erosion on a wheat field in the Palouse region of Washington state. Rill erosion is visible in the background, ephemeral gully in the foreground.

- **Ephemeral gullies** are large rills. The channel is small enough that tillage equipment can cross it and largely, but not completely, fill it in by tillage. During another heavy rainfall, water will collect in the old channel, and erosion will begin here. Each rain will wash away any soil thrown into the ephemeral gully by tillage, so soil from a wider area will be lost. The foreground of Figure 18–10 shows an ephemeral gully.
- **Gully erosion** is the most highly visible erosion. Gullies are so large that equipment cannot cross them (Figure 18–11). Gullies are typified by pronounced head cuts and collapsing sides, visible in the figure. Gullies usually begin to form near the bottom of a slope or on steep slopes, where running water has enough force to carve a deep channel. Gully heads may back up the hill as water running into the gully collapses the head cuts and sides.

Each type of erosion is important to understand for different reasons. Sheet erosion is a hidden soil loss, because there are no visible signs until the subsoil appears. Rill erosion can also be hidden, because each tillage causes the rills to disappear. The amount of the hidden erosion can be easily underestimated by a grower.

Ephemeral and gully erosion together result from a form of water movement called **concentrated flow**, in which water concentrates in channels. These channels focus erosive energy, increasing the ability to carry soil off field. Concentrated flow reduces the effectiveness of many of the conservation tools described here, such as filter strips, and accounts for a large proportion of sediments leaving fields.


Photo by Lynn Betts, USDA Natural Resources Conservation Service

Figure 18–11
Gully erosion in Iowa. Gullies increase in size as the sides collapse inward during severe storm events or spring runoff.

Predicting Soil Loss: The Universal Soil Loss Equation

Using the soil-loss factors described, an equation has been developed to predict the average soil loss from sheet and rill erosion on a specific site. The Universal Soil Loss Equation (USLE) was developed over several years from some 10,000 plot-years data from 49 test sites around the country (Figure 18–12). A conservationist can use this equation to decide what conservation practices are needed to keep soil losses within acceptable levels.

The USLE does have weaknesses. The equation predicts sheet and rill erosion only. If a slope shows signs of ephemeral or gully erosion, results from the equation will understate soil loss. The equation predicts average soil loss over time. A single, highly erosive rainfall may cause far more erosion than is predicted by the equation. Nor does the USLE provide an accurate estimate of soil losses from snowmelt runoff. Also, applications to some crops, rangeland, and to farmland in some parts of the country have not been fully reliable.

Tolerable Soil Loss

At the heart of the USLE is the assumption that a certain soil loss can be tolerated because soil-forming processes replace lost soil. The equation can then be used to determine if soil loss exceeds this amount. In virgin grasslands, erosion may amount to an inch every 5,000 years or about 3 pounds per acre per year. In the Palouse area of the Pacific Northwest, erosion levels sometimes reach 50–100 tons per acre per year (Figure 18–10). This is a loss of an inch of soil every one and a half to two years. Between these two extremes, what soil loss can be tolerated?

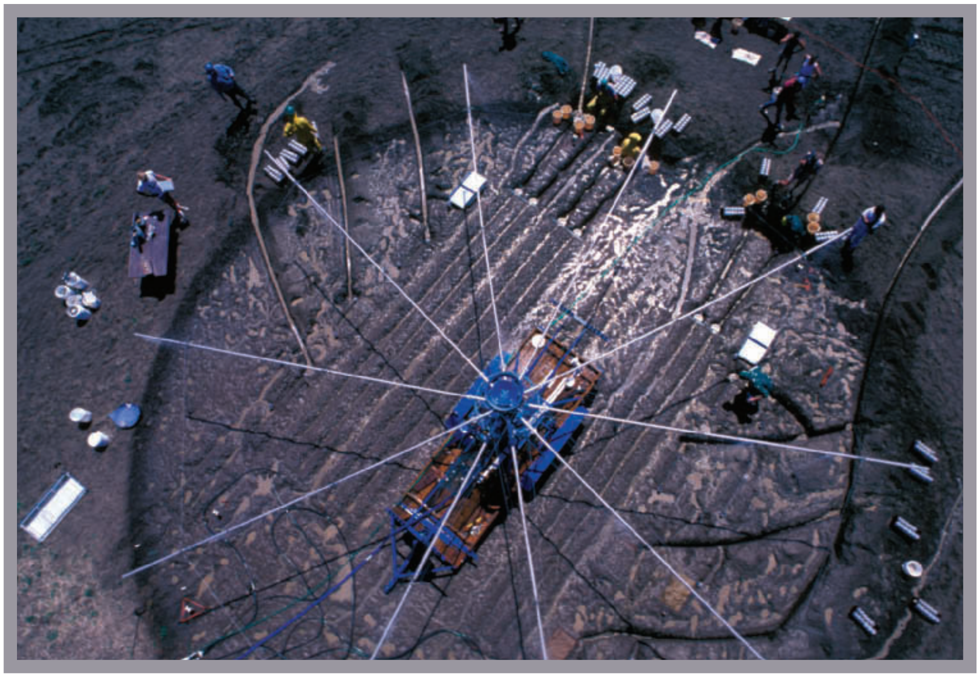


Photo by Tim McCabe, USDA Agricultural Research Service

Figure 18–12
Rainfall simulator in South Dakota. Such devices are used in research on soil erosion.

Soil scientists have decided that soil losses between 1 ton and 5 tons per acre per year can be tolerated, depending on quality and depth of a soil. It is assumed that erosion damages a deep soil least. The amount that can be tolerated is symbolized by the letter *T.* Each soil series has its own value of *T,* which is noted on a soil survey report. However, *T* certainly exceeds normal soil-formation rates. That is, even at *T,* soil is being lost more rapidly than it is being replaced, so many soil scientists maintain that *T* is not a sustainable loss over the long term and not a reliable guide to the need for erosion control measures.

The Equation

The USLE is based on a standard test plot representing an average eroded site. This plot has a 9 percent slope 72.6 feet long. The slope is kept in clean-tilled fallow, using conventional tillage up and down the slope. The equation works by comparing a specific spot to this test plot.

The equation reads as follows:

$$A = R\,K\,LS\,C\,P$$

A is the tons of soil lost per acre each year. Obviously, *A* should be less than *T.* To solve for *A,* values are inserted for the six variables and are multiplied. The variables are as follows:

- *R*—rainfall and runoff factor. *R* is based on total erosive power of storms during an average year. *R* depends on local weather conditions. The isoerodent map of Figure 18–13 shows *R* values for the United States.

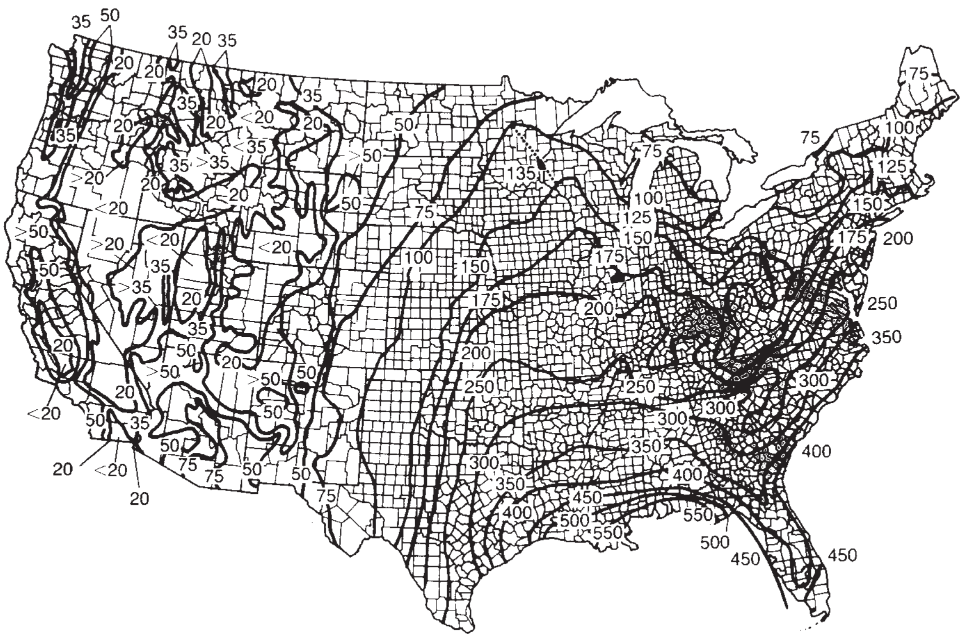


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Figure 18–13
The isoerodant map gives the average yearly values of the rainfall erosion index, factor *R*. Climate change is no doubt altering these values. The dotted line is used in examples in the text.

- *K*—soil erodibility factor. *K* depends on texture, structure, and organic matter content. Soil survey reports give the value of *K* for mapped soils. They may also be calculated.
- *LS*—slope factor. *L* compares slope length and *S* compares grade with the standard plot. *L* and *S* are separate factors, but they can be treated as one variable, *LS*. *LS* values can be determined from the chart in Figure 18–14.
- *C*—cover and management factor. *C* compares cropping practices, residue management, and soil cover to the standard clean-fallow plot. *C* values are calculated from detailed tables and are valid only within the area for which they are calculated. Natural Resources Conservation Service (NRCS) offices prepare simplified tables for use in the field, and some have computerized the computations. Figure 18–15 is a sample of such a table, and is included here for use in the solution of USLE problems presented in this text. If necessary, values can be calculated.
- *P*—support practice factor. *P* compares the effect of contour tillage and contour strip-cropping with the test plot. Figures 18–16 and 18–17 give *P* values.

Sample Solution

Let us try a sample solution for a field with the following characteristics. Assume that we measure a slope of 5.5 percent that is 100 feet long. According to the soil survey for this area, $K = 0.18$ and $T = 5.0$. Assume the grower uses conventional tillage to grow continuous corn and plows up and down the slope in the fall. The farm is in east-central Minnesota—the county is shaded on the isoerodent map. We begin with the formula:

$$A = R\,K\,LS\,C\,P$$

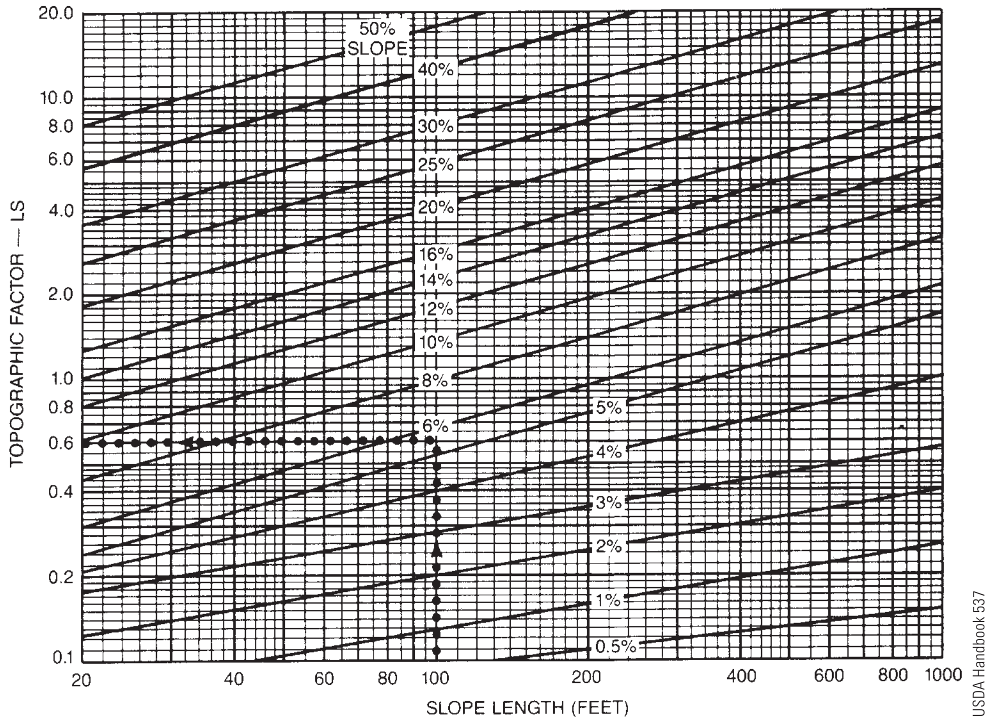

Figure 18–14

The slope effect chart provides the LS factor used in the USLE. The dotted lines refer to a sample problem in the text.

	Conventional Plowing		Conservation Tillage		
Crop Sequence	Fall	Spring	30%	40%	50%
Continuous soybeans	0.48	0.45	0.30	0.24	0.20
Corn, soybeans	0.41	0.37	0.24	0.19	0.16
Continuous corn	0.37	0.36	0.19	0.15	0.12
C, SB, SG	0.32	0.29	0.17	0.14	0.11
C, C, SG	0.30	0.27	0.14	0.12	0.09
C, SB, C, O, M, M	0.20	0.18	0.12	0.11	0.09
C, C, C, O, M, M	0.17	0.15	0.10	0.09	0.08
C, C, O, M, M, M	0.11	0.10	0.08	0.07	0.06
Permanent grass	0.003–0.013				
Grazed forest	0.01–0.04				
Ungrazed forest	0.001–0.003				

USDA, NRCS Minnesota Office

Figure 18–15

Some crop management factors for southern Minnesota. These numbers apply to the averages of crop rotations using corn (C), soybeans (SB), small grains (SG), oats (O), and meadow (M). The percentages are residue cover.

The value of R is read from the isoerodent map. Since the farm location does not lie on a curve, draw a line between the two curves it lies between and estimate the value of its place on that line (see Figure 18–13). In this case, $R = 135$:

$$A = (135)\ K\ LS\ C\ P$$

Land Slope (percent)	*P* Value	Maximum Slope Length (feet)
1–2	0.60	400
3–5	0.50	300
6–8	0.50	200
9–12	0.60	120
13–16	0.70	80
17–20	0.80	60
21–25	0.90	50

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Figure 18–16

Support practice factor *P* for fields that are contour tilled. The figures are unreliable if slopes are longer than indicated.

Land Slope (percent)	*P* Value			Strip Width (feet)	Maximum Slope Length (feet)
	A	*B*	*C*		
1–2	0.30	0.45	0.60	130	800
3–5	0.25	0.38	0.50	100	600
6–8	0.25	0.38	0.50	100	400
9–12	0.30	0.45	0.60	80	240
13–16	0.35	0.52	0.70	80	160
17–20	0.40	0.60	0.80	60	120
21–25	0.45	0.68	0.90	50	100

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Figure 18–17

Sample support practice factors for contour strip-cropping. Column *A* is a four-year rotation of row crop, small grain, meadow, meadow. Column *B* is row crop, row crop, winter grain, meadow. Column *C* is alternate strips of row crops and small grain.

The value of K is given in the soil survey report. For this soil, $K = 0.18$.

$$A = (135)\,(0.18)\,LS\,C\,P$$

The value of LS can be obtained from Figure 18–14. Find the slope length on the bottom axis (100) and follow up the chart until it touches the 5 percent slope line. Now go up to where the 5.5 percent line would be if there were one. From this point, move left to the vertical axis. The LS factor is shown as $LS = 0.6$.

$$A = (135)\,(0.18)\,(0.6)\,C\,P$$

The first three factors are fixed for the site—they are not changed by anything the farmer does, short of land leveling, terracing, or incorporating organic matter to lower K. Simplify the equation by multiplying the three factors:

$$A = (135)\,(0.18)\,(0.6)\,C\,P = (14.58)\,C\,P$$

Refer to Figure 18–15 to find the C value under conventional fall plowing in continuous corn, $C = 0.37$.

$$A = (14.58)\,(0.37)\,P$$

The farmer used no support practices, so $P = 1$, meaning it is the same as in the test plot.

$$A = (14.58)\,(0.37)\,(1) = 5.39 \text{ tons/acre/year}$$

The computed soil loss is slightly greater than the acceptable level for this soil. However, since the equation, if anything, understates losses, the farmer should curtail some of the erosion. What practices will lower the erosion level? What if the farmer changes to contour plowing rather than up-and-down plowing? For contour plowing, P changes from 1.0 to 0.5 (Figure 18–16); the other factors remain the same:

$$A = (14.58)\,(0.37)\,(0.5) = 2.70 \text{ tons/acre/year}$$

The equation says that changing to contour tillage will cut erosion in half, well below 5 tons per acre. Changing from moldboard plowing to contour chisel plowing, leaving a 30 percent cover, would save even more soil:

$$A = (14.58)\,(0.19)\,(0.5) = 1.39 \text{ tons/acre/year}$$

Applications of the USLE

The most obvious way to use the USLE is to predict erosion from a certain field and to help select the best control measures. The example showed how this can be done.

The USLE can also be used to identify erodible lands. Land planners could use this information to prepare use maps based on erodibility. Or officials could identify lands most in need of assistance.

One scheme defines an **erosion index**, or EI, as follows:

$$\text{EI} = \frac{RKLS}{T}$$

The formula calculates the "native" erodibility of land, such as slope and texture, and excludes management practices. This is divided by T to get a multiple of the acceptable soil loss if farmed without protection. Any value of EI greater than one means this land, if tilled without erosion control measures, will lose soil more rapidly than T.

This index can be used to identify soils most in need of good management practices, allowing funding and efforts to be focused on land that will return the largest return on investment. For certain federal programs, land with an EI greater than eight, labeled Highly Erodible Land (HEL), demands protection.

The Revised Universal Soil Loss Equation

Needed improvements, described earlier in this chapter, in the USLE are incorporated into the **Revised Universal Soil Loss Equation (RUSLE)**, first released in 1992 and still being refined. RUSLE follows the basic USLE equation, but has refined factor values from improved data and computer modeling. The new model allows soil-loss calculations on some crops and conditions not covered by the USLE, like horticultural crops such as vegetables. The revised equation was designed primarily for computer use.

Although RUSLE has largely replaced the USLE for erosion prediction, the older version is retained here because it is more easily described and practiced in a text such as this. The RUSLE requires more field data, such as information about crop canopy and surface roughness. However, most basic procedures remain the same.

Controlling Water Erosion

All methods of controlling water erosion are based on one of four actions:

- Reducing raindrop impact to lessen detachment. This can be done by growing vigorous crops that fill in the canopy quickly, leaving crop residues on the surface, mulching, or by growing a total vegetative cover.
- Reducing or slowing runoff. This lessens detachment by scouring and reduces the amount of soil that can be transported. Avoiding compaction, maintaining organic matter levels, and subsoiling help water infiltrate the soil. Contour practices and conservation tillage both reduce runoff.
- Carrying excess water off the field safely by use of grass waterways or tile outlets.
- Filtering soil particles out of running water.

In practice, soil conservation measures may be classified as (1) soil improvements, (2) vegetative cover, (3) conservation tillage or mulching, (4) contour practices, (5) grassed waterways, (6) terraces, and (7) conservation buffers. One could also distinguish conservation *practices*, things we do regularly to preserve soil, like conservation tillage, from conservation *structures*, permanent modifications of the land, like terraces. Most of these measures reduce erosion by several of the actions listed above, and many of these practices can be combined.

While these conservation measures apply most directly to agricultural settings or production horticulture like vegetable or nursery production, water erosion can also occur in the grounds around homes and buildings. However, landscaping, properly designed, executed, and maintained, is itself a soil conservation practice. It covers the soil with vegetation, mulches, and other materials, and retaining walls are even a form of terrace. During development, however, before landscaping is installed, soil erosion may be severe. The particular practices in these settings are described in Chapter 19.

Soil Improvements

Practices that improve infiltration of water into the soil, thus reducing runoff, diminish erosion rates. Foremost among these are practices that increase soil organic matter content and improve aggregate stability. Organic agriculture, conservation tillage, cover cropping, and other practices listed in Chapter 8 can improve, or at least preserve, soil organic matter. Meadow crops most effectively improve aggregate stability, so crop rotations including meadow crops save soil, as shown in Figure 18–18. Avoiding or treating compaction by subsoiling also improves infiltration, as do the biopores common to no-till soils. One might even consider lawn aeration (Figure 17–13) a form of soil improvement.

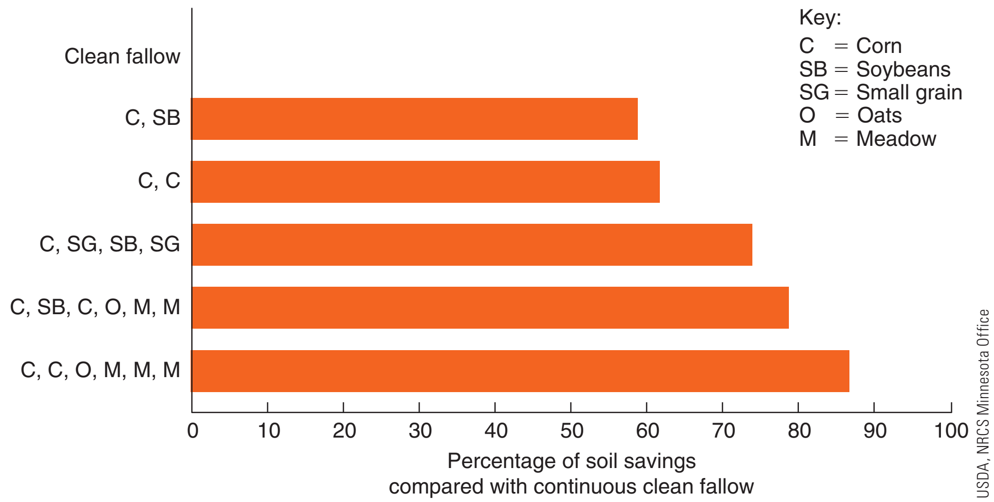


Figure 18–18

Effect of several crop rotations on soil erosion. Other USLE factors remain constant.

A newer version is the use of *polyacrylamide (PAM),* a synthetic water-soluble compound that can be sprayed on clay soils. At the molecular level PAM consists of strands that bind clay particles together to stabilize soil aggregates, improving infiltration and reducing surface sealing and crusting. Runoff and sedimentation loss are thereby both reduced. These work only in clay soils with adequate supplies of calcium and magnesium, whose ions are part of the binding process. The effects are temporary, and probably find their greatest potential use on construction sites to stabilize slopes and improve the establishment of permanent vegetation (Chapter 19).

Vegetative Cover

Vegetative cover protects soil from raindrop impact, standing vegetation impedes overland flow, and root systems help bind the soil together. A standard erosion control practice is simply selecting a crop suitable for a site's erodibility. Nursery and vegetable crops offer the least vegetative cover, and therefore are least suitable for sloping ground without protective measures. Small grains offer greater protection than common row crops, so including them in a rotation with row crops helps save soil (Figure 18–18). Row crops are prone to erosion, so should not be planted on erodible land every year, or not at all on Class IV land. Figure 3–9 relates acceptable crops to suitability classes. Permanent and complete vegetative cover such as native prairie grasses (Figure 18–9) or pasture offers the best soil protection, so is the most suitable treatment for highly erodible land. Other forms of erosion control practices such as strip-cropping and conservation buffers (covered shortly) also use vegetative cover. Crop rotations that involve small grains and forages, along with row crops, reduce erosion over continuous row crops.

Other forms of vegetative cover include cover crops, roadside vegetation, and turfgrass lawns. A well-maintained lawn with dense turf cover suffers negligible erosion, but a thin lawn may indeed erode.

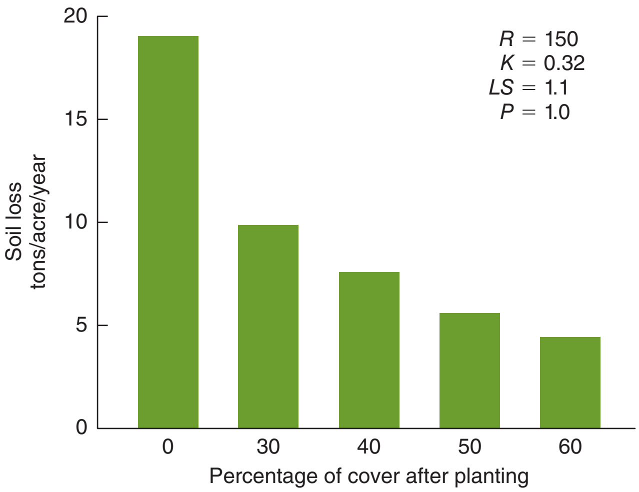
Conservation Tillage

Conservation tillage sharply reduces sheet and rill erosion. It is the lowest-cost conservation method per ton of soil saved and carries other benefits as described in Chapter 16. For these reasons, conservation tillage is the most widely accepted Best Management Practice for controlling soil losses.

Photo by Tim McCabe, USDA Natural Resources Conservation Service

Figure 18–19

A NRCS district conservationist measures residue in an Iowa field. The percentage of residue covered can be determined from the number of red markers on the cord that touch a piece of residue.



USDA, NRCS Minnesota Office

Figure 18–20

Effect of several crop residue levels on erosion according to the USDA for continuous corn. Note the large drop in going from 0 to 30 percent coverage.

The effectiveness of conservation tillage depends on a rough soil surface and surface residues, especially during the critical period before the crop canopy fills in. The definition of conservation tillage states that residue coverage be adequate to bring erosion below *T*—30 percent coverage is often taken as a minimum amount. Coverage can be measured directly by stretching a 50-foot cord, marked every 6 inches, diagonally across several rows. The number of marks touching a piece of crop residue is the percentage of coverage (Figure 18–19). For instance, if 35 marks touch crop residues, the coverage is 35 percent. This procedure should be repeated in several parts of the field and the results averaged. Figure 18–20 shows the effect of several residue levels according to the USLE.

In some settings—such as stabilizing slopes during new construction—mulching serves the same purpose of covering the soil to protect it. Chapter 19 covers this in more detail. Landscape mulches also help protect soil, though some organic mulches like wood chips can float away on steep slopes with lots of runoff.

Contour Practices

Contour practices include tillage and planting across slopes, on the contour, rather than up and down slopes. A contour is an imaginary line across a slope that remains at constant elevation. As covered in Chapter 8 (see Figure 7–16), water runs downhill perpendicular to these contour lines, so these practices prevent or impede that flow as described below.

Contour tillage means tilling on the contour, then planting following the same contour (Figure 18–21). Rainfall ponds behind the small ridges created by tillage, providing more time for water to infiltrate and impeding downhill flow. However, high-intensity rainfalls reduce the ridges, and high rainfall amounts can cause ponded water to overtop the ridges, which can be erased by water flowing over them. Therefore, areas of moderate slopes and low-intensity rainfall benefit most from contour tillage (Figure 18–22). Sometimes rows are graded not on the strict contour, but graded gently toward a grassed waterway (discussed shortly), so water can flow toward the waterway to be carried off safely. This practice also forces water to follow a less steep path, reducing its ability to erode. Combining contour tillage with conservation tillage (as in Figure 18–21) layers two technologies for greater protection.

Strip-cropping takes advantage of the fact that close-growing small grains and forage provide a dense vegetative cover, so protect the soil better than row crops. Figure 18–23 shows strips of alfalfa alternating with corn on the contour. The distance

Figure 18–21
Contour tillage and planting on this Iowa field reduces soil erosion by blocking downhill flow of water in less severe rain events. Here, conservation tillage was also used, adding another layer of protection.

of the less protected soil will be short, so less soil will be transported before entering the denser vegetative cover of the alfalfa strip, where water slows and soil particles are filtered out. Strip-cropping adds another layer of protection to contour tillage, and can be more effective in areas of moderate rainfall. Adding conservation tillage adds yet another layer of protection.

