# Land-use systems analysis

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## PREFACE

Assessing the suitability of land in one integrated analysis of biophysical and socio-economic information meets with considerable practical difficulty. A 'two stage approach' is followed instead, with a socioeconomic evaluation superimposed on an analysis of the biophysical aspects of land and land-use. This book is concerned with the first stage only; it discusses established qualitative and semiquantitative procedures and modern quantified methods for assessing the biophysical suitability of land for production of annual food and fibre crops.

The calculation procedures in Chapters 5 10 were developed by the authors, with contributions by N.G. Danalatos of the University of Athens (Greece), M. v.d. Berg, WOTRO fellow at the Instituto Agronomico de Campinas (Brazil), Yu Zhenrong of Beijing Agricultural University (P.R. of China), and the participants and support staff of the INRES project at Brawijaya University (Indonesia). The authors wish to thank publications adviser J. Chris Rigg for professional help with the first five chapters of the manuscript.

This book is used in the land evaluation courses of the Department of Soil Science and Geology of Wageningen Agricultural University. An exercise book with data files and programs used in the courses is being prepared.

Wageningen, July 1992

### Notice

Important publications, which shaped modern land evaluation are discussed in their original form. Consequently, units, symbols and definitions do not always follow the guidelines of the International Organization for Standardization (ISO).
Equations in this text include some conventions of BASIC: the multiplication sign is an asterisk; 'equals or is greater than' is >=; 'less than or equal to' is =<; 'not equal to' is <>. Some of the terms in Equations are represented by multiple letters upright roman, as in computer programs; only singleletter terms are *italicized*.

CONTENTS

# CHAPTER 1

# CONCEPTS AND DEFINITIONS IN ANALYSIS OF LAND SUITABILITY

# 1. CONCEPTS AND DEFINITIONS IN ANALYSIS OF LAND SUITABILITY

Analysis of land suitability combines a study of land (properties) with a study of land-use and determines whether the compounded requirements of land-use are adequately met by the compounded properties of the land. That sounds simpler than it actually is. Land properties vary in time and space, and land-use is equally dynamic. Over the years a variety of evaluation procedures have been proposed to cope with the complexity of land and its use. The growing confusion came to an end when the Food and Agriculture Organization of the United Nations (FAO) organized an 'Expert Hearing on Land Evaluation' in Wageningen in 1972. The objective of this meeting was to define standards for the appraisal of land suitability for agricultural uses. The definitions and concepts agreed upon were published in the FAO 'Framework for Land Evaluation' in 1976.
The terminology used in this text is basically the same as the one proposed in the Framework. A few definitions have been sharpened to eliminate conceptual inconsistencies.

## 1.1 Land and land-use

### Land and land qualities

The concept of 'land' should not be confused with 'soil' because soil is but one aspect of land, alongside vegetation, physiography, hydrology, climate/weather, infrastructure, etc. Physical areas that are homogeneous in all aspects of land are land units (LU).
To describe a land unit one refers to its major land characteristics (LCHR). Land characteristics can be single or compound. Single land characteristics are straightforward properties of the land that can be expressed by an explicit term or by a number. Annual cumulative rainfall, slope of the land, and depth of soil are examples of single land characteristics. Compound land characteristics are composed of associated single characteristics; 'available water capacity' (Awc) is an example of a compound land characteristic because it is a function of depth of soil and matrix geometry. Land characteristics do not affect the suitability of land for a certain use in an indiscriminate way. It is therefore attractive to aggregate those land characteristics which, together, cover a basic requirement of land-use and influence land suitability more or less independently of other land characteristics or aggregations of land characteristics. Such complex

clusters of land characteristics are land qualities (LQ).
The expression of each land quality is determined by a set of interacting single or compound characteristics with different weightings in different environments according to the values of all characteristics in the set.

The land quality 'water availability to a crop' is an example. This quality comprehends single characteristics, such as rainfall and potential evapotranspiration, and compound characteristics, such as available water capacity, as well as interactions between them.

Land units are (defined as) internally uniform areas of land. It is perhaps possible to identify such uniform areas if one possesses detailed soil maps, vegetation maps, hydrology maps, and so forth, but the exercise would probably be futile. It is irrelevant whether a tract of land is uniform in all aspects or not. The question is rather whether the variation that occurs affects the functioning of the land under the intended use. Therefore, the concept 'land unit' is used in this text for areas that can be considered uniform in view of the requirements of the defined (actual or intended) land-use.

Land-use and land-use requirements

The framework concept of 'major kinds of land-use' (e.g. 'deciduous forest', 'annual crops', or 'natural pasture') is too wide to be useful except in very general analysis. A land utilization type (LUT) is more specific than a major kind of land-use. It is characterized by its key attributes, i.e. by those biological, socio-economic and technical aspects of land-use that are relevant to the functioning of the land utilization type. Examples of key attributes are crop selection, availability of farm power, implements and labour.