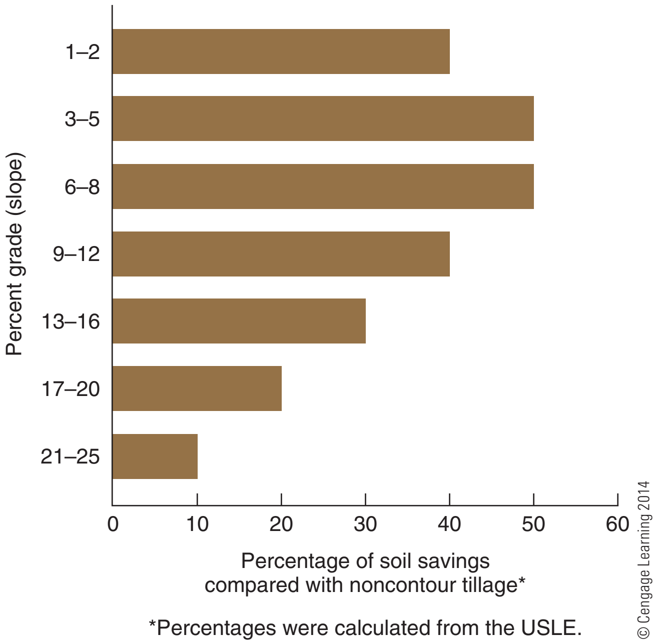


Figure 18–22
Effect of contour tillage on soil erosion for several slope grades. Other USLE factors remain constant. Contour tillage works best on moderate slopes. On longer or steeper slopes, water ponded behind the ridges can overflow and wear them away.

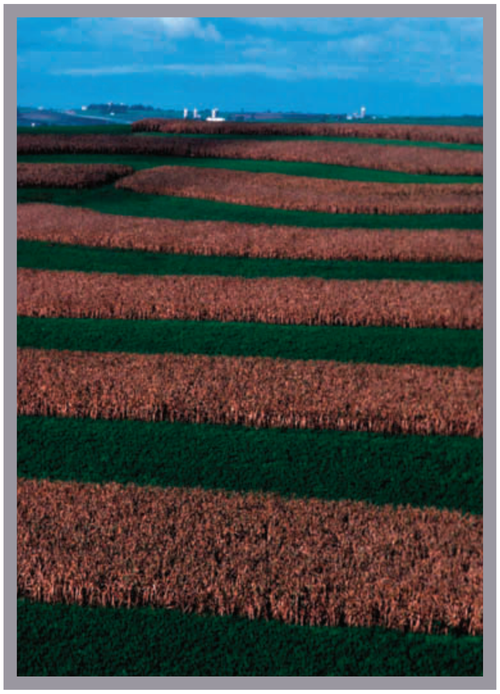


Figure 18–23
Contour strip-cropping of alfalfa and corn in an Iowa field.

Grassed Waterway

A **grassed waterway** is a shallow, sodded, wide ditch that runs down a slope (Figure 18–24). As shown in Figure 7–16, water flow concentrates where opposing slopes meet; it is precisely in such places where a grassed waterway may be installed. One of the waterways in Figure 18–24 illustrates this nicely. Since ephemeral gullies and gullies form here, grassed waterways are a BMP for prevention of such gullying. Waterways are also designed to carry excess water off the field safely, and may be used to collect water from tillage contours or terraces. Grassed waterways are also a version of conservation buffer, described next.

Conservation Buffers

Strips of permanent vegetation that retard overland flow and act as living filters to remove sediment, nutrients, and pesticides are called **conservation buffers**. Conservation buffers reduce erosion and preserve water quality of nearby bodies of water. Conservation buffers also enhance wildlife habitat for ground-nesting birds such as pheasants and other wildlife.

Conservation buffers work by slowing runoff while improving soil physical properties so infiltration is improved. Examples include enhanced structure, improved macroporosity, higher organic matter content, and lower bulk density. Microbial activity is also improved, and some buffers, especially riparian buffers, remove nitrates from water by exposing the water to enhanced denitrification.

Contour buffer strips are strips of permanent vegetation planted on the contour between strips of cultivated crops. Figure 18–24 shows contour buffer strips as well as grassed waterways. While this resembles strip-cropping, buffer strips are permanent and not cropped. These slow water flow, permitting more time for infiltration, and

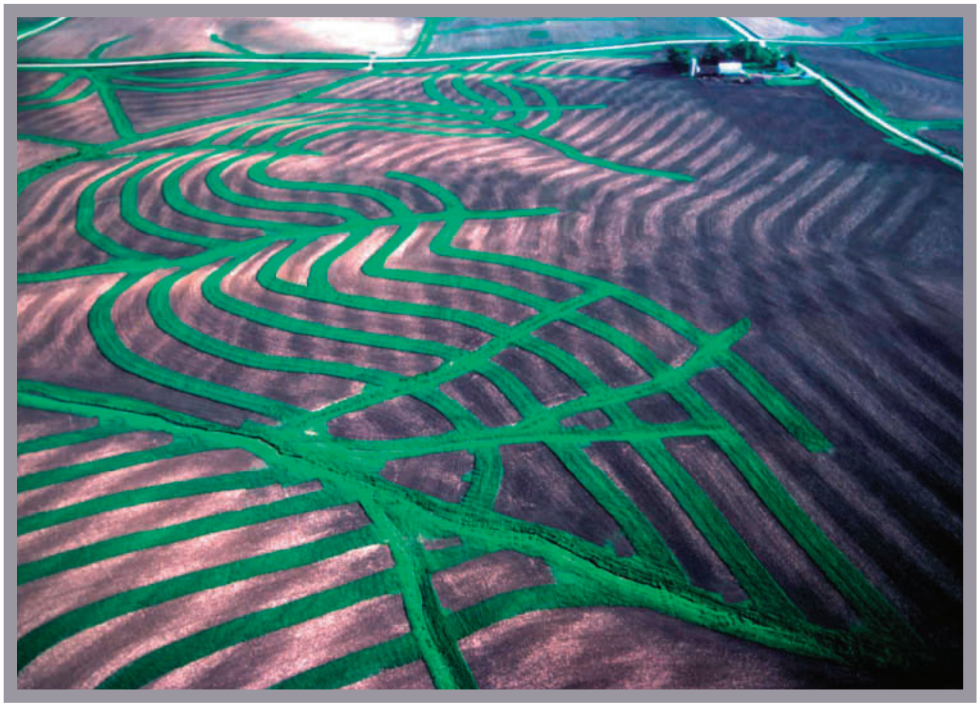


Photo by Tim McCabe, USDA Natural Resources Conservation Service

Figure 18–24
Grassed waterways and contour buffer strips in Iowa.

filter the flow. The strip should be made of a vigorous, stiff-stemmed grass that will not fall over when water flows through it.

On sloped soil, sodded row middles in clean-cultivated woody crops like nurseries (Figure 17–3) or orchards (Figure 17–2) can thought of as contour buffer strips.

Filter strips lie along the downhill edge of a field, and work primarily to filter sediment out of runoff from a field before it can enter a receiving area, such as a nearby stream. They can also filter out some nutrients and pesticides. Like contour buffer strips, a dense, stiff-stemmed grass works best.

Riparian buffers are strips of permanent vegetation along streams, wetlands, and other bodies of water, to protect water quality from field runoff. Riparian buffers include versions with herbaceous plants like stiff grasses, and woody plant buffers with trees and shrubs or some combination (Figure 8–12). A "residential" form of riparian buffer is planting dense vegetation along the shore of lakeside homes and cabins, rather than mowing right to the shore.

Conservation buffers, like all other erosion control procedures, must be properly designed to function properly, taking into account slope length and other factors. An example of a design element is the width of a vegetative strip, which must be wider if more water can be expected to enter it. For protection of surface waters, a combination of upland buffers and riparian buffers works best. Some conservation buffers can be enrolled for Conservation Reserve Program easements (Chapter 20).

Terraces

Where other measures fail to reduce erosion adequately, terraces may be built (Figure 18–25). Long or steep slopes on impermeable soil, for example, require terraces. Terraces are costly to install and are used most commonly for valuable crops or where there is a shortage of good land. In general, two kinds of terraces are used:

- Level terraces parallel the slope and do not empty into a waterway. This type of terrace is used where soil is permeable enough so that water can seep in once captured in a terrace.
- Graded terraces are needed where water cannot soak in enough. These may slope gently toward a waterway or be drained by an underground tile outlet.

Several terrace designs are shown in Figure 18–26. Of these designs, the broad-based terrace is most common. Terrace construction begins by designing them to fit conservation needs without overly hampering farming. The land is surveyed and the terraces are marked on the slope. Terraces must be properly maintained to ensure effectiveness.

Terraces are accounted for in the USLE by the *LS* factor. Terraces break up a slope into several shorter slopes. In solving the USLE, the length of a single terrace is taken as the length of the entire hill. Depending on terrace design, the slope factor may or may not change. It is assumed that most of the eroded soil within the cropped part of a terrace is deposited in the terrace channel, and that a smaller amount leaves the field in waterways or outlets. For the *P* factor, use the contour tillage or strip-cropping value.

Photo by Norm Klopfenstein, USDA Natural Resources Conservation Service

Figure 18–25
Maintaining the grass cover on a steep-backslope terrace in Missouri. See Figure 18–26.

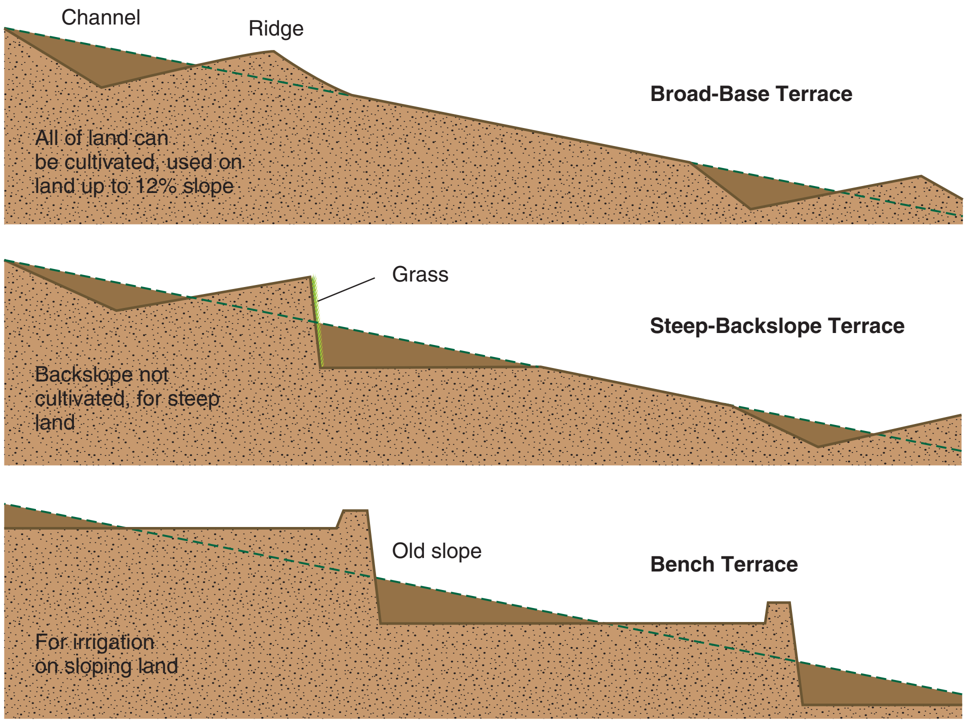


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Figure 18–26
Each terrace design serves special purposes. The broad-based design is most common. Not drawn to scale. Broken lines indicate the old grade.

Diversions are large-capacity terraces that divert runoff from higher elevations. Diversions are not farmed but are covered with grass. Their uses include:

- Protecting fields from runoff flowing from higher elevations
- Diverting water away from active gully heads
- Diverting water from feed lots, farmsteads, or other sensitive area
- Diverting water away from homes in residential housing

WIND EROSION

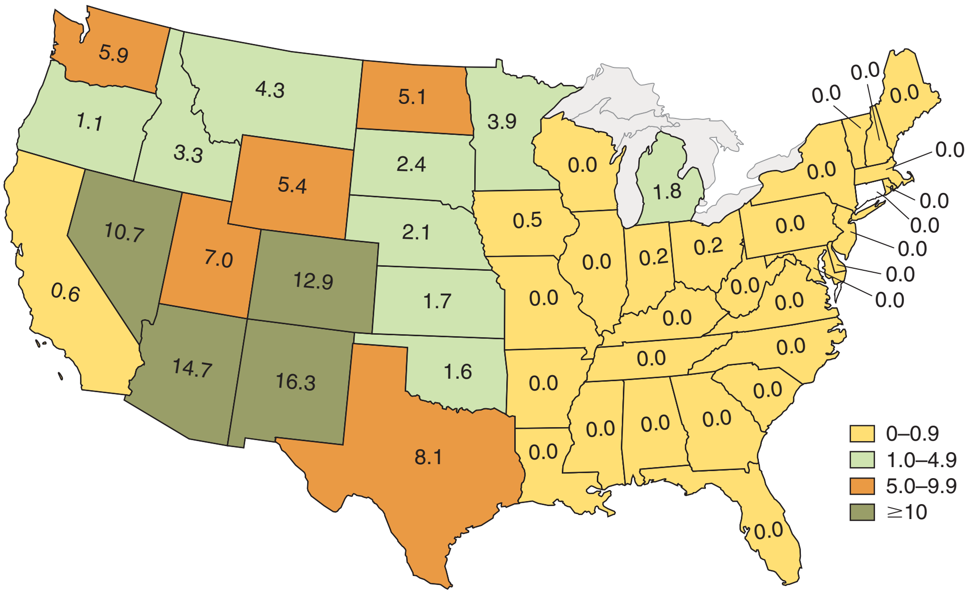
Wind erosion accounts for about 40 percent of the soil loss in the United States, mostly in the western states. Other areas with wind erosion problems include muck and sandy soils of the Great Lakes states and Atlantic seaboards. Figure 18–27 shows amount of wind erosion for each state in average tons per acre per year for cultivated land.

Dry areas with high winds are most likely to experience wind erosion. At greatest risk is soil kept bare by clean-till summer fallow.

Cause of Wind Erosion

Figure 18–28 shows the effect of wind blowing across a bare soil. A very thin layer of still air covers the soil surface, called a *boundary layer,* but larger soil particles stick up above the layer. When wind reaches 10–13 miles an hour at a height of 1 foot above the surface, soil grains begin to move.

First, wind begins to roll soil grains in the size range of 0.004–0.02 inch (0.1–0.5 millimeter), fine to medium sands. Suddenly a sand grain jumps into the air, rising as high as 12 inches. Wind blows the sand grain several feet. The grain strikes the ground, where it may bounce up again or knock loose some other particles. This process is called **saltation**—movement by short bounces—and causes



Based on USDA, 2007 National Resource Inventory

Figure 18–27
Average annual wind erosion by state on nonfederal cultivated land in tons per acre per year.

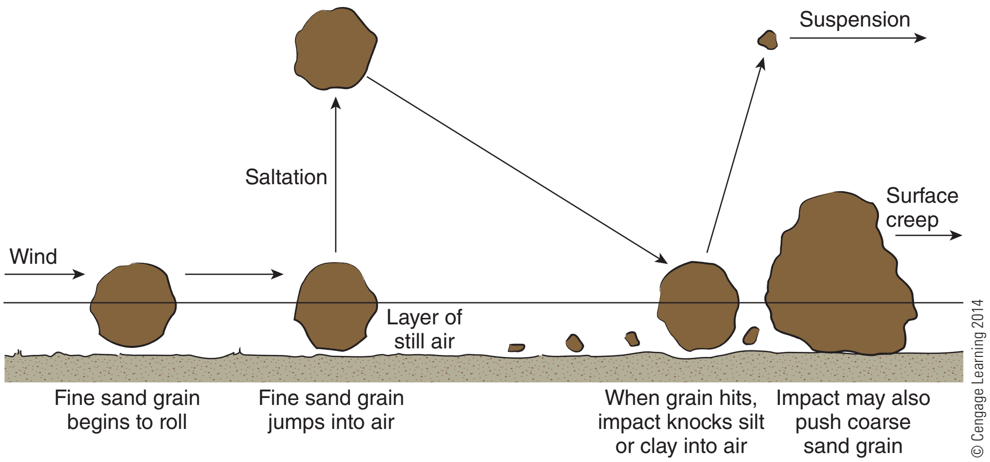


Figure 18–28
Saltation of fine sand triggers wind erosion. Fine sands are large enough to protrude above the boundary layer but small enough to be picked up by wind. Surface creep and suspension both depend upon the impact of fine sand in saltation.

50 percent to 75 percent of all wind erosion. In fact, more than 90 percent of all movement occurs within 1 foot of the soil surface.

Fine silt and clay particles are too small to be picked up by the wind because they do not protrude above the boundary layer. However, the impact of a sand grain moving by saltation may knock dust into the air. Once the wind hits it, dust rises high into the air and is carried long distances. This process, called **suspension**, accounts for about 3 percent to 40 percent of all wind erosion. Silt particles move most easily.

Coarse sand particles, ranging in size between 0.02 and 0.04 inch (0.5–1.0 millimeter), are too large to be kicked into the air. However, under the impact of saltating sand grains, they can roll along the ground. This is known as **surface creep**. It accounts for 5 percent to 75 percent of wind erosion.

Like water erosion, detachment and transport of soil particles by wind are functions of energy. The higher the wind velocity, the greater the energy. Blowing soil itself contributes to erosive energy. A soil grain has greater mass than air, and thus the impact of a soil grain carries more energy. As a result, wind erosion has an avalanche effect—as wind blows across an open field, more and more soil is picked up as the erosive energy increases.

When wind velocity dies down, so does its energy. Soil particles in saltation or suspension come to rest when the wind dies down. They may also fall out on the lee (downwind) side of an obstruction, the way snow gathers on the lee side of a snow fence (Figure 18–29).

Effects of Wind Erosion

Like water erosion, wind erosion removes the best soil first—the topsoil (Figure 18–30). It carries off fine soil particles, especially silt and organic matter. The shift toward a coarser soil texture reduces nutrient-holding and water-holding capacity. Furthermore, windblown soil particles "sandblast" young plants, tattering leaves and tearing away plant cells.

Young plants can easily lose half their dry weight when exposed to sand-laden winds. Off-site damages can also be severe—and expensive. Blowing soil can fill road or drainage ditches (Figure 18–29), affect the respiratory health of animals and people, increase cleaning and laundry costs, and wear at paint and other surfaces.

Photo courtesy of USDA Natural Resources Conservation Service

Figure 18–29

Wind-blown soil clogs a ditch in Iowa.

Photo by Lynn Betts, USDA Natural Resources Conservation Service

Figure 18–30

Topsoil blowing in the wind in Iowa.

Factors in Wind Erosion

The following factors determine the amount of wind erosion:

- Soil erodibility relates mainly to texture and structure. Soils high in fine sand and coarse silt are most liable to wind erosion; soils high in clay are least liable. Drained organic soils are also easily eroded by wind. Soil grains cemented into stable soil aggregates are less likely to be blown away.
- Soil roughness makes a larger still air layer at the soil surface. Each clod or ridge also acts like a tiny windbreak to slow wind and capture blowing soil.
- Climatic conditions that promote wind erosion include low rainfall, low humidity, high temperatures, and high winds. Dry, windy conditions cause faster soil drying, and dry soil is more erodible than moist soil. Dry soil also supports a thinner vegetative cover.
- Length of field affects erosion. On the leading edge of a field, there is no wind erosion. As the wind travels across the field, it picks up more and more soil grains, like an avalanche.
- Vegetative cover protects the soil, as does a mulch. Bare soil, on the other hand, is fully exposed to the erosive force of wind.

These factors together can be arranged to create a soil-loss formula similar to the USLE called the **Wind Erosion Equation (WEQ)**. According to the equation, erosion (E) is a function (f) of several factors:

$$E = f(I, C, K, L, V)$$

where I is a soil-erodibility factor related to particle size, C is a climatic factor related to average wind velocities and soil moisture, K is a measure of surface roughness, L is field length, and V measures vegetative cover. WEQ is complex to solve, so will not be further detailed in this text.

Preventing Wind Erosion

Preventing wind erosion means reducing the factors listed previously. The following practices help control wind erosion:

- Till at right angles to the prevailing wind, leaving the soil surface rough and cloddy. Lister furrows are very useful because they act as small windbreaks, called **cross-wind ridges**, to capture blowing soil.
- Use conservation tillage or subsurface tillage tools, such as rodweeders and subsurface sweeps, to leave crop residues on the soil surface.
- Keep soil covered with vegetation as much as possible. Cover crops act as living mulches to hold soil in place, and can reduce damage to plants by blowing sand, as in the **cross-wind trap strips** in Figure 18–31. Cover crops may also be used to protect soil over winter.
- Moistening soil with irrigation during windy conditions will temporarily hold soil particles in place.

Photo by Fred Gasper, USDA Natural Resources Conservation Service

Figure 18–31
Rye windstrips between rows of carrots in Michigan reduce wind erosion and protect the carrot tops from blowing soil.

Photo by Erwin Cole, USDA Natural Resources Conservation Service

Figure 18–32
North Dakota windbreaks protecting the soil from wind erosion.

- Plant windbreaks of trees and large shrubs (Figure 18–32). Windbreaks protect soil for a distance of about 10 times the height of the break by shortening the field, reducing wind velocity, and capturing blowing soil.
- Plant the most critical areas to permanent grasslands or other vegetative cover.

Critical Periods

Two periods are critical for wind erosion. The first is when the soil is fallowed. Large clean-fallow fields in the Great Plains are ideal grounds for wind erosion. Subsurface tillage tools that leave crop residues on the surface reduce this problem. Instead of controlling weeds by tillage, herbicides can be used to kill weeds while leaving crop stubble standing to protect the soil from wind.

The period between harvest and the following crop cover is the critical period in many areas. A good snow cover protects soil, but if the snow blows off the field, so will soil. Again, conservation tillage and winter-cover crops protect soil during the critical period.

EROSION AND CLIMATE CHANGE

Our erosion-prevention technologies were developed in response to conditions of a mid-twentieth-century climate. Since climate is changing rapidly, many soil scientists are concerned that those technologies may be overwhelmed by climate change. Indeed, there is already some evidence of a quickening of erosion rates in some locations.

Climate change models predict increases in average temperature; greater frequency of extreme weather events such as prolonged drought, heat waves, or higher-intensity storms; and changing rainfall patterns across the globe. We observe these climatic changes happening already, and they are likely to become more pronounced over time.

For water erosion, a predicted increase in the number of highly erosive rainfalls in some locations will impact water erosion. Indeed, many of us have already experienced a marked increase in extreme rainfall events in recent years. Where contour tillage had been a satisfactory way to control erosion, heavier rainfalls can erase the low-contour ridges that tillage creates and render the practice ineffective. There may also be a shift from sheet and rill erosion to concentrated flow. A 2003 report from the Soil and Water Conservation Society predicted erosion increases as high as 90 percent on some cropland.

Our erosion-prediction models like RUSLE may no longer predict erosion as accurately. The isoerodent map (Figure 18–13) we use to determine the rainfall (*R*) factor will likely become inaccurate, as could other factors, such as crop management factors (*C*). The report mentioned above suggests that climatic factors be updated immediately.

For wind erosion, some parts of the world already prone to wind erosion are predicted to become even drier. Increased frequency of prolonged drought can only aggravate that problem. And if average temperatures in those same areas rise, soil will dry out even faster. The climatic factor (*C*) in WEQ will also be altered.

Some consequences of climate change are less predictable. It may change biomass production on fields, which would alter soil cover and thus erosion. Growers may alter their cropping practices in response to climate change. For instance, increased corn production on marginal land could result from the drive to produce ethanol, or crop residues that protect soil could be removed for biofuel production, or crops better suited to warmer climates might be selected.

SUMMARY

About three-fifths of the soil lost to erosion in the United States washes away in running water. Water erosion strips the topsoil, reduces yields, and deposits sediments and other pollutants in streams, lakes, and reservoirs. About two-fifths of erosion in the United States results from wind. Wind also strips the topsoil, blows away the smallest soil particles, and buries ditches and other structures.

Falling raindrops and running water detach soil particles from the soil surface and carry them away. Depending on the slope, erosion removes soil as a sheet or in rills, and if flowing water gathers in channels, we get the concentrated flow patterns of ephemeral gullies and gullies. Water erosion is promoted by bare and erodible soil, long or steep slopes, and the lack of conservation practices.

Soil scientists use the USLE or its revised version to compute soil-water erosion loss. The USLE accounts only for losses from sheet and rill erosion and will understate soil loss where there is ephemeral or gully erosion. Using the USLE or RUSLE, a specialist can suggest practices to keep a farm productive and identify highly erodible land.

Growing vigorous crops, maintaining organic matter, and avoiding overtillage and compaction help control erosion. Both conservation tillage and crop rotation sharply curb erosion. Contour tillage, contour strip-cropping, and terraces are effective ways to slow runoff. Where these are not enough to stop runoff, they may be combined with grassed waterways or outlets to carry the excess off the field without erosion. Conservation buffers filter soil out of running water to protect nearby waters and hold soil in fields.

Wind blows soil off fields by saltation, suspension, and surface creep. Wind erosion is most likely to occur on soils that are high in fine sand or silt, or on organic soils; in hot, dry, windy climates; and where soil is kept bare, especially for summer fallow. Control practices include breaking the wind, keeping the soil rough, and planting at right angles to the wind. The most effective method is keeping the soil covered by vegetation or crop residues.

In the coming decades, climate change will likely challenge efforts to predict and control erosion.

REVIEW

1. Discuss the types of water erosion.
2. Discuss the types of wind erosion and the types of soil particles associated with each.
3. The text says that soil improvements can increase infiltration and lower erosion rates. What factor of the USLE is affected? If infiltration increases, does the factor increase or decrease?
4. Picture a nursery on a slope that is currently being clean-cultivated. Such a site would be quite erodible by water. Why? What practices or structures would alleviate the erosion? Would you expect this site to be prone to wind erosion?
5. Given identical soils, slopes, and soil cover, in which location would you expect water erosion to be more severe, central Michigan or central Mississippi?
6. A skilled landscape designer, installer, or maintenance person is, perhaps unknowingly, a soil conservationist. Think of practices that make this true. Or if you disagree, explain why.
7. You operate a farm in Washington County, Minnesota, near the location marked on the isoerodent map of Figure 18–13. For a field you farm, $K = 0.32$, and $T = 5.0$, according to the soil survey. One field has a slope of 4 percent and is 400 feet long. You grow a corn–soybean rotation. Use the C factors of Figure 18–15. Calculate average annual soil loss for the following practices:
   a. Conventional fall-plow up and down the slope
   b. Contour chisel, leaving 40 percent cover
8. Land in the Conservation Reserve Program is usually planted to permanent grass cover. What would be the average annual erosion rate on the field in question 7 under permanent grass? How does this compare to the above?
9. Climate change might have effects that change erosion rates. Recalculate the soil loss from the field of

question 7b under these two scenarios, and compare the results to your answers for question 7b.

a. In response to changing weather patterns, the grower changes from a corn–soybean rotation to continuous beans.
b. More extreme rain events raises the *R* factor in this region by 20 percent.

10. Calculate the EI for the soil in question 7. How would you rate this soil's erodibility?
11. How might you prepare an interpretive soil map rating soils as to their water-erosion hazard?
12. Describe practices that might keep sediments and chemicals from farm fields out of nearby bodies of water.
13. Surface roughness affects both water and wind erosion. How does it affect each? How might we use roughness to reduce erosion?
14. In the 1970s in a drive for increased production for grain export, many windbreaks were removed. What might have been the result in terms of erosion? Explain the processes involved.

ENRICHMENT ACTIVITIES

1. Visit growers in your area who use different conservation measures.
2. Practice the use of the USLE to land in your area using charts in this chapter and local soil survey reports. You may need to obtain *C* factors for your area, or use the ones supplied here even if they might differ somewhat.
3. This chapter concentrates on erosion problems in the United States. Investigate erosion in some other country by typing "soil erosion" and adding the name of another country into your browser. Write a short report.
4. For thousands of years, in many parts of the world like Chile, the Philippines, and Nepal, steep mountainsides have been made usable for agriculture by terracing. Look for images of these mountainsides by searching on the Internet. Many such images are travelogue photographs. Describe the terraces.
5. Research one soil conservation practice you think is most useful in your area using the Internet or other resources. Prepare a short report that provides more detail than provided in this chapter.
6. For a historical perspective, the classic 1933 article about soil erosion, "The Cost of Soil Erosion," by H. H. Bennett, is available on the Internet at https://kb.osu.edu/dspace/bitstream/1811/2640/1/V33N04_271.pdf. This is one of the early, formative presentations on the subject of soil erosion in the United States by one of the pioneers of soil conservation.
7. The Soil and Water Conservation Society's 2003 report *Conservation Implications of Climate Change: Soil Erosion and Runoff from Cropland* is available on its site at http://www.swcs.org. Its 2007 report *Planning for Extremes* is at the same site. They are listed under the Publications menu.

CHAPTER 19

Urban Soil

TERMS TO KNOW

- bioremediation
- bioswale
- brown field
- check dam
- erosion control blanket
- green roof
- hydromulching
- low-impact development
- rain garden
- recharge basin
- retention pond
- rip-rap
- sediment basin
- silt fence
- swale
- urban land
- wattle

OBJECTIVES

After completing this chapter, you should be able to:

- list characteristics of urban soils
- describe ways of dealing with urban soils
- describe modified and structured soils
- describe erosion and sedimentation control on urban sites
- discuss low-impact concepts

Urban soils, sometimes identified as **urban land** or "developed land," are those soils found within a city, town, or metropolitan area. The United States Department of Agriculture (USDA) reports that there were 111 million acres of developed land in 2007, an increase of 40 million acres since 1982. Over half the world's population, and about 80 percent of Americans, live in urban areas. In some small countries, virtually everybody lives in a city.

The problems and traits of urban soils demand a discussion in a soil text because they continue to grow as a fraction of our land surface and because most Americans—indeed, most of the world's population—inhabit such land.

If we add people to the standard list of soil-formation factors, as discussed in Chapter 2, then the most heavily human-influenced soils are these urban soils. This chapter describes characteristics of urban soils and makes suggestions for managing them.

Photo by Bob Nichols, USDA Natural Resources Conservation Service

Figure 19–1
Urban soils, like this one in Philadelphia, present challenges to users, like these gardening youth. Soil quality is probably poor and compacted, and it possibly has buried debris and lead contamination.

CHARACTERISTICS OF URBAN SOILS

Urban soils present certain difficulties to landscapers, gardeners (Figure 19–1), building contractors, and others who use them. Compared to rural soils, urban soils have been greatly altered by construction, excavation, contamination, and other activities. Earth has been moved from site to site, grades and drainage patterns changed, foundations dug, and debris and contaminants left behind.

Several characteristics of urban soils have been proposed by researchers. These include:

- Great soil variability, both vertically in the soil profile and across the urban landscape.
- Severely modified soil structure from soil moving and stockpiling (Figure 19–2), often with a very high degree of soil compaction.
- Modified soil pH caused by buried debris like concrete (which raises pH) and contaminants.
- Restricted aeration and drainage. Sometimes urban soils are also *hydrophobic*—that is, they repel water so it runs off the surface instead of being absorbed.
- Interrupted nutrient cycling because contamination and other changes alter biological processes. Mycorrhiza levels may be reduced, and in some urban soils, high earthworm populations alter recycling processes in the soil.
- Elevated soil temperatures from the "heat island" effect of cities.
- Presence of substances added by humans, including solid debris and chemical contaminants.
- Reduced soil organic matter. One of the all-purpose remediation methods for improving urban soils is the incorporation of large amounts of organic amendments.

A few of these will be examined in detail next.

Soil Variability and Classification

Much of the surface of an urban area has experienced earthmoving and "cut and fill" operations. In construction of typical suburban tracts, topsoil is removed and stockpiled (Figure 19–2), soil is moved about by bulldozers, roadbeds and foundations are built and compacted, and finally topsoil is returned (or not!) as a thin topdressing on the yards. Subsoil may be low-quality fill trucked in from some other location. Large-scale commercial building causes even more severe changes.

As a result, urban landscapes show extreme soil variability. Across the landscape, soils may vary greatly over a space of a few feet. Strange soil profiles also cause vertical variation, with man-made layers that retard drainage and aeration. This variation complicates the use of urban soils; even soil testing presents a problem when one corner of a yard may be wholly different than another.

Trying to survey and classify such variable soil presents great challenges. Many soil surveys label areas of developed soils simply as "Urban complexes." In soil

Image courtesy of Ed Plaster

Figure 19–2

Preparations for installing a sewer line in Minnesota. Topsoil is routinely removed and stockpiled, to be returned after the construction project is complete. In the process, soil quality suffers, with degraded structure and other problems.

taxonomy, urban soils may be classified as Entisols, being, in a sense, new soils in which soil-forming processes are starting over.

In the 1990s, the New York City Soil Survey Program examined 320 acres of parkland with the detail needed for such a variable landscape. To do this, five new soil series had to be named to identify human-constructed landforms. Such a detailed survey will provide valuable data for the proper use of that parkland.

Buried Debris

Urban soil usually has a lot of debris buried in it. During construction of a building, contractors may bury wood or masonry scraps on the site, rather than haul them away. Buried rubble may retard drainage or even cause excessive drainage. It can be a physical barrier to root growth. Buried masonry, which contains lime, can raise pH to unacceptable levels. The debris is also a constant source of frustration to those trying to work the soil. Recognizing this problem, many suburbs now require builders to remove debris from construction sites.

Mound Cities

The accumulation of buried debris is so associated with cities that "mound" is almost a synonym for ancient city sites. Successive civilizations would build cities atop sites of former cities, so that over the centuries cities rose in elevation. These are common enough in modern Turkey that they have a name, *Hoyuk*. One of the largest, *Catalhoyuk,* rises 65 feet above the surrounding plain. Even some of the cities of today are elevated by successive building over the generations.

Compaction

Urban soils are usually moderately to severely compacted from the use of heavy equipment on the soil during construction, vehicle parking, and maintenance equipment. Countless footsteps on yards and parks also cause compaction. Even vibration from nearby roadways settles soil. Compaction from construction may kill sensitive trees like oaks, cause greater erosion, and make it more difficult to establish a landscape. Compaction promotes the growth of compaction-tolerant weeds in yards and makes it difficult to establish good turf.

Compaction can be measured by bulk density. Chapter 1 mentioned that an "ideal soil" is about 50 percent solid particles and 50 percent porous space. The bulk density of such a soil is about 1.3 grams per cubic centimeter. As bulk density rises above 1.4, root growth begins to suffer from lack of air and direct physical resistance. At a bulk density of 1.7, roots cannot penetrate the soil. The people in charge of landscaping around the nation's Capitol measured some bulk densities on the Capitol Mall ranging between 1.8 and 2.2.

Many fine upland trees such as sugar maple thrive only on soils of high air-filled porosity. Many of our best urban trees hale from floodplains, where trees are adapted to soils often low in oxygen. Appendix 5 lists responses of many tree species to soil compaction.

Urban soil compaction also reduces water infiltration, thus increasing stormwater runoff. One 2003 study in Florida[1] found that urban compaction reduced infiltration 70 percent to 99 percent. In severe cases, the infiltration behavior of compacted soils approached that of impervious surfaces such as pavement. Reduction of urban stormwater runoff is an increasingly important goal, to be discussed later in this chapter, and avoiding or alleviating compaction is an important Best Management Practice (BMP) for achieving that goal.

Planning can avoid some compaction. For instance, on new construction sites, limit or protect areas driven on by construction equipment (Figure 19–3). Landscape architects and designers can help control pedestrian compaction by remembering that people walk the shortest route between two points. Designers should carefully analyze expected foot traffic patterns on a new site, and install sidewalks or mulched paths where people can be expected to walk.

Although difficult, it is possible to break up compaction if no plants are in the way. All completed construction sites should be treated thoroughly to alleviate the inevitable damage to soil structure and compaction before landscaping is installed; unfortunately, thorough preparation is rarely done. Deep tillage will break up compaction. The soil can then be heavily amended to stop further compaction. Digging large, solid particles such as calcined clay into the soil helps by creating a "skeleton" that resists compaction. "Black dirt" is often topdressed, but would be better incorporated into the top few inches (thus avoiding a sharp interface), with more added on top. Incorporating large amounts of organic matter such as compost is almost always advisable. Proper soil preparation improves the health of planting and reduces runoff from the yard. These are all useful practices that can help alleviate problems in urban soils, and should be implemented far more often by homeowners, landscapers, and other soil users. And, as always, match the plant to the site!

Where heavy foot traffic is expected, a deep layer of wood chips cushions the soil. Another method of dealing with foot traffic is to pave the soil with special pavers

[1]Gregory, J., et al. (2005). Effect or urban soil compaction on infiltration rate. *Journal of Soil and Water Conservation, 61,* 117–124.

Image courtesy of Ed Plaster

Figure 19–3
Some exterior remodeling on a Minnesota home. The contractor protected the soil from compaction by laying heavy plywood to drive on. The turf was covered too long, but recovered.

and grids that have large holes built into them. Grass can grow in the spaces, giving the impression of turf, yet the grid protects the soil. Water and air can also move through the spaces.

If trees or turf already occupy a site, compaction is more difficult to repair without hurting roots. Machines called aerators remove vertical cores from the soil. This process helps break up compaction. For turf, vertical coring to 6 inches breaks up the soil and makes passages for air and water movement. Machines that remove a core should be used, and the cores should be left on the surface as a topdressing (Figure 17–14). For trees suffering from the effects of compaction, coring to 18 inches is needed.

Compaction in Hardscaping

Hardscaping, the construction of such "hard" landscape features as paver patios and retaining walls, has become a major part of the landscaping trade. Hardscaping is essentially an engineering use of the soil. Instead of relieving compaction, installers must increase compaction to provide a stable base for the structure. For instance, a paver patio may rest atop several inches of Class V gravel (a mixture of limestone gravel and finer particles that compacts solidly and is used on gravel roads) compacted in *lifts*. This means the material is thoroughly compacted by laying down some gravel, compacting it with manual or mechanical tampers, laying down another layer of gravel, tamping that layer, and so on until the proper depth and density is achieved. The base is finished off with a couple inches of sand or grit, carefully leveled, and pavers laid atop the sand. The whole thing is tamped again.

This patio would shed much of the water running over it. It is possible to engineer a patio that absorbs water using, for example, permeable or pervious pavers. The next sidebar explains the difference.

Soil Contamination

Soil contamination may severely impact the usability of some urban soils. Contamination should particularly concern those interested in growing food, such as urban farmers and gardeners. These contaminants may include heavy metals such as cadmium or lead, deicing salts, or industrial and home wastes such as paint thinners and solvents. Severely affected land may require massive reclamation before use, such as stripping and replacing soil.

Deicing Salts

In northern states, roadway deicing salts may be sprayed some distance by passing vehicles and snowplows. The most common deicer, common salt (sodium chloride), is used in huge amounts. Sodium chloride creates saline or even sodic soil conditions, and chloride may reach toxic levels.

The degree of damage from road salts is proportional to the distance from the roadway and traffic levels and speed on that roadway. Consulting charts of road salt distances from roads, plantings can be designed to minimize problems. One answer is to plant salt-tolerant species. Appendix 5 provides some guidance.

Common road salts may be replaced by less harmful materials such as calcium chloride or calcium magnesium acetate (CMA), but these may be less effective in the coldest zones and more costly. Urea and sand mixtures are also used in warmer weather. In a homeowner's yard, heavy irrigation may leach salts from the root zone.

Heavy-Metal Contamination

Heavy metals, such as cadmium or lead, may be present in some soils from the parent materials. In urban settings, they tend to rise to high levels because of settling of urban dust and air pollution, as well as contaminants that enter soil such as paint chips or industrial waste. Many soil amendments and fertilizers contain low amounts of heavy metals.

Heavy-metal soil contamination is an increasing problem worldwide and is most severe in urban settings. Heavy metals are toxic to plant roots, animals, and people. Lead contamination is the most severe example in urban soils. In the soil survey of a New York park mentioned earlier, soil levels ranged from 6 parts per million to 2,003 parts per million, showing lead distribution to be quite patchy. Lead is a highly toxic metal that was once added to paints and to leaded gasoline. Such uses have been phased out in recent years, but lead remains in urban soils. It primarily affects children, causing learning, memory, behavioral, and other problems. It has been shown that lead blood level in urban children correlates with lead levels in surrounding soils.

Much lower lead levels are measured in the blood of inner-city children since lead was removed from gasoline in the 1970s and 1980s. However, urban children still acquire lead by ingesting contaminated soil or paint chips or by breathing airborne dust. In old, especially run-down neighborhoods, chips of lead-based paint may be eaten by infants and young children. Paint chips may also contaminate soil around a building.

The following suggestions may be useful in controlling health problems from lead:

- Keep yards covered by a good stand of vegetation to prevent children from playing in contaminated soil to avoid ingestion of lead on dirty hands. Sandbox sand can be changed yearly.

- Clean children's hands, keep the house free of dirt, and follow other cleanliness measures to lower the amount of contaminated soil ingested or breathed by children as dust in the air.
- Remove chipping lead-based paint from old homes, clean up thoroughly, and repaint with new paints.
- Have a child's blood tested for lead levels in high-risk neighborhoods. These include areas with old, run-down housing and areas near heavy traffic.
- Test soil for lead; many soil-testing laboratories perform lead tests.

Many home gardeners are concerned about lead in their garden soil. The biggest risk is the direct ingestion of soil by children. The other, much lesser risk, is absorption of lead by garden crops, which are then eaten by the family. Plants do not take up large amounts of lead; that which is taken up is concentrated mainly in the leafy parts of the plant, rather than seeds and fruit.

If a gardener suspects a lead problem, a number of measures may be taken. One could dig out the old soil to a depth of 6 inches, then build an elevated bed with landscape timbers or by other means (Figure 19–4). If the bed were raised 6 inches above the grade, this would give a total of 12 inches of fresh soil. This depth would contain most plant roots. A second measure is to keep the soil pH near neutral, since lead is much more soluble in acid soils. It is also possible that high levels of organic matter from compost might form a complex with lead, tying it up. As soil clinging to vegetables is more hazardous than the vegetable itself, produce from urban gardens should be carefully washed and root crops peeled.

Arsenic also contaminates some urban soils. A common component in some older pesticides and treated woods, arsenic promotes cancer and can be a nervous system

Photo by Ron Francis, USDA Natural Resources Conservation Service

Figure 19–4
Raised beds in a Texas garden. Raised beds can lift plantings out of lead-contaminated soil. Here, the beds are heavily amended with compost, an excellent way to improve urban soil quality and tie up lead.

toxin. While these uses of arsenic are being phased out, it persists in the soil. Most of the actions described to reduce lead exposure apply to arsenic as well.

Last, urban areas often experience flooding, and floodwaters are often contaminated with untreated sewage and other contaminants like heavy metals. Soil in areas that experienced urban flooding should not be used for food production without testing.

Brown Fields

Brown fields are so severely damaged by human abuse that the land is unusable without costly abatement efforts. The Environmental Protection Agency defines **brown fields** as "abandoned, idled, or underused industrial or commercial facilities where expansion or redevelopment is complicated by real or perceived contamination." Examples include land polluted by industrial chemicals, numerous piles of waste, or extensive debris burial.

Brown fields present chances for redevelopment in cities and for slowing of urban sprawl by opening more land in older parts of metropolitan areas already served by urban infrastructure. However, costs may be high, and cleanup is unlikely to occur without government aid. LEED certification gives a preference to construction on brown field sites.

Abatement begins with a site assessment, looking at historical records and sampling the site. Teams of soil scientists, chemists, geologists, and engineers may be involved. A site plan is then produced, and the plan executed. Economic development can then follow.

A site plan could include **bioremediation**—the use of living things to reduce pollution. For example, soils could be seeded with certain soil bacteria that break down organic pollutants such as spilled oil. Some plants take up and accumulate unusually large amounts of heavy metals in their above-ground parts. These plants, called *hyperaccumulators,* can be grown on contaminated sites repeatedly, harvested, and disposed of properly. For instance, the common weed pennycress (*Thlaspi* sp.) can accumulate up to 3 percent of its mass in zinc.

MODIFIED AND STRUCTURED SOILS

While in residential neighborhoods soil is healthy enough to support the growth of trees, turf, and other landscape plants, the same is not true in the urban center. The "downtown tree" has an average life expectancy of 10 years because of soil and environmental extremes.

The downtown tree is often planted in a small soil pit or elevated planter (Figure 17–9), with an extremely restricted root zone and surroundings covered by pavement. Below the pavement is a "soil" base that was severely compacted by contractors to support the pavement. This treatment severely restricts aeration and raises mechanical resistance to root growth. Trees that do survive often do so by finding better soil on the other side of the pavement, but in so doing, roots may buckle the pavement. Those roots will likely then be cut off by city crews for public safety. The difference between trees growing in tree pits and open soil is dramatic (Figure 1–7). Similarly, turf and other landscape ornamentals perform better in improved soils.

These problems can be answered by either heavy modification of existing soil or by creation of a wholly new structured soil, depending on the situation. In areas of relatively open soil exposed to extreme compaction, such as boulevards, a modified soil may suffice. In paved areas, a structured soil is more helpful.

Modified soils use regular soil with additional treatments. While actual projects need a lot of expertise, we can make suggestions here. Usually subsoil compaction should be broken up, then an A and B horizon built with modified soil, and finally the soil slightly compacted to prevent later settling.

A modified soil consists of soil with a large amount of inorganic or organic amendments mixed in. Inorganic materials include coarse sand larger than 0.25 millimeter in size (never fine sand), perlite, cindered fly ash, and others. These amendments are added in enough amounts that the grains touch each other to form little bridges that prevent compaction and to create large numbers of large pores. This could be as much as 60 percent to 75 percent of soil volume.

Organic amendments may also be used, but tend to be temporary. Such materials should be composted to prevent nitrogen tie-up and settling because of rapid decay. Examples of good materials include composted milled pine bark or redwood bark and sphagnum peat.

The designed soil should be added to create A and B horizons to a minimum depth of 18 inches, an optimum depth of 24–36 inches, and a maximum of 48 inches. Otherwise, a thin layer of 4- to 6-inch topdressing to rebuild an A horizon may be useful, but only if the subsoil is not compacted, is adequately drained, and can qualify as a B horizon. Some topdressing should first be applied, mixed into existing soil to prevent a sharp interface, then additional topdressing added to the 4- to 6-inch depth.

Structured soils are radically different than existing soil. These were devised by the Urban Horticulture Institute at Cornell University. Structured soils create a rooting zone under pavement while preserving a stable base for that pavement. The primary component of structured soils is crushed stone, into which is mixed a certain percentage of clay loam soil and a water-absorbing gel that helps hold water and "glues" the whole thing together. This mixture will meet the load-bearing needs of pavement, but creates a rigid lattice that contains large voids for air exchange that can be explored by roots. The soil occupying a portion of those voids then supports root growth.

URBAN EROSION AND RUNOFF

Urban sites, particularly during the construction phase, suffer the paired problems of severe runoff and erosion (Figure 19–5). During construction of an urban development, erosion can be 10–20 times greater than on similar farmland. Large developments often leave land bare for long periods of time, with natural vegetation removed. When streets and parking lots are installed, runoff from these impervious surfaces can run over the bare land, causing massive erosion.

While on-site damage of erosion can be severe (Figure 19–6) and negatively impact a development, the off-site impact of sedimentation (Figure 19–7) and pollution is of greater public concern. About 5 percent of the sediment load reaching American surface waters per year originates in urban development.

Photo by Lynn Betts, USDA Natural Resources Conservation Service

Figure 19–5
Erosion and sedimentation in a housing development in Des Moines, Iowa. This ground was left unprotected during construction. Regulations mentioned in the text aim to prevent this outcome.

Image courtesy of Ed Plaster

Figure 19–6
Erosion undercutting a fence in North Carolina. Urban erosion can damage structures and roads. The soil removed here was deposited elsewhere (Figure 19–7).

Urban runoff, even without sediment, creates problems. It increases downstream flooding, introduces pollutants such as phosphates and herbicides into surface waters, and reduces the amount of water available to recharge groundwater supplies. Because urban runoff is warmed by running over warm surfaces, it also threatens the health of cold-water streams in urban areas.


Image courtesy of Ed Plaster

Figure 19–7
Sedimentation in a North Carolina drainage culvert. The ground around the culvert is hard-armored with rock.

This section will look at two related topics: (1) controlling erosion and sedimentation during construction and (2) designing urban environments that reduce runoff.

Controlling Construction Erosion and Sedimentation

In recent years, more stringent regulations controlling erosion and sedimentation have been increasingly enforced. The National Pollutant Discharge Elimination System (NPDES), enforced by the federal Environmental Protection Agency and state pollution control agencies, sets stricter standards for minimizing negative impacts both during and after construction. These regulations identify construction sites as point sources of water pollution; the aim is to protect the nation's water resources. Among other things, the regulations require preparation of a Storm Water Pollution Prevention Plan for sites above a certain size and adoption of BMPs for erosion prevention and sediment control.

The science and practices of erosion control during urban construction resemble those described in Chapter 18—protect soil from raindrop impact, prevent or slow runoff, filter out sediments—but many products and practices are unique to urban situations. Controlling erosion on construction sites requires careful planning and use of BMPs. There are five general principles for controlling runoff, erosion, and sedimentation:

Keep disturbed areas small. During the planning stage, identify critical areas and plan to avoid disturbing them. Disturb only that land currently being built on rather than stripping soil over a large area. Where possible, retain natural soil cover in other areas.

Protect disturbed areas. As soon as possible, disturbed areas should be protected and stabilized. Establishment of vegetation is most critical, but a number of temporary soil covers that promote vegetation are available. These protect the soil temporarily while seed in or under the covers germinate and vegetation is established.

These include **erosion control blankets** that can be rolled over bare soil (Figure 19–8). These are biodegradable meshes containing organic materials such as chopped straw, coconut fiber, or compost. Mulches of chopped straw are common. **Hydromulching** blows mixtures of water, finely chopped straw, and seed over disturbed areas. Of these alternatives, compost blankets work best for improving soil quality and improving establishment of vegetation. Temporary plant cover such as oats may be established, and sod may also be installed. Ultimately, all disturbed areas will be covered by permanent vegetation. Polyacrylimide materials are also being sprayed on bare surfaces to stabilize structure and improve infiltration.

These procedures involving organic materials are sometimes called *soft armoring,* compared to *hard armoring* methods (Figure 19–7). These use hard materials like stones, called **rip-rap**, or concrete to cover the soil.

Keep runoff velocities low. When grading land, keep slopes short and gradients as low as possible. Keep vegetative cover intact to slow runoff where feasible. Various permanent or temporary control structures can be used. For instance, in channels where water flows, temporary or permanent **check dams** may be installed. These may be as simple as rows of straw bales across the channel, to rip-rap dams. Rip-rap may also line the channel. Across channels or across slopes, temporary devices called **wattles** may be laid. These look like large, long rolls of sausage filled with straw, compost, or coconut fiber laid across the slope to intercept water flow, and to force it to pond and drop its sediment load. In the process, they also break up long slopes into shorter segments. Figure 19–9 illustrates a straw wattle in use.

Divert runoff away from disturbed sites. Land or pavement at higher elevations can act as a small watershed, collecting rainwater and directing it onto bare soil at lower

Image courtesy of Ed Plaster

Figure 19–8
Erosion control blankets protecting a slope during a park renovation in St. Paul, Minnesota, a form of soft armoring.

elevations. These bare areas should be protected by diversions and the water diverted into waterways and outlets. Waterways can be covered by turf, rip-rap, or even concrete, depending on the amount of water flow they must handle.

Retain sediment on site. By retaining sediments on site, sediment damage is reduced elsewhere. A classic temporary structure is the **silt fence**, a dense mesh fabric buried partially underground and attached to posts to create a fence (Figure 19–10). Water backs up behind the fence and drops its sediment load while slowly oozing through. These must be properly installed, and failure commonly occurs (Figure 19–11). In addition, all storm sewer inlets (Figure 8–11) must be protected to prevent sediment from entering the system—wattles can be wrapped around the inlet. Wattles can also be used to filter sediment out of runoff.

Most modern developments include **retention ponds** or **sediment basins** to capture sediments. The development is graded to move runoff into these ponds, where energy is lost from running water in the still water, and sediment settles out. Other, temporary means are also available to dissipate energy and release sediment during construction.

Calculating Soil Loss

The Universal Soil Loss Equation (USLE) can be used to estimate soil losses from construction sites and to identify critical erosion sites. The results are not precise, but they do offer some guidance. The USLE is written as:

$$A = R\,K\,LS\,C\,P$$

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Figure 19–9
A straw wattle being used to slow runoff from a parking lot to protect a newly planted slope.

Image courtesy of Ed Plaster

Figure 19–10
A silt fence installed prior to the work seen in Figure 19-2. Silt fences are standard practice to retain soil that might otherwise run off during rains. Water ponds behind the fence, dropping its sediment load while seeping through.

Image courtesy of Ed Plaster

Figure 19–11
Silt fences, like other protective measures, will not work when improperly installed and maintained.

A is the soil loss in tons per acre. Refer to Chapter 18 for instructions on how to solve the equation. The following values can be used to solve the USLE for construction sites:

- *R*—The rainfall factor can be obtained from Figure 18–13.
- *K*—The erodibility factor can be obtained from soil survey data. If the topsoil has been removed, then the *K* value for the exposed subsoil must be used.

- *LS*—The slope factor can be obtained from Figure 18–14. Slope factors are reliable only up to a 20 percent slope, and so are not reliable for very steep roadside embankments.
- *C*—The cover and management factor for bare, stripped soil is the same as a clean-fallow plot, so *C* equals 1.0. If a mulch covers the soil, *C* is much lower. Figure 19–12 gives sample *C* values for construction sites.
- *P*—The support practice factor is usually 1.0, because few of the support practices are applicable to construction sites.