Note that this text addresses only the physical suitability of land for specific types of land utilization. Nonphysical attributes of land-use are considered at a much higher level of generalization than physical aspects. In practice, land utilization types are described by:
- selection of crop or variety
- a set of management/technology attributes of land-use. This set describes the means available to the producer or defines the limits within which management measures can be taken.

Each land-use poses specific requirements to the land. With land utilization types defined as they are, these land-use requirements (LUR) consist largely of crop requirements. Land-use requirements are expressed as 'required land properties' (with the same dimensions as the matching land characteristics or land qualities). Only then can one compare land properties (the supply side) with land-use requirements (the demand side).

## 1.2 Land-use systems

A combination of one land unit and one land utilization type (with one set of land-use requirements) constitutes a land-use system (LUS). A singleland-use system is the configuration whose performance is analysed in assessment of land suitability.
Multipleland-use systems (i.e. more than one crop on a field at one time) and compoundland-use systems (i.e. single or multiple systems in rotation) can be handled by combining analyses of singleland-use systems. Where appropriate, competition for light, water and nutrients are taken into account.
Farming systems consist of one or more land-use systems practised by one household or management unit.

## 1.3 Classification of land suitability

The comparison of relevant land-use requirements with the associated land characteristics or land qualities is the essence of analysis of land-use systems. The outcome of this matching procedure forms the basis for assessing the suitability of the land for the defined use.
Some classification systems use the term 'land capability' to express the inherent capacity of a land unit to support a defined land-use for a long period of time without deterioration. 'Land suitability' is meant to describe the adaptability of land to a specific land-use. That distinction will not be made in this text; 'land suitability' refers to the capacity of a defined land unit to support sustained application of a defined type of land utilization.
Both the land unit (specifications) and the attributes of land-use can be altered by man. Activities that cause changes of a permanent nature and can only be accomplished by big investors or government agencies are called major (land) improvements. Nonpermanent improvements or improvements which can be made by individual farmers are minor improvements. If the defined use is the current land-use and the

specifications of a land unit pertain to the land in its present state, the actual suitability of land is assessed. If the requirements of an intended use are considered or the specifications refer to 'improved' or modified land, potential land suitability is examined.

An example: if 'traditional basinirrigated rice production' were the current land-use, an analysis would produce an expression of the actual land suitability for this type of rice growing and assess the potential suitability for all other types of land utilization considered.

The Framework for Land Evaluation (FAO, 1976) recognizes four levels of generalization in classification of land suitability:
-land suitability orders reflecting kinds of suitability, i.e. 'suitable' (S) or 'not suitable' (N)
-land suitability classes indicating the degree of suitability within an order
-land suitability subclasses specifying kind(s) of limitation or kind(s) of required improvement measures within classes
-land suitability units indicating differences in required management within subclasses.
There may be land units in an area or region that are clearly not suited for a particular use, e.g. irrigated cropping outside the area where water is available. A formal analysis of land suitability is then redundant. The symbol NR ('not relevant') on maps or in tables refers to this condition.

Note that there is a difference between the designations 'not relevant' (NR) and 'not suitable' (N). The outcome of a land suitability assessment disqualifies 'not suitable' lands for the defined land-use because that use is technically impracticable or would lead to severe environmental degradation. However, this is not immediately obvious and becomes clear only with suitability analysis.

## Land suitability classes

Land suitability classes indicate the degree of suitability within an order. Arabic numbers reflect a sequence of decreasing suitability: Class S1 land is highly suitable for the defined land-use, Class S2 land is less suitable than S1 land, and so on.
The number of classes within each order is best kept to a minimum necessary to meet interpretative aims; five classes are probably the most ever needed. Often, three classes are recognized within the order 'suitable'; the names and definitions suggested in Table 1.1 are widely used.

Table 1.1. Widely used (qualitative) land suitability classes. Source: FAO (1974).

| Class | Denotation | Definition |
| --- | --- | --- |
| S1 | highly suitable | Land having no significant limitations to sustained application of the defined use, or only minor limitations that will not significantly reduce productivity or benefits and will not raise input requirements above an acceptable level. |
| S2 | moderately suitable | Land having limitations that in aggregate are moderately severe for sustained application of the defined use; the limitations reduce productivity or benefits, or increase required inputs to the extent that the general advantage to be gained from the use, although still attractive, will be appreciably inferior to that expected from class S1. |
| S3 | marginally suitable | Land having limitations that in aggregate are severe for sustained application of the defined use and will reduce productivity or benefits, or increase required inputs to the extent that the defined use will be only marginally justified. |
| N1 | currently not suitable | Land having limitations that may be surmountable in time but that cannot be corrected with existing knowledge at a currently acceptable cost; the limitations are so severe as to preclude the defined land-use at present. |
| N2 | permanently not suitable | Land having limitations that appear so severe as to preclude any possibility of successful sustained application of the defined land-use. |

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If narrower taxon specifications are needed, it is recommended to add classes, e.g. S4, and not to subdivide one or more classes. Degrees of suitability are represented by only one level in the classification structure, that of the land suitability class.