Low-Impact Development

Stormwater runoff remains an issue after a development is complete. Standard practice for design of urban sites is the rapid removal of stormwater by grading the land to move it quickly to storm sewers or culverts and discharging it into surface waters. This reduces on-site flooding and wet basements in developed sites. However, it may merely move the flooding downstream. Furthermore, urban runoff often carries pollutants and sediments to streams and rivers.

In the natural cycle of things, some of this stormwater supplies needed water to vegetation and recharges groundwater. The flow of many streams depends on groundwater, so a failure of groundwater recharge reduces stream flow. In areas with cold-water streams that support trout or salmon, runoff water raises stream temperature, making them less fit for fish habitat.

A different option is to design developed areas to retain water on site and allow it to filter into the soil, using the water as a resource for irrigation and recharge rather

Type of Mulch	Mulch Rate (tons per acre)	Land Slope (percent)	Factor *C*	Length Limit (feet)
None	0	All	1.0	—
Straw or hay, tied down by anchoring and tacking equipment	1.0	1–5	0.20	200
	1.0	6–10	0.20	100
	2.0	1–5	0.06	400
	2.0	6–10	0.06	200
	2.0	11–15	0.07	150
	2.0	16–20	0.11	100
Crushed stone, 0.25–1.5 inches	125	<16	0.05	200
	240	<21	0.02	300
	240	21–33	0.02	200
Wood chips	7.0	<16	0.08	75
	7.0	16–20	0.08	50
	12	<16	0.05	150
	12	16–20	0.05	100

Data from USDA Handbook 537

Figure 19–12

Some cover and management factors (*C*) and length limits for construction slopes. If slope length is exceeded, higher mulch application rates or some means of shortening the slope is needed.

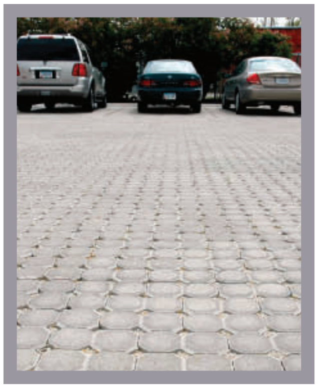


Photo by Jason Johnson, USDA Natural Resources Conservation Service

Figure 19–13

A permeable paving system in an Iowa parking lot. Water filters between the pavers, entering underground soil rather than into storm sewers. Special installation measures are needed for this paving system to be successful.

than a disposal problem. This is called **low-impact development** or zero-runoff development.

A number of BMPs can be deployed to keep most water on site. A major contributor to stormwater runoff is the large area of hard surfaces—parking lots, driveways, and the like—that cover urban areas. Many of these can be replaced by porous materials that allow water to soak into the underlying soil, such as special porous concrete or blacktop. Concrete pavers, with porous gaps between the pavers, work in many applications (Figure 19–13) and satisfy LEED points and Environmental Protection Agency (EPA) BMP performance standards. See the sidebar for more details.

Lawn itself, on compacted soils, often lacks much ability to accept water. Complete soil preparation prior to lawn establishment to improve soil properties and then protecting it from further compaction improves infiltration and reduces runoff. Or lawns can be replaced by vegetation like little pocket prairies.

In developments, water is carried away from yards in shallow ditches called **swales**. Swales can be designed with deep, porous soils and planted to dense vegetation that slows runoff, promotes infiltration, and traps sediment. These **bioswales** can lead to wetlands or basins that capture water that exits the swale.

Two kinds of basins can be constructed on site to capture runoff and promote infiltration. Retention ponds designed to promote infiltration, rather than simply holding water, can be called **recharge basins**. These will not be full of water all the time. An alternative is the **rain garden** (Figure 1–15), a shallow depression in a yard, or ringing parking lots, that receives runoff and absorbs it. The rain garden is planted to dense vegetation such as ornamental or native grasses and perennials that can tolerate periods of wetness. The rain garden should have a highly porous base, and

Permeable Pavers

Unlike the paver patio described in the last sidebar, a permeable paver surface is designed to absorb water to prevent runoff. It needs a stable base yet one that absorbs water. The Interlocking Concrete Paver Institute (ICPI) suggests this: After proper excavation and *not* compacting the soil, install a 6- to 16-inch subbase of coarse gravel, the depth depending on the permeability of the underlying soil and volume of water expected, below a 3- to 4-inch base of medium gravel. On top of that is 1 1/2 inches of washed fine gravel that supports the pavers. The fine gravel also fills the joints between the pavers; no sand. The gravel subbase and base act as a reservoir for holding water while it percolates into the soil and provides a stable base for the pavement. Because the very large pores in all the layers offer negligible matric potential, there is no hindrance to drainage between the layers, and the smaller pores in the underlying soil accept water from the larger pores of the gravel.

The enemy of this system is finer particles like sand or silt that would retard drainage. A geotextile fabric separating the soil from the subbase prevents mixing of the soil with the gravel, but finer particles washing in from above could shorten the effective life of the paving. For more details and explanation, see the

ICPI site at http://www.icpi.org.

Figure 19–14
A green roof on a downtown building.

is not meant to hold water except for brief periods during rainfall. If it holds water too long, it may fill after several rainfalls and cease to function. Rain gardens may be established in yards to intercept runoff from the yard, or along curbs with curb cuts to intercept some street runoff, as in Figure 1–15. Rain barrels or cisterns to hold roof runoff are also becoming popular. That stored water is then available for irrigation.

Green roofs (Figure 19–14) are even beginning to appear on some buildings—beds of vegetation planted on building roofs. Green roofs may be *intensive,* which have deep beds of soil that permit a wide range of vegetation to be established, or *extensive,* having beds of shallow soil planted with very drought-resistant plants such as stone-crops (*Sedum* sp.). Special lightweight soil mixes reduce loading on the roof structure while providing a suitable growing medium. Green roofs offer many benefits, such as reduced roof temperatures (thus lower cooling loads in the building) and increased roof insulation from winter cold. The relevant benefit here is absorption of rainwater that would otherwise enter the storm sewer system, which returns instead to the atmosphere by evapotranspiration.

LEED Certification

The LEED certification program mentioned elsewhere in the text offers points for water and soil conservation practices around buildings. Many of these reflect practices described in this chapter:

- Limit site disturbance during construction
- Reduce development footprint and leave open space
- Reduce stormwater runoff with green roofs, permeable paving, vegetative filter strips, bioswales, rain gardens, and other practices

- Amend soil to relieve compaction and runoff, and use mulches
- Harvest rainwater
- Use native plants (Your author does not entirely agree with this criteria—he likes and uses native plants, but some nonnatives will serve the same purposes nicely. Just an opinion.)

Points awarded for these practices are added to other points awarded for the building itself. If the total is sufficient, the owner can be awarded LEED certification, and can use this fact in promotional materials.

SUMMARY

Urban soils exhibit great variation, poor quality, buried debris, compaction, and contamination. They are difficult to classify and map because of the extreme variation. Examples of contamination include road deicing salts and lead, which lead to health problems in children. Severely damaged brown fields can be repaired and used for redevelopment.

In urban centers, soil can severely limit plant growth. Here, modified and structured soils can improve growth of trees and other plants to improve the environment for city inhabitants.

During construction of roads or housing, soil is fully exposed to the forces of water erosion. Keeping disturbed areas small, protecting the soil surface, and filtering sediments with various BMPs can reduce erosion and sedimentation. Increasingly, new developments are designed to retain stormwater on-site rather than speed its travel to surface waters.

Remember that properly executed, landscaping is the set of practices we use to protect soil and water resources in urban areas. And always add organic matter to urban soils.

REVIEW

1. Describe activities that might damage soil structure in urban soil.
2. Why might the existing county soil survey in a new suburban area not accurately describe the soil in someone's yard? Give several specific examples.
3. Using Appendix 5, identify five trees that you think would make good urban trees in highly disturbed sites. Explain your reasoning.
4. Describe strategies for limiting the amount of sediment that leaves a new construction site.
5. Compare the erosion rates off two embankments 100 feet long with a 7 percent slope. One is a bare slope with no mulch; the other is mulched with 2 tons per acre chopped straw. Show your calculation.
6. Distinguish modified soil from structured soil.
7. A case study: Known for its pristine clear waters, Lake Tahoe is beginning to suffer from pollutants running off development around the lake. A rule has been passed requiring zero runoff from properties in the Lake Tahoe watershed. Speculate as to courses of action that could be taken by various property owners.
8. A case study: In the soil survey of a park in New York described in this chapter, the surveyors described several new series. One of them, the Greenbelt, has a soil profile listed as A (0–3 inches), Bw (3–13 inches), C1 (13–27 inches), C2 (27–57 inches), Ab (57–58 inches), Bwb (58–60 inches). Create a story describing a possible history of this soil during historical times. See Appendix 3 for horizon codes.

ENRICHMENT ACTIVITIES

1. If any large-scale housing projects are being built nearby, visit them and identify erosion and sediment control practices.
2. For study of urban soils from an ecological perspective, read an interesting series of studies on changing soil conditions along an urban–rural transect beginning in New York City and ending in rural Connecticut. For example, read McDonnel, M., et al. (1997). Ecosystem processes along an urban-rural gradient. *Urban Ecosystems, 1,* 21–36.
3. Browse the Internet for information about soil lead problems in your state and how you get soil tested for lead. Entering search terms such as "lead testing " should work.
4. For more detailed information about lead in gardens, go to http://www.extension.umn.edu/ and search on: distribution/horticulture/DG2543.
5. The United States Geologic Survey has an Internet site on bioremediation at http://water.usgs.gov/wid/html/bioremed.html.
6. For more information on green roofs, go to the Internet at http://www.greenroofs.org.
7. Browse the Internet for construction sediment control systems such as straw wattles.
8. The USDA has an "Urban Soil Primer" at http://www.soils.usda.gov/use/urban/primer.html
9. For more information on LEED sustainable practices, visit the Web site http://www.sustainablesites.org.

CHAPTER 20

Government Agencies and Programs

TERMS TO KNOW

- Agricultural Experiment Station
- conservation compliance
- Conservation Reserve Program (CRP)
- Conservation Stewardship Program (CSP)
- Cooperative State Research, Education, and Extension Service (CSREES)
- cost-sharing
- Environmental Quality Incentives Program (EQIP)
- Farm Service Agency (FSA)
- Natural Resources Conservation Service (NRCS)
- Soil and Water Conservation District (SWCD)
- Wetland Reserve Program (WRP)

OBJECTIVES

After completing this chapter, you should be able to:

- list federal agencies that assist soil users
- describe some of the soil programs of these agencies

Research yearly comes up with new methods that can help growers, but growers cannot spend much of their time in school learning new methods. Market forces pressure growers to change, not always in ways best for the soil. As businesspeople, growers must often put their money where the financial return is best—which is not always for long-term benefit. A number of programs support growers with technical assistance and have information to answer questions such as: How do growers keep up with change? How can they afford soil improvements?

A network of agencies and regulations helps the grower in several ways.

- Education provides information in the form of publications, workshops, and advice (Figure 20–1).
- Technical assistance advises growers how to complete specific projects such as irrigation or grassed waterways.
- Financial assistance helps growers pay for projects.
- Research helps by creating new and better techniques.

Government programs operate through a complex web of federal, state, and local agencies. In addition to the government, there are private sources of information and help. We will concentrate here on government programs, especially federal programs in the area of soil and water conservation.

USDA AGENCIES

Help comes to growers and other soil users from many sources. One major source is the United States Department of Agriculture (USDA), established in 1862. The USDA includes several agencies that help farmers and others with soil and water management as well as many other facets of agriculture. Many USDA programs work through state or local groups.

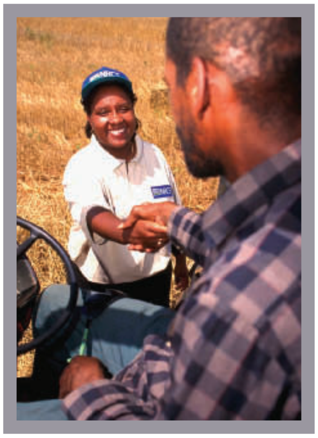


Photo by Bob Nichols, USDA National Resources Conservation Service

Figure 20–1

A South Carolina farmer receives the assistance of an NRCS technician.

Cooperative State Research, Education, and Extension Service

The **Cooperative State Research, Education, and Extension Service (CSREES)** merges extension and research activities in CSREES programs at state **Agricultural Experiment Stations**. Experiment Stations, and the CSREES programs housed in them, are located at land-grant universities and are jointly funded by state and federal dollars.

The title CSREES expresses the three traditional functions of the land-grant university agriculture departments: teaching, research, and extension. Extension positions aim to provide information and assistance to a variety of audiences and to spread information obtained by research at the Experiment Stations.

Farm Service Agency

The **Farm Service Agency (FSA)** administers and funds a number of agricultural programs, including some soil conservation programs. Many FSA programs are administered at the state and local level by local growers in **Soil and Water Conservation Districts (SWCDs)**, described later in this chapter. In carrying out its programs, the FSA utilizes the technical expertise of the Natural Resources Conservation Service.

Natural Resources Conservation Service

The **Natural Resources Conservation Service (NRCS)** replaces the older Soil Conservation Service, established by Congress in 1935 to carry out a national program of soil and water conservation. The NRCS provides a variety of assistance, including technical support to FSA programs. These include:

- Conducting soil surveys in a joint effort with Agricultural Experiment Stations (Figure 3–5)
- Helping city and county officials with land-use planning (Figure 20–2)
- Administering conservation programs except those assigned to the FSA
- Providing technical assistance in resource management issues such as soil and water conservation and wildlife habitat (Figure 3–8)
- Conducting a National Resources Inventory (NRI) of the status and trends of the nation's soil and water every five years. The NRIs serve as major databases for public land and water planning and are the source of many statistics in this text.

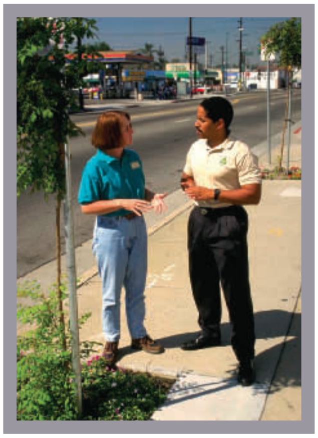


Photo by Bob Nichols, USDA National Resources Conservation Service

Figure 20–2

In Los Angeles, an NRCS conservationist discusses urban soil issues with a client.

Photo by Ken Hammond, USDA Natural Resources Conservation Service

Figure 20–3
SWCD board members meet in Hidalgo County, Texas. Many programs are administered through county Soil and Water Conservation Districts, governed by locally elected boards.

Soil and Water Conservation Districts

While not federal agencies, many USDA programs operate through Soil and Water Conservation Districts. Feeling that federal conservation programs should operate through local authority, then-President Franklin Roosevelt proposed to all state governors in 1937 a model for creating Soil and Water Conservation Districts.

Generally, the boundaries of an SWCD follow county boundaries. Each district is governed by locally elected or appointed boards of growers or ranchers (Figure 20–3). The districts plan for and carry out programs they feel have a priority in their districts. The actual role and duties of the SWCD vary from state to state, because they are state, not federal, agencies.

All districts have formal agreements with the U.S. Secretary of Agriculture to set up programs. The secretary, in return, agrees to help the districts. Many districts have NRCS soil scientists assigned to them for technical aid.

USDA CONSERVATION PROGRAMS

The Natural Resources Conservation Service and the Farm Service Agency, among other duties, operate several programs aiming to conserve the nation's soil and water resources. These programs are authorized by periodic "farm bills" of Congress, which often carry ponderous titles like the *Food, Conservation, and Energy Act of 2008*. Programs described here were authorized or reauthorized by that 2008 farm bill. The 2008 farm bill continues to stress environmental quality and increased efforts on protecting working land. The next farm bill was being considered but had not passed at the time of this writing.

The 2008 farm bill includes some slight changes of focus. Prior farm bills focused on traditional agricultural crops grown conventionally. While that does not change dramatically, the 2008 bill establishes funding and programs for "specialty crop" producers; these are mostly producers of horticultural crops like vegetables, fruits, nursery stock, and ornamentals. The 2008 farm bill also increases help to people engaged in organic agriculture, especially when transitioning from conventional production.

USDA soil and water conservation measures are voluntary. The agency does not have the authority to force participation. However, it can nudge growers to adopt conservation practices by providing technical and financial assistance. Here we describe only a few USDA programs that are significant for soil and water resource preservation.

Environmental Quality Incentives Program

The **Environmental Quality Incentives Program (EQIP)** aims to protect private and tribal "working lands"—lands being actively managed by growers. EQIP, a voluntary program administered by the FSA and NRCS, helps growers in soil and water conservation efforts by providing money on a cost-share basis. **Cost-sharing** means the USDA shares part of the cost for conservation efforts with a grower and provides technical assistance. Growers can enter into 5- and 10-year agreements with the USDA for technical, educational, and cost-share assistance.

Conservation Stewardship Program

Another working-lands program, the **Conservation Stewardship Program (CSP)** was first authorized in the 2002 farm bill. A voluntary program operated by the NRCS, it aims to identify and reward growers on private or tribal lands meeting high standards of conservation on their operations and to create incentives for others to do the same. Growers who already practice some soil conservation practices are aided in increasing their efforts and in preserving prior efforts. A variety of payments are offered to growers meeting various levels of conservation.

Conservation Reserve Program

The **Conservation Reserve Program (CRP)** was first authorized by the 1985 farm bill. The CRP purchases 10- to 15-year easements from growers. In exchange for payments, growers plant the land to permanent cover such as native grasses (Figure 18–9) or trees on erodible or environmentally sensitive land. It is administered by the FSA and NRCS.

About 33 million acres of land are enrolled in the CRP. The USDA estimates that CRP land experiences an average reduction in soil loss of 19 tons per acre per year, and much of the national reduction in erosion in recent years has been attributed to the CRP. The CRP also creates greatly improved habitat for pheasants, ducks, and other wildlife, so is widely supported by wildlife and hunting groups. The 2008 farm bill caps enrollment at 32 million acres, which is lower than prior legislation.

An accompanying program, the Conservation Reserve Enhancement Program (CREP), like the CRP itself, protects land by means of easements. The CREP, however, is a partnership between the USDA and state, tribal, county, or even private agencies to create local programs addressing specific concerns of the host state. Many states host CREP initiatives.

Wetland Reserve Program

The **Wetland Reserve Program (WRP)** functions like the CRP, except it is designed to protect wetlands. Chapter 7 discussed wetland values that motivate such a program. Most important, these include wildlife habitat, as well as contributions to water quality, flood control, groundwater recharge, and other wetland functions. The WRP is a joint program of the NRCS, FSA, and the federal Fish and Wildlife Service and state agencies. It involves 10-year wetland restoration cost-sharing as well as 30-year or permanent easements. About a million acres are enrolled in the WRP.

Conservation Compliance Programs

Conservation compliance requires growers to take certain conservation measures to remain eligible for federal price-support programs. Conservation compliance provides a stronger nudge for adoption of conservation practices. For instance, growers are asked to submit and execute soil erosion control plans for certain highly erodible lands. According to the NRCS, during the decade 1985–1995, 1.7 million such plans were developed and implemented on 143 million acres of highly erodible land.

Wetlands in agricultural land may also be protected by "swampbuster" provisions of the farm bill. These provisions deny eligibility for other USDA programs to growers who drain and farm certain wetlands.

STATE AND LOCAL EFFORTS

In addition to federal programs, states and localities also have laws and programs. Foremost of these, of course, are the Soil and Water Districts, Agricultural Experiment Stations, and Extension Services. Obviously, this text cannot list all the state and local efforts.

One example is the Reinvest in Minnesota program, or RIM, enjoyed by citizens and outdoor enthusiasts of Minnesota. Enrolled land is planted to wildlife cover, especially to native vegetation. Wetlands have also been restored. RIM is administered through the Soil and Water Conservation Districts. The intent is to protect erodible land and water quality, and to promote wildlife habitat.

Many local and state laws involve controlling land use, such as zoning laws. For instance, many outer suburban areas limit how far land can be subdivided. To save farmland, many states have "green acre" laws, which give tax breaks to land in developing areas kept as farmland. Some of these and other efforts aim to slow the loss of farmland to urban use.

SUMMARY

Several groups assist growers with education, technical help, financial assistance, and research. Many of these groups are part of the United States Department of Agriculture.

The Cooperative State Research, Education, and Extension Service, attached to state Agricultural Experiment Stations, conducts research and provides education through extension services.

The Farm Service Agency conducts a number of funding programs, as well as administering the Environmental Quality Incentives Program and the Conservation Reserve Program. The former supplies cost-sharing for conservation activities, while the latter puts highly erodible land into 10-year easements.

The Natural Resources Conservation Service administers several other conservation programs and provides a wide range of technical assistance in conservation.

Many federal conservation programs operate through Soil and Water Conservation Districts, state funded and administered by local grower committees.

While CRP and other programs are voluntary, several other laws require some protection of our soil and water resources to qualify for certain other USDA programs, such as conservation compliance regulations. These include swampbuster provisions to protect wetlands, sodbuster provisions to keep uncultivated highly erodible land from being plowed, and conservation compliance measures to increase the number of soil conservation projects undertaken on farms. These programs are largely responsible for erosion and wetland loss reductions over the past decades, as noted in earlier chapters.

REVIEW

1. Discuss the National Resource Inventories. Find at least three examples of data in this book supplied by the NRIs. (*Hint:* Look at the captions of various charts in the text that are included to give a picture of soil use and conditions in the United States.) A search on the Internet finds more information.
2. What is the CRP? What are its benefits? What percentage of U.S. nonpublic land is under CRP (see chart in Chapter 1).
3. Discuss the cooperation between federal, state, and local agencies that is part of soil and water conservation efforts. Give examples.
4. Who in the agencies and programs described here performs agricultural science research? How are the results communicated to the community?

ENRICHMENT ACTIVITIES

1. Visit your local FSA, SWCD, or NRCS office. Often these are housed together. Find out what local projects they are involved in. Or invite a guest speaker from one of these agencies to your class.
2. Tour the content of the USDA and the NRCS on the Internet through their homepages at http://www.usda.gov and http://www.nrcs.usda.gov, respectively. Find information on the 2008 or 2012 farm bill.
3. Research the history of the CRP on the Internet.
4. Search the Internet for your state's CREP program. Entering your state's name followed by "Conservation Reserve Enhancement Program" into the Web browser should do it.

APPENDIX 1

Some Basic Science

ATOMS AND ELEMENTS

Elements are the building blocks of all matter. Examples of the 109 known elements include oxygen, carbon, and iron. Each element is assigned a symbol made of a letter or letters from the English or Latin word for the element. For example, oxygen is "O," carbon is "C," and iron is "Fe" from the Latin "ferrous."

The smallest unit of an element is the *atom*. While modern models of the atom are more complex, a simple picture of the atom, called the Bohr model, helps us understand how chemical processes occur in the soil. Atoms are made of three particles: a negatively charged *electron,* a positively charged *proton,* and a neutral *neutron*. According to the Bohr model, protons and neutrons inhabit a *nucleus,* and electrons circle the nucleus like planets orbiting the sun, as in Figure A–1. These electrons occupy "orbitals," each of which will hold a certain number of electrons.

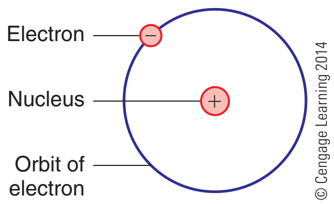


Figure A–1
Hydrogen atom.

The simplest element is hydrogen, which is composed of a single proton and electron, occupying the innermost orbital. Elements get successively heavier and more complex as more protons, neutrons, electrons, and electron orbits are added. Oxygen, for instance, has eight of each particle and electrons occupy two orbitals. The total weight of all the protons, neutrons, and electrons in an atom of an element is its *atomic weight*. Electrons have negligible mass, so the atomic weight of oxygen, with 8 protons and 8 neutrons, is about 16.

COMPOUNDS

Atoms combine to form *molecules.* A molecule is symbolized by writing the atomic symbols of each element in the molecule; a number in the form of a subscript indicates how many atoms of each element are present in the molecule. Thus, water, or H_2O, is a molecule with two atoms of hydrogen combined with one atom of oxygen.

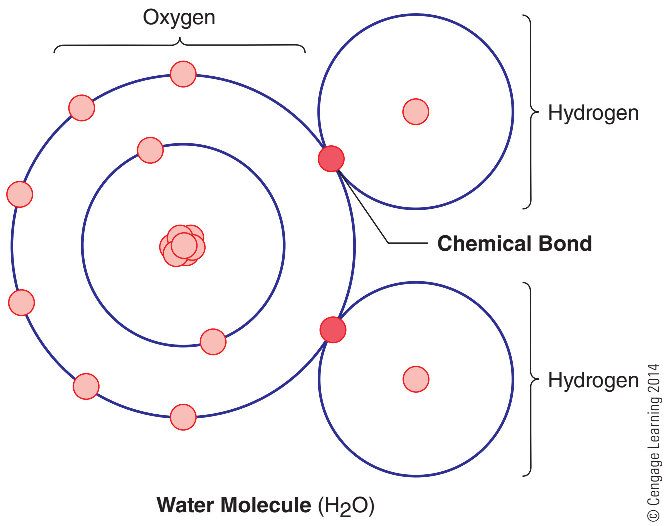


Figure A–2
Water molecule. In many molecules, chemical bonds result from sharing of electrons.

One way for molecules to form is for atoms to join by sharing electrons, as shown for the water molecule in Figure A–2. This sharing fills the outer orbital of the oxygen atom, which can hold eight electrons. A filled outer orbital is more stable than a partially filled one, so oxygen is "eager" to react in ways that will fill that outer orbital. This is one way to form a *chemical bond* between two atoms. There are others.

A collection of like molecules is a *compound,* as in the compound water. Silicon dioxide, or SiO_2, is a compound containing two oxygen atoms attached to a silicon atom. Silicon dioxide is the mineral quartz, the major component of sand and one of earth's most common minerals. Pure solid compounds of the earth's crust, like quartz, are called **minerals**. *Rocks* are mixtures of minerals. Granite, for instance, consists of the minerals feldspar, quartz, and others.

ORGANIC COMPOUNDS

The common minerals are **inorganic**, distinguishing them from a special class of compounds that are labeled **organic**. Organic compounds all contain carbon and hydrogen, and most have oxygen, sulfur, nitrogen, or other elements. Organic compounds are the stuff of life; all life is made of them. When this text refers to organic matter, it refers to organic compounds in the soil, all of which come from living creatures and plants. However, humans also synthesize a variety of organic compounds.

IONS

A normal atom or molecule has an equal number of electrons and protons; their charges balance and the net charge is zero. Sometimes an imbalance occurs, and the resulting atoms or molecules are called **ions**. For instance, when salt (NaCl) dissolves in water, the molecule breaks apart into sodium ions that are short one electron and chlorine ions with an extra electron. Thus, each sodium ion carries a positive charge, while chlorine ions have a negative charge:

$$NaCl \rightarrow Na^{+} + Cl^{-}$$

salt → sodium cations + chlorine anions

solid salt → salt in solution

Positively charged ions are called **cations**, negatively charged ones **anions**. A **solution** results when compounds disassociate in water with ions dissolved in it.

The hydrogen ion, H^{+}, is a special case. Having lost its sole electron, the hydrogen ion, in one form, is simply a single proton. Its presence has a potent effect on many biological and nonbiological systems, including the acidity of soil. This is discussed in Chapter 11.

MOLES

A mole is a unit of measurement, a way of expressing the number of something: numbers of atoms, numbers of molecules, or numbers of charges. A mole of something is 6.02×10^{23}, otherwise known as Avogadro's number. For those not familiar with scientific notation, that is 6.02 followed by 23 zeros. A mole of hydrogen atoms is 6.02×10^{23} atoms. A mole of charges in a solution of calcium ions (Ca^{+2}) is half that because each calcium ion has two charges. A unit used in this text is centimoles of charges; in the metric system, a centimole means 1/100 of a mole.

The concept of moles gives rise to two other measurements. *Molar mass* is the weight of one mole of some substance, whether it be a pure element or compound. The molar mass is simply the atomic weight or molecular weight of the substance in grams. So the molar mass of water, with a molecular weight of about 18, is 18 grams. A unit of concentration in a solution is *molar concentration*, or the number of moles of something in a liter of a solution.

CHEMICAL AND PHYSICAL REACTIONS

Two types of reactions are important in soils: *chemical reactions* and *physical reactions.* Chemical reactions involve the actual rearrangement of atoms to form new molecules and compounds, as in the reaction of hydrogen and oxygen to form water, shown in equation (*a*). The reaction, as written, states that two hydrogen molecules (in the natural environment, hydrogen and oxygen are two-atom molecules) combine with one oxygen molecule to form two molecules of water.

$$(a) \quad 2H_2 + O_2 \rightarrow 2H_2O$$

$$(b) \quad H_2O \text{ (liquid)} \rightarrow H_2O \text{ (solid ice)}$$

In physical reactions, the physical form but not the chemical form changes, as in the freezing of water in reaction (*b*) or the disintegration of rock by physical forces. Both physical and chemical weathering contribute to soil formation. Reaction (*a*) suggests that a chemical reaction is a one-way process. In actuality, all reactions go in both

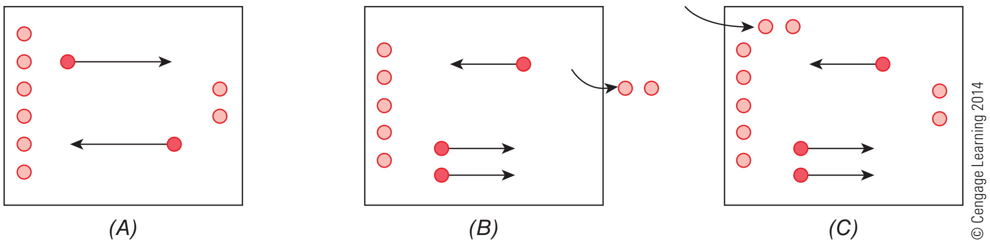


Figure A–3
Chemical reaction equilibria as represented by movement of people in a room. (A) Reaction in equilibrium, people move back and forth but the balance remains the same. (B) Equilibrium is disturbed by people leaving room to right. Reaction shifts to right to compensate for change. (C) Equilibrium is disturbed by people entering room from left. Reaction again shifts to right.

directions at once but will favor one side of the reaction or the other. One might compare a reaction to a room full of people. Assume that 10 people are in a room, and they are asked to go to one side of the room or the other. People who go to the left side are *A* people, those who go to the right are *B* people. In this "reaction," assume 7 people go to the left, and 3 go to the right. We could write this "reaction" as:

$$\underset{\textbf{(7 people)}}{A} \leftrightarrows \underset{\textbf{(3 people)}}{B}$$

In a real reaction, the people do not stop; a few continue to walk back and forth across the room, but the numbers of people will continue to balance out to 7:3 (see *A* in Figure A–3). This balance is called the *equilibrium* of the reaction and is constant for a given reaction at a given condition. The concept of equilibrium is important to understand what happens in soil. An equilibrium is dynamic, not static. In the example, the equilibrium is not maintained by all 10 people remaining statically in one spot.

If the conditions of a reaction change, the equilibrium shifts to try to achieve a new balance. Say that in the room full of people, 2 of the 3 people on the right side of the room leave altogether. To achieve a new equilibrium, the reaction will shift to the right—that is, more people will walk to the right side of the room than back to the left until a new balance is achieved (see *B* in Figure A–3). On the other hand, if a group of people enters the room on the left, the room is "unbalanced" and the "reaction" again shifts to the right to achieve a new equilibrium (see *C* in Figure A–3).

This shifting equilibrium that occurs when the amount of a material on one side of a chemical equation changes we will here call "mass action." The equilibrium shift—say moving the reaction to the left—always works in a direction that reduces the original change. Those of you with knowledge of chemistry recognize this as Le Chatelier's principle: if the conditions of an equilibrium change, equilibrium shifts to minimize the change. This principle is important because it governs chemical processes in the soil, including many related to farming activities such as soil liming or fertilization.

OXIDATION–REDUCTION REACTIONS

A very important type of reaction in the soil is the *oxidation–reduction reaction*. Technically, an oxidation occurs when an element loses an electron in a reaction (oxidation), and some other element gains that electron (reduction). The electron donor (the "loser") is said to be oxidized and the electron acceptor (the "gainer") is said to be reduced. An important oxidation–reduction reaction in the soil is the reduction of ferric iron to ferrous iron under low-oxygen conditions:

$$Fe^{+3} \rightarrow Fe^{+2}$$

$$\text{ferric iron, oxidized iron} \rightarrow \text{ferrous iron, reduced iron}$$

Oxidized iron (ferric), found in aerated soils and colored red to yellow, gains an electron and is reduced to the gray-blue ferrous form. The gray color is a strong indicator of a soil that is usually too wet.

If in the preceding reaction ferric iron acted as an electron acceptor (was reduced), then what gave up that electron or was an electron donor (was oxidized)? The answer is carbon in organic matter, which gave up electrons during the decay process. Ordinarily, in well-aerated soil, oxygen is the most powerful electron acceptor, and aerobic decay is the oxidation of organic matter by microorganisms using oxygen as the electron acceptor.

In soils with little or no oxygen, organisms may use other electron acceptors, like ferric iron.

Most oxidation reactions involve oxygen, hence the term oxidation. Often in the soil, oxidations involve addition of oxygen to a molecule, sometimes with loss of hydrogen. For instance, soil methane (CH_4) in the presence of oxygen is oxidized by certain soil bacteria to carbon dioxide (CO_2). Often reduction involves addition of hydrogen to a molecule, for instance, reduction of gaseous nitrogen (N_2) in the atmosphere to the ammonium molecule (NH_4^+) by other bacteria in root nodules on legumes. Both reactions are discussed in the text.

Very important oxidized forms of elements in the soil include carbon (CO_2, carbon dioxide or CO_3^-, carbonate ion), nitrogen (NO_3^-, nitrate ion), sulfur (SO_4^-, sulfate ion), and iron (Fe_2O_3, ferric oxide). Reduced forms include reduced nitrogen as the ammonium ion (NH_4^+), reduced carbon as methane (CH_4), and organic matter.

ACIDS, BASES, AND SALTS

Certain chemicals in nature, and in the soil, behave as acids or bases. *Acids*, when they dissolve in water, release hydrogen ions, which are simply protons. These reactions are reversible, but how reversible depends on the substance. So, for example:

$$HCl \rightarrow H^+ + Cl^-$$

This acid, hydrochloric acid, is a *strong acid* because it dissociates almost completely to hydrogen and chloride ions. To say that a solution is highly acidic is to say that it contains many hydrogen ions.

A *base* is a substance that combines with hydrogen ions, a substance that *neutralizes* an acid. In the reaction above, chlorine could act as a base because it might combine with the hydrogen ion to create hydrochloric acid again. However, chlorine has little tendency to do so, and so is a very *weak base*. We could say that when an acid dissolves, it produces a hydrogen ion and a base, which is the anion in the original acid.

Weak acids dissociate only partially, creating solutions that are equilibrium mixtures of the acid, hydrogen ions, and the associated base anion. In soil science, such an acid is carbonic acid:

$$H_2CO_3 \leftrightarrow H^+ + HCO_3^-$$

In this reversible reaction carbonic acid partially dissociates to a hydrogen ion and the base ion, bicarbonate. It is carbonic acid that gives soda pop its tang. Because carbonic acid is a weak acid, solutions of it are not as acidic as a solution of a strong acid like hydrochloric acid.

Bicarbonate here is a base. It readily reacts with hydrogen ions to re-create the carbonic acid, reversing the above reaction. Common baking soda, sodium bicarbonate, can be taken as an "antacid" to neutralize stomach acids during indigestion, and the bicarbonate that is dissolved in hard water can dramatically reduce the acidity of soils in potted plants. Every time one irrigates with hard water, one adds bicarbonate to the soil, driving the equilibrium to the left in the above reaction, and removing hydrogen ions from the soil solution.

An example of a *strong base* is lye (sodium hydroxide), which liberates hydroxide ions (OH^-), a very strong base:

$$NaOH \rightarrow Na^+ + OH^-$$

Hydroxide can combine with hydrogen ions to form water. It can neutralize acids:

$$H^+ + OH^- \rightarrow H_2O$$

One definition of a base is a substance that releases hydroxide ions, the most common strong base. In discussing pH in the text, we use that definition and state that basic solutions have high hydroxide concentrations. But this does not cover all possible bases, like bicarbonate.

A product of the reaction of a base and an acid is a *salt*. For example, if one reacts lye with hydrochloric acid, common table salt results:

$$HCl + NaOH \rightarrow NaCl + H_2O$$

Many soils contain salts, and most common fertilizers are salts.

ENERGY

Both chemical and physical reactions in the soil depend on *energy*. Energy is simply the capacity to do work or produce heat. The greater the energy, the more work that can be done. An understanding of energy is important because everything that happens in the soil—the "work" of soil and plants—is fueled by energy. Energy comes in many forms, such as heat, electricity, light, and motion. The following forms are important to soil:

- *Light energy* is energy contained in sunlight. Plants use that energy for photosynthesis, which creates organic matter for the soil.
- *Chemical energy* is energy contained in a chemical bond. During photosynthesis, plants convert energy in sunlight to energy in chemical bonds. This chemical energy is "stored" for later use by the plant or animals that eat it.
- *Potential energy* is stored energy, such as the energy stored in an object that can fall. The energy is released when the object does fall, such as rocks falling off a cliff, water falling over a dam, or rain falling from the sky. Chemical energy is also a form of potential energy. We express the energy of water in the soil as potential energy.
- *Kinetic energy* is the energy of a moving object. Soil erosion by wind and water is a result of motion energy. The amount of energy in a moving object is a function of its mass (m) times velocity (v) squared, according to the following formula:

$$\text{Energy} = \frac{1}{2}mv^2$$

Thus, rapidly moving water can do more work than slowly moving water. The equation says, for instance, that if the velocity of running water doubles, it can do four times as much work (two squared), or cause four times as much erosion.

To understand chemical and physical reactions in the soil, it is important to know two rules. First, *energy can change forms.* For instance, sunlight energy can change to heat energy when it strikes pavement—a fact one can become painfully aware of when walking to the beach barefoot on a sunny day. In the process of transformation, no energy can be either lost to the universe or created. This is the law of conservation of energy, also known as the First Law of Thermodynamics.

Second, *matter tries to achieve the lowest possible energy state.* An electrical-generating dam is a good example. Water at high elevation behind the dam is in a high state of energy—it has a lot of potential energy. By flowing downhill through or over the dam, that potential energy is released to energy of motion. When the water reaches the lower level, it is now at a lower elevation and in a lower-energy state. In the process, the "lost" potential energy was converted to motion. That motion energy can, in turn, be changed to electrical energy when it does the work of turning the turbines in the generating plant. Notice that while water has lost energy, it has not been lost to the universe, but simply converted to other forms. This second rule is a version of the Second Law of Thermodynamics.

These two rules of energy control all the physical and chemical reactions in the soil. They are especially important to the behavior of water in the soil (Chapter 6) and erosion (Chapter 18).

Gradients

One result of the tendency for lower-energy states is the concept of *gradient,* which controls the movement of materials and energy in the soil. A gradient is a change of something over distance. The simplest gradient to understand is a slope, or hill, which is an elevation gradient. A cyclist on top of a hill can coast down the hill without pedaling, because he or she is moving to a lower-energy state. To go up the hill, however, is to go to a higher energy state. To do that, the cyclist must feed in energy—which is to say, pedal the bike.

The preceding example presents a rule about gradients—that *movement down a gradient occurs without effort, while movement up a gradient requires an input of energy.*

Many gradients exist in nature. A spoon in a hot cup of coffee creates a temperature gradient. Heat will flow naturally from the hot end in the cup to the cool end where you hold it. Water will move in the soil from where it is moist to where it is dry (moisture gradient). Vapors from an opened perfume bottle will scent an entire room as they move from where they are concentrated near the bottle to where they are less concentrated (this is called diffusion along a concentration gradient). A similar diffusion through soil water moves soil nutrients toward plant roots.

Gradients vary in how steep they are. A hill with a large change in elevation over a short distance is steep; the same change of elevation over a longer distance is a more shallow gradient. Movement is quicker on steeper gradients. Heat will be lost more quickly in a house with 4-inch-thick walls than one with 6-inch walls, and heat will be lost more quickly the colder the temperature outside.

Remember that normal movement is down a gradient—from where there is more of something, like heat, water, or elevation, to where there is less. The opposite movement requires an input of energy—which is the same as saying, it takes work. Water flows downhill spontaneously, but it has to be pumped to make it go uphill.

CLIMATE CHANGE

This text makes many references to global climate change. Climate change results from rising temperature in the atmosphere; as atmosphere is global, so is climate change. The increase in heat results from increasing concentrations of gases in the atmosphere, called *greenhouse gases*, that prevent heat from escaping into outer space.

The earth is warmed by radiant energy (sunlight) that reaches earth from the sun. Most radiant energy emitted by the sun is in visible wavelengths of light (Figure A–4). The atmosphere is largely transparent to visible light; that is, gases in the atmosphere do not block most visible light. That energy warms the earth.

All objects emit light energy, including the reader. The wavelength of light emitted by an object depends on its temperature. The temperature of the earth is such that it emits radiation in wavelengths longer than visible light, around the infrared range (Figure A–4). That radiant energy mostly escapes back into outer space, cooling the planet. The temperature of the earth remains stable over time if incoming energy from the sun is balanced by outgoing radiation.

Greenhouse gases in the atmosphere, while mostly transparent to visible light, block the outgoing longer-wave radiation of the earth. These greenhouses gases include weak ones such as water vapor, strong ones such as carbon dioxide, and even stronger ones such as methane. If carbon dioxide is given a climate change potential value of 1, methane has a value of 23 and nitrous oxide a value of 296. These are naturally occurring, and the earth would be much colder than it is if they were not in the atmosphere.

Climate change is occurring because we inject greenhouse gases into the atmosphere by burning fossil fuels, destroying and burning forests (a large reservoir of

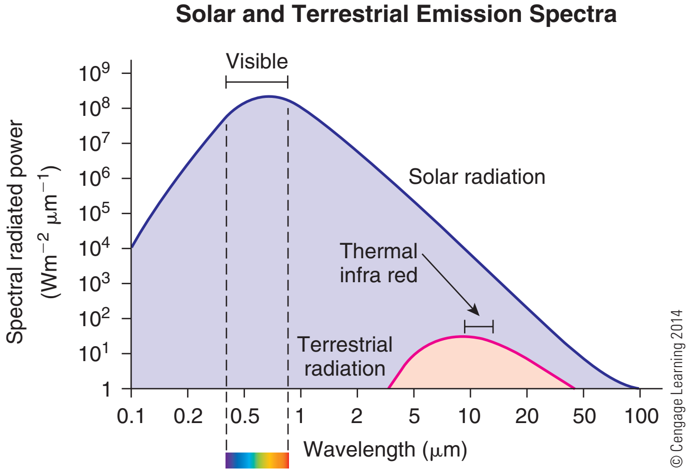


Figure A–4
Radiated power curves for sunlight and radiation from the warmed earth. Light hits the earth mostly as shortwave radiation, around the range of visible light. The warmed earth radiates energy into space as longwave radiation that can be blocked by greenhouse gases.

carbon), and numerous other activities. Before the industrial revolution, the atmosphere contained about 280 parts per million (ppm) carbon dioxide; as of 2000, the amount had risen to 370 ppm, and is bound to rise higher in the future.

This text takes up the topic of climate change because soil interacts with the atmosphere in ways that increase or decrease atmospheric concentration of those gases. Soil can be managed in ways that speed or slow climate change.

Predicted results of climate change include rising average global temperatures. This does mean in all locations every day. Today's temperatures are *weather*, a short-term event. Climate is long term. One should not be confused by short-term weather events such as a cold spell or heavy snowfalls into thinking climate change is not occurring.

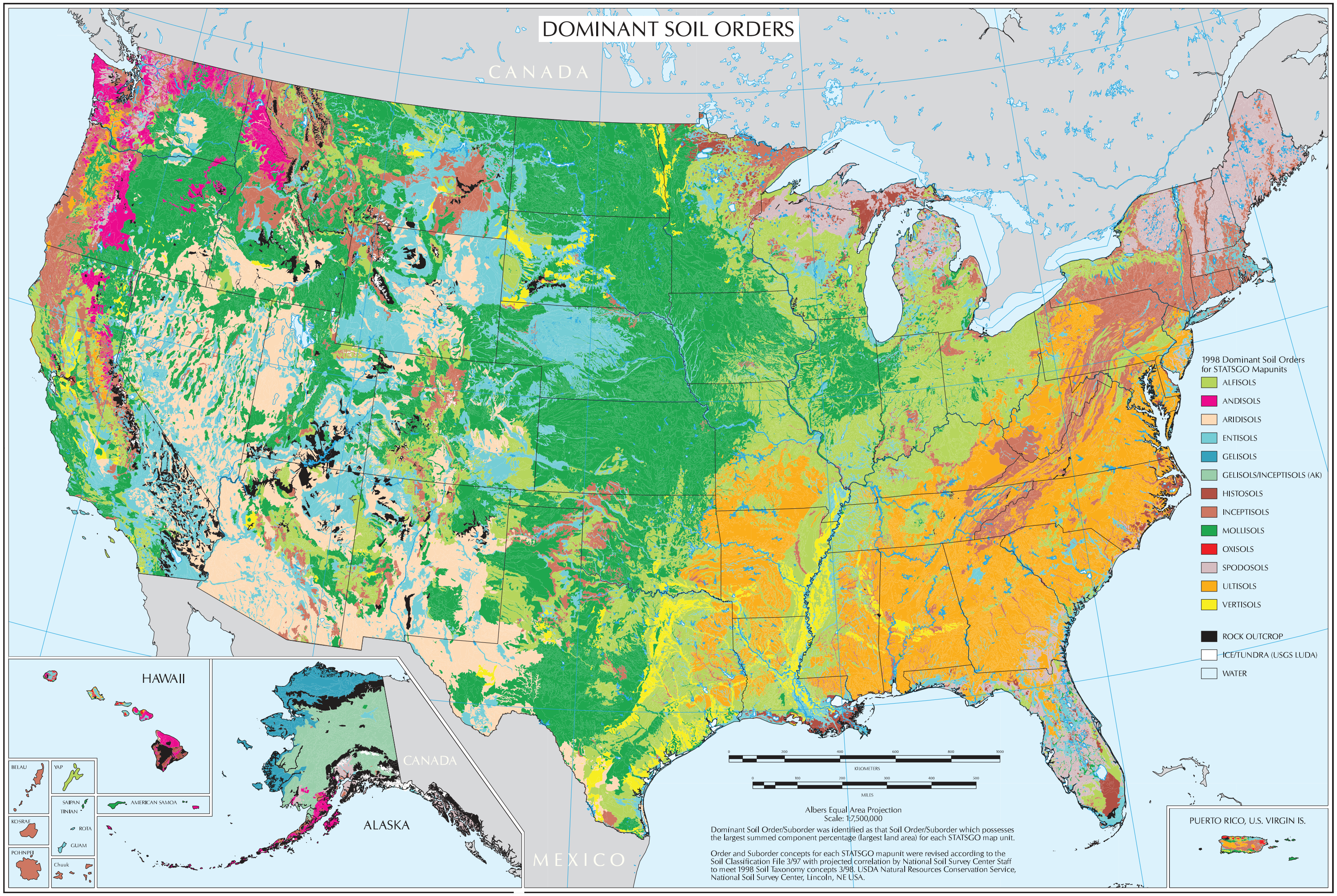
Climate is also predicted to become more erratic, with greater frequency of severe weather events such as extreme storms with high-intensity rainfall, severe and prolonged droughts, or longer and hotter heat waves. Extreme weather events are becoming ordinary, with a resulting increased frequency of related events such as forest fires and floods. Indeed, the term *global warming* fails to capture all the effects of the phenomenon; climate change is much more accurate a term.

If soil can affect climate, these climatic changes will, in turn, affect soils. For instance, regions that experience more powerful rainfalls will see more soil erosion. Because climate is one of the soil-formation factors (Chapter 2), soils will slowly change over time.

The current state of knowledge about climate change was published in *Climate Change 2007* by the Intergovernmental Panel on Climate Change (IPCC). It can be accessed online at http://www.ipcc.ch/. That report includes contributions of agriculture to climate change and its possible role in its mitigation. The new edition of the report was being prepared as this text was being revised and is expected to be released around 2013.

APPENDIX 2

Soil Orders of the United States



Courtesy of USDA

Figure A–5
Dominant soil order map of the United States.

APPENDIX 3

Soil Horizon Symbol Suffixes

These lowercase letters are used as suffixes to label certain types of master horizons. One or more suffixes may follow a master horizon designation—such as Bky—which indicates a B horizon that has accumulated both carbonates (k) and gypsum (y). The main symbols are shown as follows:

a Highly decomposed (sapric) organic material. This suffix is used with the O horizon.

b Buried horizon. Such a soil layer is an old mineral horizon buried by sedimentation or other processes.

c Concretions or hard nodules. A nodule or concretion is a hard "pocket" of soil cemented by iron or another substance.

d Physical root restriction, either human made or a naturally dense layer that roots can enter only through fractures.

e Moderately decomposed (hemic) organic material. Used with the O horizon.

f Frozen soil. A horizon, usually the C, that contains permanent ice (permafrost).

g Strong gleying. Such a horizon is gray and mottled, the color of reduced (nonoxidized) iron, resulting from saturated conditions.

h Illuvial accumulation of organic matter. The symbol is used with the B horizon to show that complexes of humus and sesquioxides have washed into the horizon. Includes only small quantities of sesquioxides. May show dark staining.

i Slightly decomposed (fibric) organic matter. Used with the O horizon.

k Accumulation of carbonates (CO_3^{-2}). Indicates accumulation of calcium carbonate (lime) or other carbonates in the B or C horizons.

m Cementation. The symbol indicates a soil horizon that has been cemented hard by carbonates, gypsum, or other material. A second suffix indicates the cementing agent, such as “k” for carbonates. This is a hardpan horizon; roots penetrate only through cracks.

n Accumulation of sodium. Indicates a high accumulation of exchangeable sodium, as in a sodic soil.

o Accumulation of sesquioxide clays after intense weathering.

p Plowing or other human disturbance. Horizon was heavily disturbed by plowing, cultivation, pasturing, or other activity. Applies to O and A horizons.

q Accumulation of silica (SiO_2).

r Weathered or soft bedrock. Used with C horizon to indicate bedrock that can be dug with spade and roots can enter through cracks.

s Illuvial accumulation of both sesquioxides and organic matter. Both the organic matter and sesquioxide components of humus–sesquioxide complexes are important.

t Accumulation of silicate clays. Clay may have formed in horizon or moved into it by illuviation, usually as coatings on ped faces. Mostly used in B horizon, sometimes in C.

v Plinthite. An iron-rich, humus-poor material common to tropical soils that hardens when exposed to air. B and C horizons.

w Development of color or structure. The symbol indicates that a B horizon has developed enough to show some color or structure but not enough to show illuvial accumulation of material.

x Fragipan or other noncemented natural hardpans. These are horizons that are firm, brittle, or have high bulk densities from natural processes.

y Accumulation of gypsum ($CaSO_4$) in B or C.

z Accumulation of salts more soluble than gypsum in B or C.

APPENDIX 4

Land Evaluation

Land may be evaluated for a number of uses, such as suitability for row crops, home landscapes, or building sites. Such evaluations might be done by soil scientists, land planners, landscape designers, or even students engaged in a soil-judging contest. While land evaluation purposes and methods vary between regions of the country, this appendix suggests some simple and general soil features to use when evaluating a soil.

DEFINITION OF TERMS AND CRITERIA

Suitability

Land can be said to be good, fair, or poor for any use. The same terms can also be applied to a particular feature of the land, such as slope or soil texture. Looking at the chart that follows, for each land use there is a series of criteria listed on the same line to the right.

Each can be rated, and the "total" used to rate the land:

- Good land is well suited to the use being considered. There are no serious limitations or hazards. Ratings for each criterion are good, or perhaps a couple are fair.
- Fair land is suitable for the use if a few limitations are corrected. Several of the features are rated as fair.
- Poor land is unsuitable for the use, or corrections are too expensive to be practical. Even one or two severe limitations may be enough to gain this rating, or a large number of "fair" descriptions.

Slope

Slope is expressed as a percentage. For instance, a slope of 2 percent suggests a 2-foot change of elevation over a 100-foot horizontal distance. Figure 3–7 gives some slope ranges that may help interpret these numbers. Changing slope would involve expensive earth moving.

Soil Texture

Chapter 4 describes how to determine a soil texture. The textural class groupings used in this chart are grouped as follows:

Group	**Textural Classes**
Fine	Sandy clay, silty clay, clay
Moderately fine	Sandy clay loam, silty clay loam, clay loam
Medium	Silt, silt loam, loam
Moderately coarse	Sandy loam
Coarse	Sand, loamy sand

Except for small areas, such as a garden, texture cannot be changed practically.

Flooding

Flooding concerns how often or how long the land is actually covered with water during the season. Such flooding could be due to stream flooding, heavy rains, or snowmelt. Flooding may be able to be corrected, in some small areas, by earth moving to change drainage patterns. In many cases, only large-scale projects such as the construction of levees can solve these problems.

Internal Drainage

Internal drainage can be determined from Figure 4–19. Many cases of poor drainage can be corrected by installing drainage systems, and excessive drainage may be improved by irrigation.

Depth to Restrictive Layer

Restrictive layers can interfere with rooting depth and plant anchorage, roadbeds, foundations, and home drain fields. Such layers could be bedrock, soil pans, water tables, or others. Some can be corrected, such as ripping a soil pan, while bedrock cannot be altered easily.

Available Water for Plants

The available water is here rated as the number of inches of water held in the top 5 feet of soil. Because most soils will contain layers, one will have to add the capacity of each layer down to 5 feet. Figure 9–22 rates the water retention of soil textures. Here, a capacity greater than 9 inches for 5 feet is good, 6 to 9 inches is fair, and less than 6 inches is poor. Poor capacity can be alleviated by irrigation, where practical and acceptable.

Erodibility

Erodibility is related to slope, texture, and other factors discussed in Chapter 18. Classes are as follows:

- Slight means that under average conditions there is little chance of excessive erosion. Slopes are gentle and short, and internal drainage is good. Wind erosion is unlikely.
- Moderate could occur on medium- or fine-textured soil on gentle slopes over 300 feet long, or shorter moderate slopes. Wind erosion is possible due to texture or lack of cover.
- Severe erodibility occurs on slopes over 12 percent, or areas that experience teaches are quite erodible.

The Erosion Index described in Chapter 18 could be used to infer erodibility.

Other Features

Other features may also limit a soil for certain uses. Examples are stoniness, soil pH, soil fertility, or salinity. Some of these can be improved easily, such as liming agricultural soil to raise pH. On the other hand, improving soil fertility is more difficult for forest uses.

Site Inspection

Much of the information needed for this evaluation can be obtained from published soil surveys. As a lab exercise for students, a soil pit should be dug to allow examination of the soil profile.

Select an area of uniform character, preferably a single mapping unit on a soil map. Dig a pit measuring 3 feet × 3 feet at the surface, and about 3 feet deep. Orient the pit so that the sun shines on the side to be observed. That side should be vertical; the other side can be sloping to save digging.

Some of the information needed can be discovered from examining the pit. Other information, like the slope, can be obtained from the surroundings. The instructor will need to provide such information as flooding.

As the student examines each feature, he or she should circle the best description on the chart included in this appendix. Then consider how important the feature is, or how easily it can be corrected. Finally, come up with an overall rating, as described earlier in this appendix.

Information in this appendix is based on Halsey, Clifton F. (1974). Environmental Education Activity Sheet #1: Selecting suitable uses for land. St. Paul, Minnesota: University of Minnesota, Agricultural Extension Service, Bulletin Room.

SELECTING SUITABLE USES FOR LAND

			Features of the Land and Soil						
Use	Suitability	% Slope	Soil Texture (surface soil only unless specified otherwise)	Flooding During Growing Season or Use (frequency/duration)	Internal Drainage	Depth to Restrictive Layer (in.)	Available Water for Plants (in.) Capacity in 5 ft deep	Erodibility	Other Important Features Not Easily Improved
Home lawns, shrubs, and gardens	Good—no important limitations	0–6	Medium, moderately coarse	None	Well drained, moderately well drained	More than 36	More than 9	Slight	
	Fair—1 or 2 important limitations	6–12	Moderately fine, fine, coarse	Once a year, not over 3 days	Somewhat poor, poor	20–36	6–9	Moderate	Stony, compacted
	Poor—severe limitations	More than 12	Organic	More frequent or more than 3 days	Excessive	Less than 20	Less than 6	Severe	Moderately to strongly alkaline, severely compacted
Cultivated crops	Good	0–6	Medium, moderately coarse	None	Well or moderately well drained	More than 36	More than 9	Slight	
	Fair	6–12	Moderately fine, fine, organic	Once a year, less than 48 hours	Somewhat poor (needs drainage)	20–36	6–9	Moderate	Stony
	Poor	More than 12	Coarse	More frequent, longer	Poor or excessive	Less than 20	Less than 6	Severe	Moderately to strongly alkaline
Permanent grass pasture	Good	0–18	Medium or moderately fine, fine	Up to 4 times annually, less than 48 hours	Well or moderately well drained	More than 36	More than 9	Slight	
	Fair	18–25	Moderately coarse	More than 48 hours	Somewhat poor, poor	20–36	6–9	Moderate	
	Poor	More than 25	Coarse, organic	5 times or more annually	Excessive	Less than 20	Less than 6	Severe	Moderately to strongly alkaline

SELECTING SUITABLE USES FOR LAND (*Continued*)

		Features of the Land and Soil							
Use	Suitability	% Slope	Soil Texture (surface soil only unless specified otherwise)	Flooding During Growing Season or Use (frequency/ duration)	Internal Drainage	Depth to Restrictive Layer (in.)	Available Water for Plants (in.) Capacity in 5 ft deep	Erodibility	Other Important Features Not Easily Improved
Forests—conifers, for wood products, Christmas trees	Good	0–18	(Entire Root Zone) Medium, Moderately Coarse	Never	Well drained, moderately well drained	More than 20	More than 6		Soil fertility: medium to high, pH: 5 to 6
	Fair	18–45	Moderately fine, coarse	Never	Somewhat poor, excessive		3–6		Soil fertility: low
	Poor	More than 45	Fine, organic	Any flooding	Poor	Less than 20	Less than 3		
Forest—deciduous, for wood products	Good	0–18	(Entire Root Zone) Medium, moderately fine	Once in 10 years	Well drained, moderately well drained	More than 20	More than 9		Soil fertility: medium to high, pH: 6 to 8
	Fair	18–45	Moderately coarse	Annual spring flooding	Somewhat poor, excessive		6–9		Soil fertility: low
	Poor	More than 45	Coarse, fine, organic	More than once annually	Poor	Less than 20	Less than 6		PH: less than 5, more than 8
Forest—wildlife habitat	Good	0–25	(Entire Root Zone) Moderately coarse to moderately fine	Once in 10 years, less than 24 hours	Well or moderately well drained	More than 20	More than 9		
	Fair	25–50	Coarse or fine, organic	Up to 4 times annually, 24 to 48 hours	Somewhat poor, excessive		6–9		
	Poor	More than 50		More frequent, more than 48 hours	Poor	Less than 20	Less than 6		pH: less than 5, more than 8

continues

SELECTING SUITABLE USES FOR LAND (*Continued*)

		Features of the Land and Soil							
Use	Suitability	% Slope	Soil Texture (surface soil only unless specified otherwise)	Flooding During Growing Season or Use (frequency/duration)	Internal Drainage	Depth to Restrictive Layer (in.)	Available Water for Plants (in.) Capacity in 5 ft deep	Erodibility	Other Important Features Not Easily Improved
Water fowl habitat	Good	Can have surface water continuously, open water all summer			Poor drainage				
	Fair	Can have surface water and open water during spring only			Somewhat poorly drained				
	Poor	Can have short periods of open water			Moderately well to excessively drained				
A. Athletic, play and picnic grounds	A. Good B. Good	0–2 0–6	Medium, moderately coarse	None during use	Well and moderately well drained	More than 36	More than 9	Slight	
B. Public campgrounds, primitive campsites	A. Fair B. Fair	2–6 6–12	Coarse, moderately fine	Once—less than 24 hours	Somewhat poor	20–36	6–9	Moderate	
	A. Poor B. Poor	More than 6 More than 12	Fine, organic	2–3 times during season	Poor, excessive	Less than 20	Less than 6	Severe	
Nursery	Good	0–3	Moderately coarse, medium (BR), medium, medium fine (BB)	None	Well drained	More than 48	More than 9	Slight	
	Fair	3–6	Coarse, medium fine (BR), moderately coarse, fine (BB),	Once a year, not over 1day	Moderately well drained	36–48	6–9		Stony
	Poor	More than 6	Fine (BR) coarse (BB)	More frequent or longer	Excessive, Somewhat poor, poor	Less than 36	Less than 6	Moderate, severe	Large stones

SELECTING SUITABLE USES FOR LAND (*Continued*)

			Features of the Land and Soil						
Use	Suitability	% Slope	Soil Texture (surface soil only unless specified otherwise)	Flooding During Growing Season or Use (frequency/ duration)	Internal Drainage	Depth to Restrictive Layer (in.)	Available Water for Plants (in.) Capacity in 5 ft deep	Erodibility	Other Important Features Not Easily Improved
Land exposed to erosion during construction or use	Good	0–2	Coarse, moderately coarse					None to slight	
	Fair	2–6	Medium to fine					Moderate	
	Poor	More than 6						Severe	
Houses and other low buildings	Good	0–6	To 5 ft deep, coarse, moderately coarse, medium		Excessive, well drained, moderately well drained, none	To bedrock, water more than 36			
	Fair	6–12	Moderately fine	None	Somewhat poor	20–36			
	Poor	More than 12	Fine, organic	Any	Poor	Less than 20			
Basements and utility excavations	Good	0–6	To 5 ft deep, medium, moderately coarse, coarse	None	Well drained, excessive	To bedrock, water more than 5 ft			
	Fair	6–12	Moderately fine	None	Moderately well drained	$3\frac{1}{2}$–5 ft			
	Poor	More than 12	Fine, organic	Any	Somewhat poor, poor	Less than $3\frac{1}{2}$ ft			

continues

SELECTING SUITABLE USES FOR LAND (*Continued*)

			Features of the Land and Soil						
Use	**Suitability**	**% Slope**	**Soil Texture (surface soil only unless specified otherwise)**	**Flooding During Growing Season or Use (frequency/duration)**	**Internal Drainage**	**Depth to Restrictive Layer (in.)**	**Available Water for Plants (in.) Capacity in 5 ft deep**	**Erodibility**	**Other Important Features Not Easily Improved**
Home sewage absorption fields	Good	0–6	To 5 ft deep, medium, moderately coarse	None	Well drained	6 ft			
	Fair	6–12	Moderately fine	None	Moderately well drained	6 ft			
	Poor	More than 12	Coarse, fine, organic	Any	Somewhat poor, poor, excessive	Less than 6 ft			
Local streets	Good	0–6	To 5 ft deep, moderately coarse, coarse	None	Excessive, well drained, moderately well drained	To bedrock, more than 36			
	Fair	6–12	Moderately fine, medium	Once a year, not over 3 days	Somewhat poor	20–36			
	Poor	More than 12	Fine, organic	More frequent, more than 3 days	Poor	Less than 20			

Data from Halsey, Clifton F. (1974). Environmental Education Activity Sheet #1: Selecting suitable uses for land. St. Paul, Minnesota: University of Minnesota, Agricultural Extension Service, Bulletin Room.

APPENDIX 5

Preferred Soil Characteristics for Selected Trees

The following table suggests soil preferences for a number of trees. The information is gathered from a number of sources, including the author's own experience. No information was found for blank entries. These are only general guidelines, and in fact, there is often disagreement between experts. Please keep in mind that a particular plant variety, growing in a particular location, may differ from suggestions in this table.

Botanical Name	Common Name	Text	pH	Comp	Drain	Salt
Abies balsamea	Balsam fir	CM	4.0–6.5	I	2–4	S
A. concolor	White fir	CM	4.0–6.5	S	3–5	I
Acer ginnala	Amur maple	CMF	4.0–7.5	I	3–5	I
A. campestre	Hedge maple	CMF	5.0–7.5	R	3–5	I
A. negundo	Box elder	MF	5.0–7.5	R	2–5	I
A. palmatum	Japanese maple	CMF	5.0–6.5	S	4–5	I
A. platanoides	Norway maple	MF	5.0–7.5	I	3–5	I
A. rubrum	Red maple	CMF	4.5–6.5	S	2–4	S
A. saccharinum	Silver maple	CMF	5.5–6.5	R	2–5	I
A. saccharum	Sugar maple	MF	6.0–7.0	S	3–4	S
Aesculus glabra	Ohio buckeye	CMF	6.0–7.0	I	3–5	I
Alnus glutinosa	European alder	MF	5.0–7.0	I	1–5	I
Amelanchier sp.	Serviceberries	CM	6.0–7.0	S	4–5	S
Betula nigra	River birch	CMF	4.0–6.5	R	2–4	I

continues

(*Continued*)

Botanical Name	Common Name	Text	pH	Comp	Drain	Salt
B. papyrifera	Paper birch	CM	5.0–7.0	S	3–4	I
Catalpa speciosa	Eastern catalpa	CMF	6.0–8.0	R	2–5	I
Cedrus atlantica	Blue atlas cedar	CMF	5.0–7.0	S	3–5	I
C. deodora	Deodor cedar	CMF	5.0–7.0	I	3–5	
Celtis occidentalis	Common hackberry	CMF	6.0–8.5	I	2–5	I
Cercidiphyllum japonicum	Katsura tree	MF	5.0–7.0	S	3–4	S
Cercis canadensis	Eastern redbud	CMF	6.0–8.0	I	3–4	S
Cornus alternifolia	Pagoda dogwood	M	6.0–7.5	I	3–4	I
C. florida	Flowering dogwood	CMF	5.0–6.5	S	3–4	S
C. kousa	Kousa dogwood	M	4.5–6.5	S	4–5	S
Crataegus sp.	Hawthorns	CMF	5.5–7.5	I	3–6	I
X *Cupressocyparis leylandii*	Leyland cypress	CMF	5.0–7.5	I	4–5	R
Diospyros virginiana	Persimmon	CMF	5.5–7.0	I	2–5	I
Eleagnus angustifolia	Russian olive	CMF	5.0–8.0	I	3–6	R
Eucalyptus sp.	Gum trees	CMF	6.0–8.0	I	4–6	I
Fagus grandifolia	American beech	CM	5.0–6.5	S	3–4	I
Fraxinus americana	White ash	CMF	6.0–7.5	I	3–4	R
F. nigra	Black ash	MF	4.0–6.5	R	1–3	R
F. pennsylvanica	Green ash	CMF	5.5–7.0	R	2–5	I
Ginkgo biloba	Ginkgo	CMF	5.5–7.5	R	3–4	I
Gleditsia triacanthos	Honeylocust	MF	6.0–7.5	R	3–4	R
Gymnacladus dioicus	Kentucky coffeetree	MF	6.5–7.5	I	3–4	R
Ilex aquifolium	English holly	CM	4.0–6.0	I	2–4	
I. opaca	American holly	CMF	5.0–7.0	R	3–5	R
Juglans nigra	Black walnut	MF	6.5–8.5	I	3–5	I
Juniperus chinensis	Chinese juniper	CMF	6.0–7.5	S	4–5	I
J. scopulorum	Rocky mountain juniper	CM	6.0–8.0	S	4–6	I
J. virginiana	Eastern red cedar	CMF	6.0–8.0	S	3–6	I
Koelreuteria paniculata	Golden raintree	CMF	5.5–7.5	I	3–5	S
Lagerstroemia indica	Crape myrtle	CMF	5.0–7.5	I	3–4	I
Larix laricina	Tamarac	CMF	4.5–7.5	R	1–4	I
Liquidambar styraciflua	Sweetgum	CMF	5.5–6.5	R	2–5	I
Liriodendron tulipifera	Tulip tree	MF	5.5–6.5	S	4–5	S

(*Continued*)

Botanical Name	Common Name	Text	pH	Comp	Drain	Salt
Magnolia grandiflora	Southern magnolia	CMF	5.0–7.0	I	2–6	R
M. virginiana	Sweetbay magnolia	CMF	5.0–6.5		1–4	I
Malus spp.	Crabapple, apple	MF	5.0–7.5	R	3–5	I
Morus alba	White mulberry	CMF	5.0–8.0	I	3–5	R
Nyssa sylvatica	Black gum	CM	5.0–6.5	I	1–4	I
Ostrya virginiana	Ironwood	CMF	6.0–8.0	S	4–6	S
Picea glauca densata	Black Hills spruce	MF	4.0–6.5	S	3–5	I
P. pungens	Colorado spruce	MF	4.0–7.0	S	3–5	I
Pinus banksiana	Jack pine	CM	4.0–6.5	S	4–6	S
P. flexilis	Limber pine	CM	4.0–7.0	S	4–6	S
P. nigra	Austrian pine	CM	5.0–7.0	S	3–5	I
P. ponderosa	Ponderosa pine	CM	4.0–6.5	S	3–6	I
P. resinosa	Red pine	CMF	4.0–6.5	S	3–6	S
P. strobus	White pine	CMF	4.0–6.5	S	3–5	S
Pistache chinensis	Chinese pistachio	CMF	5.0–7.5	I	3–6	I
Platanus occidentalis	Sycamore	CMF	6.0–8.5	R	2–5	S
Populus deltoides	Cottonwood	CMF	6.5–7.5	R	2–5	I
P. tremuloides	Quaking aspen	CMF	4.5–6.5	S	4–6	I
Prunus sp.	Plums, cherries	CMF	5.0–7.0	S	3–4	I
Pseudotsuga menziesii glauca	Douglas fir	CM	5.5–6.5	S	4–5	S
Pyrus ussuriensis	Ussurian pear	MF	6.0–7.5	I	2–6	
P. calleryana	Callery pear	CMF	5.0–7.0	R	2–5	I
Quercus alba	White oak	CMF	5.5–7.0	S	4–6	I
Q. bicolor	Swamp white oak	MF	5.0–6.5	R	1–5	I
Q. macrocarpa	Burr oak	CMF	4.0–8.0	S	3–6	I
Q. palustris	Pin oak	MF	4.5–6.5	R	2–5	S
Q. phellos	Willow oak	CMF	4.5–6.5	R	2–4	I
Q. rubra	Red oak	CMF	4.5–6.5	S	4–5	I
Q. shumardii	Shumard oak	CMF	6.0–8.0	I	2–5	I
Q. virginiana	Live oak	CM	5.0–8.0	I	3–6	R
Rhus sp.	Sumacs	CMF	5.5–7.5	S	4–6	I
Salix sp.	Willows	CMF	6.0–7.5	I	1–4	I
Sapindus drummondii	Soapberry	CM	6.0–8.0	I	3–6	S
Sassafras albidum	Sassafras	MF	5.5–6.5	S	4–6	I
Sophora japonica	Japanese pagodatree		5.5–7.5		3–5	R
Sorbus sp.	Mountain ash	CMF	5.0–7.0	I	3–5	S

continues

(*Continued*)

Botanical Name	Common Name	Text	pH	Comp	Drain	Salt
Taxodium distichum	Baldcypress	CMF	6.0–6.5	R	1–4	I
Thuja occidentalis	Arborvitae	MF	6.0–8.5	R	2–4	I
Tilia sp.	Lindens	CMF	5.5–7.5	S	4–5	S
Tsuga canadensis	Eastern hemlock	MF	4.0–6.5	S	3–4	S
Ulmus americana	American elm	M	6.0–8.5	I	2–5	I
Zelkova serrata	Japanese zelkova	CMF	5.0–7.0	R	3–4	I

Key

Texture:

C—coarse texture

M—medium coarse, medium, medium fine

F—fine

Compaction and salt:

S—sensitive

I—intermediate

R—resistant

Drainage:

1—very poorly drained

2—poorly drained

3—moderately poorly drained

4—moderately well drained

5—well drained

6—excessively well drained

GLOSSARY

A

Acid soil. A soil that contains more hydrogen ions than hydroxyl ions; soil pH is less than 7.0.

Actinomycete. An order of microbes common to soil; are bacteria but resemble fungi in having a mycelium. Important decomposers.

Adhesion. Force of attraction between two different substances. In soil, used to define the force that attracts water to soil particles.

Adhesion water. Inner layer of water molecules in a water film around a soil particle, held tightly by adhesion so it cannot move or be absorbed by plants.

Adsorption. Bonding of an ion or compound to a solid surface, usually temporarily. In soil, cations are adsorbed on clay and humus particles.

Aeration pores. Large (noncapillary) pores that normally drain free of liquid water because of gravitational drainage and fill up with air.

Aeration, turf. The procedure of removing numerous small cores of soil from turf to relieve compaction and improve soil aeration and water infiltration.

Aerobic. An adjective applied to organisms that grow, or processes that occur, in the presence of oxygen.

Agricultural lime. Products that neutralize acidity and contain Ca^{+2} and/or Mg^{+2} (carbonates, oxides, and hydroxides).

Air-dry soil. Soil allowed to dry out in open air without heating. Still contains hygroscopic water.

Alfisol. One of 12 soil orders. A mineral soil, usually formed under forest, common to northern and midwestern states. Usually has brown surface horizon with medium to high base content and a B horizon with illuvial accumulation of clay.

Algae. Simple chlorophyll-containing plants. Single-celled algae add organic matter to soil by photosynthesis.

Alkaline soil. A soil that contains more hydroxyl ions than hydrogen ions; pH greater than 7.0.

Alkalinity. A measure of the carbonate and bicarbonate content of water.

Allelopathy. Suppression of the growth of plants by substances exuded by the roots of other plants.

Alluvial fan. A fan-shaped alluvial deposit formed where flowing water slows down and spreads out at the base of a slope.

Alluvial soil. A soil developed from mud deposited by running water.

Amendment, soil. A substance mixed into the soil to improve its properties, excluding fertilizer.

Amino acid. A nitrogen-containing organic acid, each with an amino group ($–NH_2$) and an organic acid group (–COOH), that links into chains to form proteins.

Ammonia volatilization. Loss of NH_3 gas from the soil surface.

Anaerobic. (1) An adjective applied to organisms that grow, or processes that occur, in the absence of oxygen. (2) An adjective applied to soil void of oxygen.

Anchorage. Function of soil to hold plant firmly in place.

Andisol. Soil order with volcanic parent materials.

Anion. An ion with a negative or minus charge.

Anion exchange. Total sum of the number of exchangeable anions a soil can adsorb, expressed as milliequivalents per 100 grams of soil, or as centimoles charge per kilogram of soil.

Antagonism. The suppression of the growth of one organism by another organism by the production of toxic or growth-inhibiting (antibiotic) substances.

Antibiotic. A substance produced by one species of organism that will kill or inhibit growth of some other organism.

Antitranspirants. Compounds that slow transpiration by plants to reduce water loss.

Aquifer. An underground formation that holds water. It is porous enough that water can flow through it to a well, so can be a source of groundwater.

Arable land. Land suitable for the production of cultivated crops.

Arid climate. A low-precipitation region where evapotranspiration greatly exceeds precipitation. Receives too little rainfall to produce crops without irrigation.

Aridosol. One of 12 soil orders, common to arid regions. Soil is dry and low in organic matter.

Arthropods. A phylum of animals with no backbone, jointed body and legs, and usually a hard shell. Includes such soil animals as insects, spiders, sowbugs, and others.

Association, soil. A soil mapping unit in which two or more taxonomic soil units that occur together are combined.

Autotroph. An organism that can produce its own food from carbon dioxide and/or carbonates by photosynthesis or oxidation of inorganic compounds.

Autotrophic. Capable of producing one's own food from carbon dioxide and/or carbonates by photosynthesis or oxidation of inorganic compounds.

Available nutrient. An essential element, or nutrient, in the soil in a form that plants can absorb into roots.

Available water. Mostly cohesion water, defined as lying between the field capacity and the wilting point (–1/3 to –15 bars, or –3.3 to –1.5 MPa soil matric potential).

B

Banding. Placement of fertilizer, at planting, near the seed. May also be applied to surface or subsurface placement of fertilizer in strips.

Base saturation. The ratio of the quantity of exchangeable bases to the cation exchange capacity.

Basic soil. *See* alkaline soil.

Bedrock. Solid, or consolidated, rock lying under the soil. It may be, but is usually not, the parent material of the soil lying above it.

Beneficial element. Chemical element that may play a beneficial role in the development of many plants but that does not meet the criteria for being considered an essential element.

Best Management Practice (BMP). A practice recommended to reduce environmental impact of such activities as farming or land development, that is practical for the practitioner. In this text, applied to such land management practices as soil conservation, manure handling, stormwater management, and others.

Biopore. Large soil macropore created by life, for example, earthworm tunnels or channels remaining after root decay.

Bioremediation. The use of biological processes and agents such as plants or microbes to help degrade and thereby clean up environmental contaminants.

Biosolids. *See* sewage sludge.

Bioswale. Swale, or shallow ditch, heavily planted, designed to absorb runoff water.

Blocky structure. Blocklike peds commonly found in B horizons. Two kinds are recognized: angular or subangular.

Border-strip irrigation. Surface irrigation in which water is run into strips bounded by low earthen borders.

Bradyrhizobia. Genus of symbiotic nitrogen-fixing bacteria hosted by soybeans.

Broadcasting. Application of fertilizer by spreading on the soil surface, usually before planting and incorporated by tillage.

Brown fields. Urban land rendered unusable by soil contamination or other problems, improved by remediation or abatement.

Buffer strip. A field border of soil-conserving vegetation or mulch; leaving strips of tall vegetation at right angles to the prevailing wind.

Buffer test. Method of measuring lime requirement for an acid soil.

Buffering capacity. The ability of a solution, like the soil solution, to resist changes in pH when acid or alkaline substances are added. Often used when speaking of soil to describe its resistance to pH changes when limed or acidified.

Bulk density (BD). Mass of oven-dry soil per unit volume, usually expressed as grams per cubic centimeter.

Burned lime. CaO formed by roasting $CaCO_3$ in a kiln to drive off CO_2 as a gas; also called quicklime.

C

Calcareous soil. Soil high in calcium carbonate (lime), usually derived from limestone-rich parent materials. Will bubble or "fizz" if treated with cold, dilute (0.1 N) hydrochloric acid.

Calcitic limestone. Limestone rich in calcite ($CaCO_3$).

Calcium carbonate equivalent (CCE). The acid-neutralizing ability of a lime product compared to that of an equal weight of $CaCO_3$.

Caliche. A soil layer near the surface cemented by calcium and/or magnesium carbonates that precipitated out of solution.

Capillary. A very thin tube that water will flow into because of adhesive and cohesive forces. In the soil, small soil pores can act as capillaries.

Capillary fringe. A zone of soil just above a water table that is nearly saturated because of capillary rise.

Capillary rise. Movement of water upward in the soil through soil capillaries. Occurs as soil surface dries, drawing moisture from below.

Capillary water. Old term for water held loosely in capillary pores in the soil, capable of moving in the soil and being absorbed by roots.

Carbon cycle. The manner in which carbon cycles on the earth, beginning as carbon dioxide in the atmosphere, converted to organic carbon compounds primarily by photosynthesis, cycling through various food chains, and finally returning to the atmosphere as carbon dioxide by respiration of organisms. Detritus decay in the soil is a major portion of the cycle. There is also a geologic portion of the cycle not discussed in the text.

Carbon–nitrogen ratio (C:N ratio). Ratio of the weight of carbon to the weight of nitrogen in an organic material. Obtained by dividing the percent carbon by the percent nitrogen.

Carbon sequestration. Removal of carbon dioxide from the atmosphere and its deposition in some sink. Soil organic matter, especially in Gelisols and Histosols, is a very large carbon sink.

Carbon sink. A location where, as part of the carbon cycle, carbon is trapped for a time so it does not return to the atmosphere as carbon dioxide. Examples of sinks include wood in trees, carbon dioxide dissolved in the oceans, carbonate minerals, and, in this text, humus in soil and organic matter trapped in Gelisols and Histosols.

Catena. A group of neighboring soils formed of similar parent materials under similar conditions at about the same time. The soils differ because of variations in relief and drainage. Synonym: toposequence.

Cation. An ion with a positive charge.

Cation exchange. Exchange between a cation in solution and one adsorbed on a soil colloid.

Cation exchange capacity (CEC). Total number of exchangeable cations a soil can adsorb. A measure of the soil's ability to hold nutrients that are cations in the soil. Expressed as milliequivalents per 100 grams of soil, or centimoles charge per kilogram of soil.

Cellulose. A compound that is a polymer (chain) of glucose (sugar) molecules in a certain configuration. Plant cell walls are constructed mainly of cellulose fibers. Cellulose, unlike another sugar polymer, starch, cannot be digested by animals directly. Cellulose is used to make paper.

Cemented. Hardened because soil particles are "glued" together by substances such as lime or iron oxides. Hardness persists even when wet.

Center-pivot irrigation. Irrigation by a pivoting boom of sprinkler nozzles driven slowly in a circular pattern about the pivot point by the hydraulic pressure of the water in the boom.

Check dam. A temporary dam laid across a ditch or swale to reduce the velocity of concentrated flow in construction zones. Dam may consist of hay bales, logs, or stones. Eventually, when the slope is permanently protected, the check dam is removed.

Chelate. Noun or verb. A chemical compound in which a metal ion is firmly attached to an organic molecule by multiple chemical bonds. May be naturally occurring or synthetic. Humic acids and other organic soil compounds can chelate metallic plant nutrients in the soil, and synthetic chelates are used as micro nutrient fertilizers.

Chemical guarantee. The percent Ca, percent Mg, and calcium carbonate equivalent for a lime product.

Chemical weathering. Breakdown of rocks and minerals by chemical reactions, mostly with water.

Chiseling. (1) Primary tillage with a chisel plow, which pulls long, curved teeth through the soil to loosen it without turning it over. (2) Using a subsoiling chisel plow to break up deep compacted soil layers. (3) Using chisels to inject fluid fertilizers or ammonia into the soil.

Chlorite. A 2:1 silicate clay in which a fourth sheet holds together the 2:1 layers.

Chlorosis. Common sign of nutrient shortage, showing as a loss of normal green color in a plant. Color loss means a failure to make enough chlorophyll and may result from shortage of nutrients involved in chlorophyll formation (nitrogen, sulfur, iron, and others).

Chroma. One of the three variables in the Munsell color system. Chroma is the purity, or strength, of a color; its opposite is the amount of grayness.

Clay. (1) The class of smallest soil particles, smaller than 0.002 millimeter in diameter. (2) The textural class highest in clay.

Claypan. A dense subsoil layer with a higher clay content than the soil above it. *See also* pan.

Clod. A user-made soil aggregate, produced by tillage when a soil is too wet or dry. Clods may vary in size from 0.25 inch to 10 inches.

Coarse fragments. Mineral particles in the soil larger than sand, larger than 2.0 millimeters.

Coarse-textured soil. A soil texture whose traits are largely set by the presence of sand. Includes sands, loamy sands, and most sandy loams.

Cohesion. The force attracting similar substances. In the soil, applied to attraction of water for itself.

Cohesion water. Outer film of water around soil particles, loosely held in place by cohesion to the inner film of adhesion water.

Colloid. A very tiny particle capable of being suspended in water without settling out rapidly. Soil colloids, mostly humus and clay, have a charged surface that attracts cations.

Colluvium. A deposit of rock and soil resulting from materials sliding down a slope under the force of gravity.

Compaction. The squeezing together of soil particles by the weight of farm and construction equipment, vehicles, and animal and foot traffic. Compaction reduces average pore size and total air space in the soil.

Complete fertilizer. A fertilizer containing all three of the primary macronutrients—nitrogen, phosphorus, and potassium.

Composite sample. The soil sample sent to a soil-testing laboratory, resulting from mixing together many individual samples. It should represent the average soil in a field.

Compost. Noun or verb. Organic residues that undergo decay in a moistened pile above the ground or by some other method. Creates an organic soil amendment with a low carbon–nitrogen (C:N) ratio.

Concentrated flow. Movement of water downslope in a channel that produces soil erosion.

Conductivity. The concentration of soluble salts in soil or potting mixes.

Conductivity meter. An instrument used to measure the concentration of soluble salts in soil or potting mixes. It uses the principle that the more ions dissolved in water, the better the water will conduct electricity. Conductivity is directly proportional to concentration. In greenhouses, also used to infer nutrient content of growing media.

Cone penetrometer. A device with a rod with a cone-shaped tip that is pushed into the soil. A dial measures the pressure required to penetrate the soil. Readings are used as an index of compaction.

Conservation buffer. Several different types of dense vegetative strips on land to reduce erosion by slowing water flow, increasing infiltration in the strip, and filtering of soil particles.

Conservation compliance. Federal programs that require growers to take certain conservation measures to remain eligible for federal price-support programs.

Conservation tillage. A tillage practice that leaves crop residues on a rough soil surface to reduce erosion. Generally requires a coverage greater than 30 percent.

Consumptive use. Amount of water transpired from plants, incorporated into plant tissue, and evaporated from soil.

Contour. An imaginary line across a slope that stays at the same elevation.

Contour buffer strip. A type of conservation buffer. Wide strips of permanent vegetation, usually grass, running across the slope on the contour. Not cropped.

Contour tillage. Tillage following the contours of a slope, rather than up and down a slope. Helps prevent erosion and runoff.

Conventional tillage. A tillage system that uses primary tillage, such as a moldboard plow, and secondary tillage, such as harrows, that produces a fine seedbed and buries most crop residues.

Cost-sharing. Programs in which the USDA shares part of the cost for conservation efforts with a grower.

Cover crop. A crop planted to prevent erosion on a soil. Cover crops can be planted on soils not currently being farmed, between crop rows, or after the main crop harvest.

Cropland. Land suited or used for the purpose of raising crops.

Crop rotation. A repeated and planned sequence of different crops grown on the same plot of land to reduce pest and weed problems and maintain soil quality. May reduce erosion and fertilization needs, depending on selection of crops in the rotation.

Cross-wind ridges. Low ridges in soil at right angles to prevailing wind, created by tillage, to reduce wind erosion.

Cross-wind trap strips. Bands of vegetation planted at right angles to prevailing wind to trap soil particles blowing across a field.

Cultivation. Tillage to control weeds and loosen soil.

Cyanobacteria. Certain nitrogen-fixing microbes, previously called blue-green algae, now classified as bacteria.

D

Decomposers. Microbes that obtain their food from dead organic materials, causing decay and decomposition.

Delta. A usually fan-shaped alluvial deposit created where a stream or river enters a body of quiet water such as an ocean or a lake.

Denitrification. Chemical reaction caused by certain microbes in the soil that change nitrate nitrogen to gaseous nitrogen or gaseous nitrogen oxides.

Deposit. Loose material left in a new place after being carried by wind, water, ice, gravity, or humans.

Desertification. Conversion of land to desert, often caused by overgrazing, deforestation, or other disturbance.

Detritus. Dissolved or particulate dead, but not decomposed, organic material.

Diagnostic horizon. Any of a series of specific types of soil horizons used to assign a soil to its proper soil order.

Diffusion. Flow of matter through a liquid or gas by the random movement of molecules. In soil science, applied to movement of nutrient ions through soil solution. The movement is caused by a concentration gradient, with the ions moving from more to less concentrated.

Dissolution. The process of a solid passing into solution. One of the processes of chemical weathering.

Diversion. Changing the direction of movement. In soil conservation, a special terrace built to divert the flow of running water.

Dolomitic limestone. Limestone rich in the mineral dolomite (calcium-magnesium carbonate).

Double cropping. Harvesting two crops from the same piece of land in one year.

Drainage. (1) The speed and amount of water removal from soil by runoff or downward flow through soil. (2) Amount of time when soil is free of saturation.

Drip irrigation. Irrigation method in which water drips out of a specially designed trickler onto the soil surface under a plant.

Drought. A period of soil dryness that seriously harms plant growth.

Dryland farming. Methods of producing crops in low-rainfall areas without irrigation.

Duripan. A soil layer hardened and cemented by silica.

E

Effective neutralizing power (ENP). A measure of the ability of an agricultural lime product to neutralize soil acidity in a reasonable length of time, a function of the chemical type of lime, its purity, and the fineness of its grind. The concept may be described by other terms, depending on the state.

Eluviation. Removal of a material, such as clay or nutrients, from a layer of soil by percolating water.

Entisol. One of 12 soil orders. An undeveloped soil with no distinctive subsurface diagnostic horizons within 1 meter of the soil surface.

Enzymes. Protein molecules synthesized in the cells of living organisms that mediate or accelerate chemical reactions in a catalytic mode.

Eolian deposits. Wind-deposited soil material, mostly silt and fine sand.

Ephemeral gullies. Erosion in which running water makes large rills that are not completely filled in when the ground is tilled, leaving a channel for further erosion. Soil carried off fields by ephemeral erosion is not predicted by the Universal Soil Loss Equation.

Erodible. Soil that is easily eroded, due to a variety of factors.

Erosion control blanket. A temporary soil covering to prevent erosion and enable establishment of permanent vegetation on construction sites. It consists of two layers of fine mesh filled with material such as straw, compost, wood fiber, or coconut fiber. It can be unrolled over a slope and staked down.

Erosion index (EI) or erosion potential. Measurement of the inherent erodibility of a soil used without preventive measures. Using the Universal Soil Loss Equation, $EI = RKLS/T$.

Essential element. An element needed by plants for proper growth and reproduction.

Eutrophication. The rapid increase in growth of aquatic plants and algae caused by pollution of water by phosphates and, to a lesser extent, nitrates.

Evaporation pan. An open pan of water that experiences the same climatic conditions as a nearby crop, and from which water evaporates as a result of the climatic conditions. Generally of standard, specified dimensions. Measuring water loss from the pan measures evapotranspiration losses from the crop, and can be used to schedule irrigation.

Evapotranspiration. The sum of water lost from soil by evaporation and transpiration.

Exchangeable base. A cation, excluding hydrogen and aluminum, held on cation exchange sites that can be easily replaced by another cation. Considered to be available for plant growth.

Expanding clays. Clays that expand greatly upon adsorption of interlayer water and shrink upon drying.

F

Fallow. Soil left idle to accumulate water and/or mineral nutrients. Weeds are controlled during fallow chemically or by cultivation.

Family. Level of soil taxonomy just above the soil series.

Fertigation. Fertilizing with soluble fertilizers through an irrigation system.

Fertilizer. A material added to the soil to supply essential elements. State laws may set minimum requirements for materials sold as fertilizers.

Fertilizer analysis. Composition of fertilizer measured by chemical tests. On a bag of fertilizer, would appear as a listing of the percentage of each of the nutrients contained in the bag, including primary, secondary, or trace elements.

Fertilizer burn. Damage to plant tissue resulting from overapplication of fertilizer, a form of soluble salt damage.

Fertilizer carrier. A compound mixed into a fertilizer to supply a nutrient.

Fertilizer filler. A nonnutrient material added to fertilizer; for instance, clay, sand, or corncob granules.

Fertilizer grade. The guaranteed minimum analysis in whole numbers of nitrogen, available phosphate, and water-soluble potash, listed as "N-P_2O_5-K_2O."

Fertilizer, inorganic. Fertilizer that contains no carbon. For the purposes of this text, fertilizers that are unaltered minerals are considered separately. Urea, while chemically organic, is often classified as inorganic because of rapid hydrolysis in the soil to ammonium ions.

Fertilizer, organic. Fertilizer that contains nutrients plus carbon and hydrogen. Often excludes urea. *See also* fertilizer, inorganic.

Fertilizer ratio. Proportion of the primary nutrients in a fertilizer. Obtained by dividing the grade by the lowest common denominator.

Fertilizer, starter. A small amount of fertilizer placed near seeds or transplants to promote early growth, generally high in phosphorus.

Fibric. Adjective applied to only slightly decomposed organic matter.

Field capacity. The percentage of water remaining in the soil after drainage has just stopped.

Filter strip. Strip of heavily vegetated land bordering bodies of water designed to filter sediments and pollutants out of runoff before it enters the body of water.

Fine earth fraction. The portion of the mineral particles of soil smaller than 2 millimeters. Larger particles are considered coarse fragments. The term *texture* applies to the fine earth fraction.

Fine texture. Soil with a large amount of clay. Usually includes clay, sandy clay, clay loam, silty clay, and silty clay loam.

Finishing harrow. This secondary tillage device completes the job of pulverizing the soil; a drag.

Fixation. (1) A process that changes chemicals from soluble or available forms to insoluble or unavailable forms in the soil. (2) Conversion of gaseous nitrogen to ionic forms.

Floodplain. Land near a stream that is commonly flooded when the stream is high. Soil is built from sediments deposited during flooding.

Fluid fertilizer. Fertilizer used in liquid form, either a solution or a suspension.

Fluid lime. Finely ground lime in a slurry or suspended form in water.

Foliar feed. Application of fertilizer by spraying a liquid fertilizer on plant foliage. Also known as foliar fertilization.

Forest soil. Soils developed under forest vegetation.

Fragipan. Naturally occurring hard, brittle subsoil layer high in clay that restricts root growth.

Friable. A consistency term expressing how easily a moist soil can be crumbled.

Fritted trace element (FTE). A slow-release trace element fertilizer in which fertilizer carriers are mixed into glass powder.

Frost wedging. Breakage of rocks caused by pressure created by water freezing in cracks in the rocks.

Fungi. Important soil organisms, especially as decomposers. Considered to be either primitive plants or as one of five kingdoms of living organisms.

Furrow irrigation. Delivery of irrigation water down furrows from a source ditch.

G

Gelisol. One of 12 soil orders, established in the soil taxonomy in 1998. A soil whose subsoil is permafrost.

Glacial drift. General term for debris deposited by glaciers. Common in the northern tier of states.

Glacial outwash. Glacial drift deposited in water flowing away from a melting glacier. Outwash is sorted by the running water and is usually coarse textured.

Glacial till. Unsorted deposits of glacial drift deposited by the ice.

Gley. Soil layer that develops under poor soil drainage conditions; has gray color and mottles. Color results from chemical reduction of iron under anaerobic conditions.

Glomalin. A material exuded by mycorrhizal fungi that stabilizes soil structure. A complex of sugar proteins.

Granular structure. Commonly found in A horizons. Each ped is roundish.

Granules. Aggregates of fertilizer particles, often all of a uniform guaranteed nutrient content.

Grassed waterway. A shallow waterway densely planted to grass to carry water down a slope and off a field to prevent erosion. Established in areas of natural concentrated downhill flow.

Gravitational flow. Water movement driven by gravity in the soil in a downward direction in the earth's gravitational field.

Gravitational potential. That part of the soil total water potential associated with position in a gravitational field. This energy of position (potential energy) could be (+) or (−) in sign depending on vertical position with respect to a reference level, but is usually positive.

Gravitational water. Water that moves through the soil under the influence of gravity.

Great group. A taxonomic level of the current soil classification system.

Greenhouse effect. Warming of the earth as energy (long-wave radiation) radiating from the earth is trapped by certain atmospheric gases, including carbon dioxide, methane, and others.

Greenhouse gas. A gas in the atmosphere that blocks the loss of energy from the earth as long-wave radiation, leading to the greenhouse effect. Includes water vapor, carbon dioxide, methane, and nitrogen oxides; each may be released into the atmosphere by soil processes.

Green manure. A crop grown to be turned under while still green to improve the soil.

Green roof. A building roof supporting a growing medium and planted to vegetation. The medium retains water from rainfall to reduce runoff, as well as provide other benefits.

Green-tissue test. A qualitative testing or evaluation of nutrient content in freshly collected and macerated green leaf tissue.

Groundwater. Water stored underground in a saturated zone of rock, sand, gravel, or other material.

Gully erosion. A form of water erosion characterized by deep and wide channels. The channels are too wide to cross with ordinary equipment.

H

Halophyte. A plant adapted to growing in a high-salt environment, such as saline soils or soils affected by seawater or sea spray.

Hand-move irrigation. Irrigation equipment that is moved by hand from one location of operation to the next.

Hardpan. A hard subsoil layer caused by cementation by carbonates or other chemicals; limits root growth and the infiltration of water.

Heavy metal. Group of high-density metallic elements including lead, cadmium, and others. A few are needed as essential elements in trace amounts by plants or animals, but are otherwise toxic to biological systems. May be naturally occurring in soils or contained in fertilizers, sludges, composts, other soil amendments, or contaminants.

Hemic. Adjective applied to moderately decomposed organic matter.

Hemicellulose. A complex polymer of sugars of almost random structure; part of plant cell walls that binds cellulose fibers together in a certain pattern. *See also* cellulose.

Heterotroph. Organism not capable of producing its own food. Obtains energy for life processes by oxidation of organic compounds.

Histosol. One of 12 soil orders. Histosols are organic soils.

Horizon, soil. A horizontal layer of soil, created by soil-forming processes, that differs in physical or chemical properties from adjacent layers.

Hue. One of the three color variables in the Munsell color system. Refers to the actual color of soil. *See also* chroma and value.

Humid climate. Climate in which, in a normal year, moisture does not limit crop production. Depends upon average precipitation, timing of precipitation, and temperature. More rainfall is required in hotter climates with higher evapotranspiration.

Humification. The process of transforming organic matter to humic substances through biological and nonbiological processes.

Humus. Decay-resistant residue of organic matter decomposition. Humus is dark colored and highly colloidal.

Hydrated lime. $Ca(OH)_2$ produced by adding a controlled amount of water to CaO; also called slaked lime.

Hydration. Addition of a water molecule to another substance. One of the processes of chemical weathering.

Hydraulic conductivity. A trait of soil relating to the ease of water movement in that soil. The finer the soil texture, the lower its hydraulic conductivity.

Hydric. *See* hydric soil.

Hydric soil. A soil that is saturated, flooded, or ponded long enough during the growing season to develop anaerobic conditions in the upper part.

Hydrogen bond. Bond between two molecules in which a hydrogen of one molecule bonds to an oxygen or nitrogen of another molecule.

Hydrologic cycle. The circular route of water from the atmosphere back to the atmosphere after it has undergone precipitation, runoff, percolation, storage, or evapotranspiration.

Hydrolysis. Addition of a hydrogen atom from water to another substance. One of the processes of chemical weathering.

Hydromulching. Method of protecting and vegetating bare soil in construction zones by spraying a mixture of grass seed, shredded organic mulch, and water with a specialized machine.

Hydrophilic gel polymers. Synthetic gel polymers capable of modifying the water-retention characteristics of soil or potting soil media.

Hydroponic crops. Crops grown in nutrient solutions rather than soil.

Hygroscopic water. Water held tightly by adhesion to soil particles. Cannot be used by plants and remains in soil after air-drying. Can be driven off by heating.

Hyphae. Individual strands of the vegetative body of fungi. Hyphae can grow into organic matter to cause decay and can surround a mass of soil particles to make soil aggregates.

Hypoxia. A state of severe oxygen shortage in water such that respiration of aquatic organisms is restricted.

I

Igneous rock. Rock formed from the cooling of molten rock from deep in the earth.

Illuviation. Deposition in a soil layer of materials transported from a higher soil layer by percolating water.

Immature soil. A young soil that is still changing relatively rapidly in response to its surroundings. Usually has little horizon development.

Immobilization. Absorption of an available nutrient by a soil organism or plant, changing it to an unavailable organic form.

Inceptisol. One of 12 soil orders, usually young soils with weak horizons.

Infiltration. Downward entry of water into the soil. *See also* percolation.

Inoculation. Adding microbes to soil, seed, or a culture medium. For instance, to treat legume seeds with bacteria from the *Rhizobium* genus.

Inorganic. Any chemical that does not contain both carbon and hydrogen. Inorganic nitrogen, for instance, includes nitrates (NO_3^-) but not urea (NH_2CONH).

Inorganic fertilizer. *See* fertilizer, inorganic.

Interception. The arrival of nutrients at a root surface simply by displacement of a soil volume by root growth.

Ions. Atoms or molecules that are electrically charged because of gaining or losing electrons.

Irrigation. Artificial application of water to the soil to improve crop growth, or sometimes for other purposes such as activating herbicides.

Isomorphous substitution. Replacement of one atom by another of similar size in a crystal lattice. May result in a charge if the atom has a different charge than the one replaced.

L

Labile. Carbon source readily transformed by soil microorganisms, that is, easily decayed.

Lacustrine. Mineral sediments deposited in still freshwater.

Land capability classes. Eight soil classes ranked for their suitability for agriculture according to risk of erosion and other factors.

Landscape. (1) The natural features of the earth's surface such as hills, trees, and water. Usually the piece of land that can be seen by the eye in a single view. (2) The designed landscape around buildings or other structures of the built environment.

Land-use planning. Developing plans for using land that will best serve the long-term public interest.

Leaching. Removal of soluble material in solution from the soil by percolating water.

Leaching fraction. The extra portion of irrigation water that prevents buildup of soil salts by draining away accumulating salts. Common in irrigation in arid climates and in containerized plants.

Leaching requirement. The fraction of the water entering the soil that must pass through the root zone in order to prevent soil salinity from exceeding a specified value.

Legume. A member of the Fabaceae family of plants, such as soybeans, peas, clover, alfalfa, locust trees, and many other economically important plants. Legumes host the *Rhizobia* bacteria that fix nitrogen.

Levee. Alluvial deposit of a shallow ridge along a river, resulting from coarse deposits during flooding.

Lignins. Complex, decay-resistant organic chemicals that glue together cellulose fibers in a plant to make it rigid. Lignins do not contain nitrogen.

Lime. Material used to neutralize acidity, containing calcium or magnesium carbonate, oxide, or hydrate.

Lister plow. A special kind of plow that has two moldboards mounted back to back, resulting in a pattern of 10-inch-high ridges and furrows across the field.

Load-bearing capacity. Ability of a soil to carry a load such as a roadbed or building without shifting.

Loam. A medium soil texture class, in which sand, silt, and clay contribute almost equally to soil properties.

Lodging. Breaking of plant stems because of stem weakness, often caused by excess nitrogen and low potassium.

Loess. Wind-deposited silt.

Long-wave radiation. Radiation emitted by the earth's surface in the infrared and nearby wavelengths that escapes into space or is partially absorbed by the atmosphere. Compare to sun's shortwave radiation that reaches earth.

Low-impact development. Land development of urban sites that aims to reduce environmental damage by retaining runoff water on-site rather than exporting it off-site.

Luxury consumption. Absorption by plants of more nutrients, especially potassium, than they need at the time. The nutrients may, however, be used for later stages of growth and can be used by animals feeding on the plant.

M

Macrofauna. Larger, easily visible soil animals.

Macronutrients. An essential element used in large amounts by plants, including nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur.

Macropores. Large, noncapillary pores that transmit water rapidly and are important for soils to drain readily. As they drain, water is replaced with air.

Mapping unit. Basis for setting boundaries in a soil map. May be phases of series, families, or other taxonomic units, or may be associations of such units.

Marine sediments. Parent material that settled to the bottom of old oceans and seas.

Marl. A soft, limey material deposited in freshwater that can be used as an agricultural lime.

Mass action. A law of chemistry that states that the rate of a chemical reaction is directly proportional to the concentrations of the chemical substances. As a consequence, changing the concentration of one component of reaction can change the speed and direction of the reaction.

Mass flow. Movement of nutrients by movement of soil water.

Massive soil. A structureless soil in which each soil particle sticks to neighboring particles. Common in C horizons or puddled soils.

Master horizons. O, A, E, B, C, and R horizons.

Matric potential. The soil energy level associated with attraction of water to soil solids.

Mature soil. A soil in equilibrium with its surroundings, usually with well-developed horizons.

Mechanical analysis. The measurement of the amounts of sand, silt, and clay in a soil. This measurement uses the principle that the larger a particle, the faster it sinks in water.

Media. Mixtures that are used to grow potted plants. They have high air- and water-holding capacities.

Medium-textured soil. Soil intermediate between fine- and coarse-textured soil. Includes loam, fine sandy loam, silt loam, and silt.

Mesic. Describes a moist soil-moisture regime in which plants do not normally suffer water shortages or periods of soil saturation.

Mesofauna. Small soil animals slightly larger than microscopic, about 0.2–2 mm in size, including large nematodes and small but visible arthropods.

Mesophilic. A preference for temperature in an intermediate range, between 15°C and 35°C.

Mesophilic organism. Organisms whose optimum temperature for growth is an intermediate range, between 15°C and 35°C. Dominant microorganisms in early and late stages of composting.

Metamorphic rock. Rock that has been changed by heat or pressure in the earth.

Methane. Flammable gas, also known as swamp gas; main component of the fuel natural gas. Chemical formula is CH_4. Produced by biological processes in anaerobic soils, and a potent greenhouse gas.

Methanogenesis. Production of methane by anaerobic bacteria in saturated soil.

Micelle. An individual particle of silicate clay.

Microfauna. Microscopic soil animals or animal-like organisms, including protozoa, nematodes, and tiny arthropods.

Microflora. Soil bacteria, fungi, algae, or viruses.

Microirrigation. The frequent application of small quantities of water as drops, tiny streams, or miniature spray through emitters or applicators placed along a water delivery line. Microirrigation encompasses a number of methods or concepts such as drip or microspray.

Micronutrient. Essential element used in small quantities by plants.

Microorganism. An organism too small to be seen without the aid of a microscope.

Micropores. Small, capillary pores that transmit water slowly and hold water against gravity. They are important for the storage of water.

Microspray irrigation. A form of microirrigation that employs small sprayheads to sprinkle a small area, such as a landscape bed of shrubs or a single tree in an orchard.

Mineral. A pure inorganic compound in the earth's crust. Most rocks are mixtures of minerals. Often used in soil science to mean the inorganic solid particles of soil.

Mineralization. Conversion of elements in organic forms to inorganic forms by decay. *See also* immobilization.

Mineral soil. A soil whose traits are determined mainly by its mineral content; mineral soils contain less than 20 percent organic matter.

Minimum tillage. Tillage methods that involve fewer tillage operations than conventional tillage. *See also* conservation tillage.

Mixed fertilizer. A fertilizer containing more than one primary nutrient.

Moisture regime. The average soil-moisture conditions of a site through the year, a function of natural precipitation, slope, soil-water-holding-capacity, and presence or absence of soil layers that perch percolating water.

Moldboard plow. A primary tillage tool that shears off a section of soil, tips it upside down, and fractures it along several planes.

Mollisol. One of 12 soil orders. A soil with a high-organic-matter topsoil and high base saturation; usually formed under prairie vegetation.

Mottling. Spots of different colors in a soil, usually indicating poor drainage. *See also* gley.

Muck. An organic soil in which the organic matter is mostly decomposed. *See also* peat.

Mulch. A material spread on the soil surface, such as straw, leaves, plastic, or stones, to protect soil from freezing, raindrop impact, evaporation, and heaving, and to reduce weed growth. Usually reduces evaporative loss of water from the soil.

Munsell color system. A system used to identify soil color by means of three variables: hue (color), value (intensity), and chroma (purity). Identification is done by comparing soil to a set of standard color chips.

Mycelium. A word for the hyphae or filamentous strands of fungi.

Mycorrhizae. Fungi that form a symbiotic relationship with plant roots. The fungi help the plant absorb water and nutrients, while they receive food from the plant.

N

Nematode. Small unsegmented worm; many are parasitic on plant roots.

Nitrification. Microbial conversion of ammonium nitrogen to nitrate nitrogen.

Nitrogen cycle. Series of changes of nitrogen from atmospheric nitrogen, fixation in soil, a series of changes in the soil, and a return to the atmosphere.

Nitrogen depression period. Period of time during decay of organic matter in which nitrogen is being used up by microbes faster than it is being released by decay (immobilization exceeds mineralization). Resulting temporary nitrogen tie-up can cause nitrogen shortage in crops.

Nitrogen fixation. Microbial conversion of gaseous nitrogen to organic nitrogen in the soil.

Nonexchangeable ions. A term applied to an ion so strongly adsorbed to a soil colloid that it is not normally available to be exchanged with ions in the soil solution.

Nonpoint source. Source of water pollutants that does not come from a single, easily identified point. Example would be runoff from farm fields. *See also* point source.

Nonsymbiotic nitrogen fixation. Microbial conversion of gaseous nitrogen to organic nitrogen in the soil by free-living bacteria that do not live on plant roots.

No-tillage or no-till. Method of growing crops that involves no tillage. Seeds are planted in slits in soil and chemicals are used to control weeds.

Nutrient carriers. Compounds in fertilizers that are included as useful forms of plant-available nutrients.

Nutrients. Elements in the form of ions or molecules used in the metabolism of plants, animals, and microbes.

O

Order, soil. Highest taxonomic level in the USDA soil classification system. There are 12 recognized soil orders.

Organic. A material containing both carbon and hydrogen, and often oxygen, nitrogen, sulfur, or other elements. *See also* inorganic.

Organic amendment. A soil amendment that is mostly organic matter.

Organic farming. Farming without using inorganic fertilizers or artificial pesticides.

Organic fertilizer. *See* fertilizer, organic.

Organic matter. Material of plant or animal origin that decays in the soil to form humus.

Organic soil. Soil containing more than 20 percent organic matter. Soil properties are dominated by the organic matter.

Osmotic potential. The contribution of dissolved salts or sugars (osmotically active solutes) to the energy of water. The more osmotically active solutes, the lower the energy level of the water.

Oven-dry soil. Soil dried at 105°C until it reaches a constant weight.

Oxidation–reduction. A chemical reaction in which an element loses electrons to another participant in the reaction, often oxygen. For instance, iron is oxidized by oxygen to form rust.

Oxide clay. *See* sesquioxide.

Oxisol. One of 12 soil orders; highly weathered and leached tropical soils, limited in the United States to Hawaii, and Puerto Rico.

P

Pan. A dense, hard, or compacted layer in soil that slows water percolation and movement of air and obstructs root growth. Pans may be caused by compaction, clay, or chemical cementation.

Parasite. An organism that lives off another organism (the host). The host is injured by the parasite. *See also* symbiosis.

Parent material. The unconsolidated mineral or organic matter from which the solum (A, E, B horizons) has developed.

Particle density (PD). The mass per unit volume of soil particles, excluding pore space. Most mineral soils have a particle density of about 2.65 grams per cubic centimeter.

Peat. Undecayed or slightly decayed organic soil, formed underwater where low-oxygen conditions inhibit decay.

Ped. A natural soil aggregate, such as a granule or prism.

Pedology. Study of the formation and classification of soil.

Pedon. The smallest soil body. A section of soil that extends to the root depth and has about 10–90 square feet of surface area.

Perched water table. A zone of saturated soil that, because of obstructions or other reasons, is maintained above the normal water table. Also applied to the layer of saturated soil in the bottom of a pot of soil, because excess water cannot drain to the normal water table in the soil.

Percolation. Downward movement of water through the soil profile.

Percolation test. A test for soil drainage that involves timing the speed at which water will drain out of a hole dug in the ground.

Perforation. A method of fertilizing shade trees by drilling holes in the soil under the tree in a grid pattern and then filling the holes with fertilizer and sand.

Perlite. Large granules of lightweight, expanded volcanic glass used in potting mixes.

Permafrost. Continuously frozen material under the solum or a perennially frozen soil horizon. Feature of soils of the order Gelisols.

Permanent wilting point. Water content of soil when a plant wilts and does not recover when placed in a humid chamber. Also called the permanent wilting percentage.

Permeability. Ease with which gases, liquids, and plant roots pass through a specific mass of soil.

pH (soil). Measure of the acidity or alkalinity of a soil. Technically, reciprocal of the logarithm of the hydrogen ion concentration in the soil solution.

Phase. A subdivision of the soil series, designating a difference from the series norm. Includes slope, degree of erosion, stoniness, and surface texture.

Phosphorus index. A rating system for the hazard of a site to cause phosphorus pollution in surface waters. There are several different phosphorus indices.

Photosynthesis. The reaction, in the presence of chlorophyll, of carbon dioxide and water to form sugar, using light energy.

Physical guarantee. The size guarantee or fineness factor for a lime product.

Physical properties. Traits of a soil caused by physical forces that can be described by physical terms or equations. Examples are soil texture, structure, and bulk density.

Physical weathering. Breakdown of rock particles by physical forces such as frost action or wind abrasion.

Plasticity. A consistence term describing how easily a mass of soil can be shaped and molded when wet.

Platy structure. Soil structure in which platelike soil peds lie horizontally in the soil. Common in E horizons or compacted A horizons.

Plinthite. A mixture of various chemicals in the soil that when exposed to cycles of wetting and drying permanently hardens to a bricklike state. Common to tropical soils.

Plow layer. Upper part of a soil profile disturbed by humankind by plowing or other disturbances; *P* horizon suffix.

Plowpan. A tillage pan formed just under the plow layer.

Point source. Source of water pollutants easily traced to a single point, such as a factory pipe or animal feedlot.

Polypedon. A group of similar neighboring pedons that makes up a soil series.

Pop-up fertilizers. Fertilizers placed directly in contact with crop seeds. If large amounts of water-soluble fertilizers are used, these can cause osmotic injury and not have the desired promotion of early growth.

Pore space. Portion of soil not occupied by solid material but that is filled with air or water.

Porosity. Percentage of soil volume not occupied by solid material.

Potentiometer. Device to measure soil-water potential and particularly soil-matric potential. (Tensiometer is an older term.)

Prairie soil. Soil formed under grassland vegetation.

Precipitate. Formation of particulate solids when ions in solution in water react to form an insoluble chemical. These reactions may be pH dependent.

Precipitation. (1) A form of water falling to earth from the atmosphere; may be rain, snow, mist, or hail. (2) In chemistry, formation of particulate solids when ions in solution in water react to form an insoluble chemical. These reactions may be pH dependent. One way essential elements can become unavailable in the soil.

Precision agriculture. A system of crop pest and fertility management on very small locations so that very specific (almost prescription) recommendations and applications can be made for fertilizer or pesticides.

Predator. An organism that hunts and eats prey.

Preferential flow. Usually, flow of free water through large macropores such as biopores, bypassing the general soil matrix.

Pressurized liquid. A fertilizer delivered to an applicator knife through a pressurized delivery system. Anhydrous ammonia is an example.

Prills. Fertilizer pellets that are spherical in shape.

Primary consumer. Organism that feeds on plants; the second level of the food chain.

Primary macronutrient. The three macronutrients (nitrogen, phosphorus, potassium) needing to be added to the soil in the greatest amounts for good crop growth.

Primary producer. Lowest level in the food chain, organisms that produce their own food. Mostly chlorophyllous plants and microorganisms.

Primary tillage. The first step in seedbed preparation in conventional and mulch tillage. Breaks up and loosens soil and buries some or all crop residue.

Prime farmland. Farmland that has the best combination of physical and chemical characteristics for producing agricultural crops, and that is available for that use.

Prismatic structure. Soil structure with large, prism-shaped peds arranged vertically in the soil, usually in the B horizon.

Protein. Important nitrogen-containing compounds in living matter, from which comes most of the nitrogen in organic matter.

Protozoan. Single-celled, nonbacterial life form formerly classified mostly as small animals, like amoeba.

Puddling. Dispersal of soil aggregates caused by working soil when wet, creating a massive surface layer.

Pulverized fertilizers. Finely ground or divided fertilizer solids.

R

Rain garden. Residential or commercial landscape feature that is a shallow depression planted to permanent vegetation designed to capture runoff water from a site like a yard or parking lot, allowing it to filter into the soil. Not meant to retain water, but may fill with water during rain events.

Rangeland. Land in arid or semiarid areas with permanent plant cover used for grazing.

Recalcitrant. Carbon source not readily transformed by soil microorganisms, such as high-lignin plant residues. *See also* labile.

Recharge basin. Landscape depression in which ponded water percolates through the soil to recharge an underlying aquifer.

Reclaimed water. Water that has already been used, like treated water from sewage treatment or "greywater" from homes that can be suitably used for irrigation under certain circumstances and with proper attention to possible contaminants.

Redoxymorphic feature. Soil color patterns indicating alternating reducing and nonreducing conditions (saturated/nonsaturated), such as mottles.

Reduced tillage. *See* minimum tillage.

Reduction. Half of an oxidation–reduction reaction. The gain of electrons in an atom or molecule from another atom or molecule (the electron donor). The chemical that is reduced is said to be an electron acceptor. Often involves the loss of an oxygen or the gain of a hydrogen atom.

Relief. Variations in elevation in the landscape.

Residual soil. Soil formed in place from bedrock, rather than from transported parent materials.

Resistance block. A gypsum block with internal electrodes that when in equilibrium with moist soil allows (with calibration) electrical resistance to be interpreted as soil-water content.

Respiration. Biological reaction in which carbohydrates are broken down to carbon dioxide and water with the release of energy. Opposite of photosynthesis.

Retention pond. Human-made depression installed to collect runoff water. May or may not be also a recharge basin.

Revised Universal Soil Loss Equation (RUSLE). A water erosion prediction model incorporating improvements to the Universal Soil Loss Equation (USLE).

Rhizobium. Genus of bacteria that live symbiotically on legume roots and can fix atmospheric nitrogen.

Rhizosphere. A zone of soil immediately surrounding plant roots that supports a high population of microorganisms feeding on organic materials released by the root.

Rill erosion. A form of water erosion characterized by numerous shallow and narrow channels. The channels can usually be filled in by ordinary tillage equipment.

Riparian buffer. A BMP for protecting bodies of water from nutrient and sediment loads in runoff from nearby land. A riparian buffer is a buffer zone planted to vegetation that intercepts runoff, slowing it so sediments are deposited and absorbing nutrients in the soil and vegetation.

Rip-rap. Large stones laid on top of the soil to protect it from erosion.

River terrace. A former river floodplain now at a higher elevation.

Root interception. *See* interception.

Root wedging. Rocks forced apart by root pressure.

Row crops. Crops planted in wide rows for ease of cultivation or other weed control practices; commonly corn, soybeans, cotton, peanuts, and others.

Runoff. Water that falls on the soil but fails to be absorbed; flows on the soil surface.

S

Salination. The accumulation of soluble salts in the soil, usually from irrigation.

Saline seep. Small area of saline soil resulting from summer fallow.

Saline-sodic soil. Soil that has both high soluble salt and sodium levels. The pH is between 7.0 and 8.5; electrical conductivity is greater than 4.0 millimhos per centimeter; exchangeable sodium percentage is greater than 15.0.

Saline soil. A soil high in soluble salts but without too much exchangeable sodium. The pH is between 7.0 and 8.5; electrical conductivity is greater than 4.0 millimhos per centimeter; exchangeable sodium percentage is below 15.0.

Saltation. Movement of soil particles in which wind causes fine sand to hop along the soil surface.

Salt index. An index of the relative salinity of a fertilizer compared to sodium nitrate, given the value 100.

Sand. (1) Largest of the soil separates, between 0.05 and 2.00 millimeters in diameter. (2) Coarsest textural class.

Sapric. Adjective applied to fully decomposed organic matter.

Saprophyte. Microorganism that feeds on dead organic matter.

Saturated flow. Water movement in the soil when all pores are filled with liquid water.

Saturation. (1) All or most soil pores filled with water. (2) The amount of the cation exchange capacity filled with a certain cation.

Secondary consumer. An organism that feeds on a primary consumer; the third level of a food chain.

Secondary macronutrient. Those macronutrients used less often as fertilizers than the primary elements. Includes calcium, magnesium, and sulfur.

Secondary tillage. Tillage operation following primary tillage that smooths out the soil for a fine seedbed.

Sediment. A layer of loose material deposited by wind or water. Term often applied to eroded soil deposited off the field, such as in lakes or streams.

Sedimentary rock. Rock made of sediments hardened over time by chemicals or pressure.

Sediment basin. A constructed basin in land development. Nearby land is graded to move runoff into the basin, where sediment settles out. Prevents sediment from reaching nearby natural bodies of water.

Seeps. Hillside springs or zones where water flowing laterally within the soil breaks out into the open.

Semiarid climate. Area where rainfall is low enough to limit crop production, but where dryland farming can be used. Evapotranspiration slightly exceeds precipitation.

Series, soil. The basic unit of soil classification, consisting of soils alike in all profile traits except for slight differences in surface texture, slope, erosion, or stoniness. *See also* phase.

Sesquioxide clays. Finely divided particles of iron and aluminum oxides, most common in soils of warm, humid regions.

Sewage sludge. Semisolid wastes, collected by sedimenation from sewage, that, when properly treated, can be used as an organic fertilizer.

Sheet erosion. Form of erosion in which soil washes off the land in a thin, uniform layer.

Shortwave radiation. High-energy radiation, primarily in the visible range, emitted by the sun and shining on the earth. Unlike long-wave radiation, it passes through the atmosphere without being absorbed by greenhouse atmospheric gases.

Shrink–swell potential. How much a mass of soil swells when wet and shrinks when dry; a function of the amount of swelling clays. An important engineering property of soil.

Sidedressing. Application of fertilizer alongside the rows of an already established crop.

Silicate clay. Clays formed by association of structural units based on silica sheets (silica tetrahedra) and alumina sheets (alumina octahedra).

Silt. Medium-sized soil separate, particles between 0.05 and 0.002 millimeter in diameter.

Silt fences. Tightly woven plastic fabric used to filter sediments from construction sites.

Single-grain soil. A structureless soil in which each soil grain is loose in the soil. Usually in sand.

Site-specific management. Trying to tailor all crop management practices to the unique needs of small sampling units in each field.

Slick spots. Small areas of a field that are slick when wet because of high sodium content.

Slope. On a land surface, the degree of variation from horizontal, often measured as percent slope, the vertical change over a horizontal distance expressed as a percentage.

Slope aspect. Direction a slope faces. Affects the temperature and moisture content of the soil, and often, the vegetation growing there.

Slow release. Term applied to fertilizers that, by various means, release their nutrients slowly. Such fertilizers may be only slowly soluble in water or be coated with substances that hinder solution.

Small grains. Crops that are planted in closely spaced rows about 7 or 8 inches apart or may be broadcast seeded. These crops usually refer to the cereal grains such as wheat, oats, rye, barley, and others.

Sodic soil. Soil high in sodium and low in soluble salts. The pH is between 8.5 and 10.0; electrical conductivity is below 4.0 millimhos per centimeter; exchangeable sodium percentage is above 15.0.

Sodium adsorption ratio. The balance of Na^{+} to Ca^{+2} and Mg^{+2} in soil-water extracts or water for irrigation. $[Na^{+2}]/\{([Mg^{+2}] + [CA^{+2}])/2\}^{0.5}$ where [ ] = concentration of the ion.

Soil. Loose mineral and organic material on the earth's surface that serves as a medium for the growth of land plants.

Soil aeration. Process by which air in the soil is replaced by air from the atmosphere. Related to number, size, and continuity of soil pores and to internal drainage.

Soil aggregate. A mass of fine soil particles glued together by clay, organic matter, or microbial gums. Aggregates are part of soil structure.

Soil air. Gas phase of soil; space of soil not filled with solid or liquid.

Soil amendment. *See* amendment, soil.

Soil association. *See* association, soil.

Soil classification. The arrangement of soils into classes of several levels.

Soil conservation. Protection of soil from erosion.

Soil consistence. Characteristics of a soil in its response or resistance to pressure, as described at various soil-moisture contents. Such characteristics include stickiness, plasticity, hardness, and friability.

Soil degradation. Loss of soil quality through such processes as erosion, salination, contamination, severe compaction, and numerous others.

Soil fertility. Ability of a soil to supply the elements needed for plant growth.

Soil genesis. (1) The mode of origin of the soil with special reference to the processes or soil-forming factors responsible for development of the solum, or true soil, from unconsolidated parent material. (2) The branch of soil science that deals with soil genesis.

Soil horizon. *See* horizon, soil.

Soil-loss tolerance. The average maximum yearly loss of soil in tons per acre that will not lead to loss of productivity over time. This amount, usually between one and five, is characteristic of a soil series.

Soil matrix. The arrangement of solid soil particles and soil pore spaces, which is a three-phase system of solid, liquid, and gas.

Soil-moisture tension (SMT). An older term used to describe the force attracting water molecules to soil particles; can be thought of as the "suction" required to pull water from the soil particles.

Soil order. *See* order, soil.

Soil pH. *See* pH (soil).

Soil profile. The vertical section of a soil through all its horizons, ending in the parent material.

Soil quality. Capacity of a soil to provide the needed functions for human or natural ecosystems over the long term.

Soil reaction. The degree of acidity or basicity in the soil expressed by the pH scale. An obsolete term in soil science, but still widely used.

Soil sampling. The systematic gathering of soil samples for use in soil testing.

Soil separate. Classes of mineral particles less than 2.0 millimeters in diameter; includes clay, silt, and several sizes of sand.

Soil series. *See* series, soil.

Soil solution. The liquid phase of soil, consisting of water and dissolved ions.

Soil strength. Ability of a soil to resist deformation, related to solid phase cohesion and adhesion, water content, and degree of cementation or compaction.

Soil structure. *See* structure, soil.

Soil survey. The examination, description, and mapping of soils of an area according to the soil classification system.

Soil taxonomy. *See* taxonomy, soil.

Soil testing. Using various tests to measure properties that affect how well soil will support plant growth.

Soil texture. The relative proportion of the soil separates in a soil.

Soil triangle. Used to place a soil in a soil (textural) class by plotting the percentages of sand, silt, and clay.

Soil type. *See* type, soil.

Soil-water potential. The amount of work a small amount of water can do in moving from the soil to a pool of pure, free water at the same location. Includes matric, gravitational, and salt potential. Normally, matric potential is the main component, but salt potential is significant in salted soils.

Solarization. A nonchemical method to sterilize soil using the sun to heat the soil under a clear plastic sheet.

Solid-set irrigation. Sprinkler irrigation from a permanently installed delivery system.

Soluble salts. Salts in the soil that are more soluble than gypsum.

Solum. The upper, weathered part of the soil profile; the A, E, and B, and many O horizons.

Solution. Water with ions dissolved in it. Applied to soil, the soil solution is the water in the soil with nutrients and other materials dissolved in it.

Specific surface area. Total surface area of all the soil particles in a volume of soil.

Splash erosion. The movement of soil particles by splashing from the impact of a drop of water.

Split application. Applying the total desired fertilizers needed in several smaller doses somewhat matching the crop's nutrient uptake needs through the season.

Spodosol. One of 12 soil orders. Mainly acid, coarse-textured forest soils of cool, humid regions. Has subsoil layer with illuvial accumulation of humus, aluminum, and sesquioxides.

Starch. A compound that is a polymer (chain) of glucose (sugar) molecules in a certain configuration. A form of energy storage in plants. Unlike cellulose, can be digested by mammals and is a major food or energy source for animals that eat plants, such as humans eating potatoes or pasta.

Starter fertilizer. *See* fertilizer, starter.

Stem-girdling roots. Tree roots that cross the trunk at or just below the soil surface, inhibiting trunk growth and compressing conducting tissues at that side and leading to poor tree health and stability. Often result from deep planting.

Stomata. Small openings in plant leaves through which oxygen, carbon dioxide, and water vapor are exchanged.

Strip-cropping. Planting different types of crops in alternate strips to prevent wind or water erosion. Strips are usually planted on a slope contour or across the direction of the prevailing wind.

Structured soil. Human-made growing medium containing gravel, loam, and adhesive installed in urban landscapes to act as base for paving yet permit growth of tree roots.

Structureless soil. Soil with no visible aggregates. *See also* massive soil and single-grain soil.

Structure, soil. The arrangement of soil particles into aggregates, or peds.

Stubble-mulching. Practice of leaving crop stubble standing between the time of harvest of one crop and beginning stages of growth of the following crop to reduce erosion or capture snow.

Subgroups. In soil taxonomy, a category below the great group category and above the family category.

Subirrigation. Method of irrigation in which capillary rise from a saturated zone in the soil carries water to plant roots.

Suborders. In soil taxonomy, a category below the order category.

Subsidence. The lowering of a surface. Organic soils subside because organic particles are lost to decay or wind erosion.

Subsoil. Soil below the plow layer, generally the B horizon.

Subsoiling. Breaking up compact subsoils or pans by the use of a chisel or other tool.

Subsurface drainage. A method of artificially draining wet soils by burying a system of tiles or perforated pipes that carry excess subsurface water off the field.

Subsurface tillage. Tillage with special tools that are drawn beneath the soil surface to kill weeds and loosen soil without mixing crop residues into the soil for protection against wind erosion.

Surface creep. Movement of sand particles along soil surface by being rolled in the wind.

Surface drainage. A method of artificially draining wet soils by digging a system of ditches that collect water and carry it off the field.

Surface irrigation. Broad term for flooding the soil surface with water released from canals or piping systems.

Surface soil. The top few inches of soil, usually mixed during tillage. Often the same as the plow layer.

Surface water. Water in natural or human-made bodies of water on the earth's surface, such as lakes or reservoirs.

Suspension. (1) A system of tiny particles hanging in a liquid or gas. (2) Movement of clay or silt particles in the wind by being suspended in the air.

Sustainable agriculture. A philosophy and collection of practices that seek to protect resources while ensuring adequate productivity, strives to minimize off-farm inputs such as fertilizer and pesticides, and to maximize on-farm resources such as livestock manure and nitrogen fixation by legumes. Soil and water management are central components.

Swale. A shallow ditch in the landscape that water tends to collect in and flow through. Vegetated swales are constructed in housing developments to move stormwater. A *bioswale* is constructed and vegetated to promote water absorption rather than transport, a BMP in low-impact development.

Symbiont. An organism that lives in close association with another organism, an association known as *symbiosis*. In this text, the association is mutually helpful to both organisms, a form of symbiosis known as *mutualism* in the field of ecology.

Symbiosis. The relationship between organisms that live with other organisms in a partnership helpful to both.

Symbiotic nitrogen fixation. Fixation of nitrogen by microbes living in symbiosis with plant roots, usually by *Rhizobium* bacteria and several species of actinomycetes.

Syringing. A light sprinkling of turf or other plants to reduce heat stress and transpiration.

T

Talus. Deposits of dry rock and soil that have slid to the base of a slope under the force of gravity.

Taxonomy, soil. System of classifying soils to show their relationships.

Temporary wilting point. Point of plant water content at which plant wilts but at which plant will recover if watered, cooled, or placed in humid air.

Terrace. (1) Geologic: An older floodplain on a level above the current river channel and modern floodplain. (2) Soil and water conservation: A series of low ridges and shallow channels running across a slope or on the contour to capture water so it can soak into the soil or to control erosion.

Thermophilic. A preference for temperatures above 35°C.

Thermophilic organism. Heat-loving organism whose optimum temperature range for growth is above 35°C. Dominates composts during middle stage of decay.

Tillage. Mechanically working the soil to change soil conditions for crop growth, kill weeds, or bury crop residues.

Tillage pan. A soil pan induced by tillage operations.

Tilth. Physical condition of the soil in terms of how easily it can be tilled, how good a seedbed can be made, and how easily seedling shoots and roots can penetrate.

Tissue testing. Nutrients in the plant itself, instead of nutrients in the soil, are tested.

Topdressing. Applying fertilizer on an established turf, hay meadow, pasture, and so on without incorporation by tillage.

Topography. *See* relief.

Topsoil. The A horizon; or soil stirred during tillage.

Total neutralizing power (TNP). An older term for calcium carbonate equivalent.

Total pore space. Portion of soil not occupied by solid material but that is filled with air or water. *See also* pore space and porosity.

Trace elements. *See* micronutrient.

Transported soil. Soil formed in parent materials brought to the final location of soil formation by transporting agents such as gravity, flowing water, wind, and glacial ice sheets.

Traveling-gun irrigation. Sprinkler irrigation from a large traveling sprinkler moved by a cable attached to a heavy tractor or winch.

Type, soil. An old term, meaning the same as a textural phase of a soil series.

U

Ultisol. One of 12 soil orders. Leached soils of warm climates.

Universal Soil Loss Equation (USLE). Equation developed to predict average soil losses from a soil because of sheet and rill erosion.

Unsaturated flow. Water movement through the soil when the largest pores are not filled with liquid water.

Urban land. Areas altered by urban activities and structures, so that the soil is difficult to identify.

V

Value. One of three variables of the Munsell color system. Refers to the lightness or intensity of color.

Vermiculite. (1) One of the expanding clay minerals. (2) Expanded mica that is lightweight and porous. It is used in potting mixes.

Vertical mulching. A band or column of mulching material is placed into a vertical slit or narrow hole in the soil.

Vertisol. One of 12 soil orders. Soils high in swelling clays that have deep wide cracks when dry. Surface soil falls into the cracks, causing soil mixing.

Virgin soil. Soil that has not been disturbed by humans.

Volatilization. Evaporation. Also applies to loss of nitrogen in ammonium fertilizers and urea as soil reactions convert it to ammonia gas that is lost to the atmosphere.

Volumetric water content. The volume of water contained in a given volume of soil, expressed compared to the same volume of soil in a dry state.

W

Water content. A measure of the water content of the soil by weight, also, but less accurately, known as moisture percentage. Calculated by subtracting dry weight from moist weight, then dividing by the dry weight.

Waterlogged soil. Soil whose pores are filled with water and so are low in oxygen. Caused by high water tables, poor drainage, or excess moisture from rain, irrigation, or flooding.

Watershed. The total land area in which runoff water flows into the same stream.

Water table. Upper surface of a layer of saturated material in the soil.

Water table, perched. *See* perched water table.

Water-use efficiency. Crop production per unit of water reaching the land the crop occupies.

Wattle. A temporary barrier to water flow laid across a slope to slow downhill water flow that causes sediments to drop out behind the barrier. Maybe a long flexible tube filled with straw, compost, or coconut fiber. Often used to prevent erosion on construction sites.

Weathering. Natural process that breaks down rock into parent materials.

Wetland hydrology. The behavior of water in a soil is such that the soil is saturated or flooded with groundwater or surface water long enough or often enough during the growing season to exclude plants not adapted for life in saturated soils.

Wetlands. Areas that have a predominance of hydric soils and that are inundated or saturated by surface water or groundwater at a frequency and duration sufficient to support, and under normal circumstances do support, a prevalence of hydrophytic vegetation typically adapted for life in saturated soil conditions.

Wheel-move irrigation. A line of sprinklers mounted on wheels that slowly rolls down the field as it sprinkles the land.

Wind Erosion Equation (WEQ). A wind erosion prediction model that uses the following factors: soil erodibility, soil roughness, climatic conditions, field length, and vegetative cover.

X

Xeric. (1) In soil taxonomy, a type of climatic regime. (2) In more common usage, a dry soil-moisture regime.

Xeriscaping. A kind of landscaping adapted to dry climates designed to reduce water use.

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