Land suitability subclasses

Land suitability subclasses indicate the kind of the limitations that seriously restrict the suitability of land; one or more lowercase letters are suffixed to the class symbol (e.g. S2m: moderately suitable land due to limited availability of moisture). There are no subclasses to class S1.

The number of subclasses recognized and the limitations chosen to identify them will differ for different purposes. The following guidelines are generally valid.

-The number of subclasses should be kept to a minimum that still allows distinction (within a class) between land units with significantly different requirements for management or potential for improvement due to limitations.

-As few suffixes as possible should be used in the subclass symbol. The dominant symbol (i.e. the symbol which determines the class) should be used alone if possible. If more than one severe limitation affects land-use, the limitations should be listed in order of seriousness, e.g. S3me.

Land suitability units

All land units of a particular (suitability) subclass have the same degree of suitability and similar kinds of limitations. They may still differ from each other in their production characteristics or in minor aspects of their management requirements (often definable as differences in detail of their limitations).

The recognition of land suitability units permits detailed interpretation at the farm planning level. Land suitability units are distinguished by arabic numbers introduced by a hyphen, e.g. S2e-1, S2e-2. There is no limit to the number of units recognized within a subclass.

Conditional suitability

The designation 'conditionally suitable' is sometimes added if a land unit is unsuitable or poorly suitable for a particular use but would be suitable if certain conditions can be fulfilled, i.e. after one or more specifications of the land unit or attributes of the land-use have been modified. Conditional suitability is indicated by a lowercase letter 'c' between the order symbol and the class number, e.g. Sc2. Codes referring to the conditional suitability of land are placed at the bottom of the listing of S classes.

The taxa and codes used in the classification of land suitability are summarized in Table 1.2. Depending on the scale and purpose of the analysis, either the full range of suitability orders, classes, subclasses and units is distinguished or classification is restricted to one or more of the higher categories.

Table 1.2. Structure of land suitability classification.

| Order | Class | Subclass | Unit |
|---|---|---|---|
| S suitable | S1 | S2m | S2e-1 |
| S2 | S2e | S2e-2 | |
| S3 | S2me | etc. | |
| etc. | etc. | | |
| conditionally suitable | Sc3 etc. | Sc3m etc. | |
| N not suitable | N1 | N1m | |
| N2 | N1e | | |
| | etc. | | |

# CHAPTER 2

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# QUALITATIVE ASSESSMENT OF LAND SUITABILITY

## 2. QUALITATIVE ASSESSMENT OF LAND SUITABILITY

**Most established methods of land suitability assessment are qualitative. The methods differ among applications but matching 'relevant' land-use requirements against the corresponding land qualities or land characteristics in singleland-use systems forms the core of the procedure in all cases.**
**'Experts' determine which land-use requirements are relevant to the functioning of a particular system, the adequacy of the corresponding land qualities, and the overall land suitability. Different experts may hold different views. Conventional methods are therefore prone to being subjective. Yet, they are widely applied because reliance on expert knowledge is often the only option if primary information and analytical means are limited.**
**Qualitative analysis of land suitability assesses the fitness of land for a defined use in terms of** comparative suitability. **Many studies of this kind have been published. They all pass through the following stages.**
-selection **of relevant land-use requirements**
-matching **of selected land-use requirements with corresponding land characteristics and land qualities; the sufficiency of each land characteristic or land quality is expressed in a rating**
-conversion **of the various ratings to a qualitative indication of the suitability of the land for the defined use (i.e. an indication of the comparative success of the land-use system examined).**

### 2.1 Selection of relevant land-use requirements

**Selection of relevant land-use requirements is the starting point of any analysis of land suitability. A** land utilization calendar, **i.e. a timetable of successive land-use stages in a land-use system, is used to identify relevant land-use requirements. Table 2.1 presents an example of a land utilization calendar; it lists typical land-use stages for a singleland-use system with an annual crop. The selection of relevant land-use requirements from this list is made on the basis of field observations, discussions with farmers and extension workers, and expertise acquired elsewhere, in places similar to the one under study.**

Note that **land-use requirements and land qualities often have the same label. The term 'resistance to erosion', for example, connotes both the** land-use requirement and the land quality. In the first connotation the term is to be read as 'required resistance to erosion'; in the latter as 'actual resistance to erosion'.

The selection of land-use requirements in Table 2.1 is purely hypothetical. In practice, relevant land-use requirements are selected with the actual (attributes of) land-use and the actual (range in) specifications of land units in mind.

Table 2.1. Example of a land utilization calendar. The listed land-use stages and land-use requirements pertain to a singleland-use system with an annual crop.

| | LANDUSE STAGES | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | LAND PREPARATION | SOWING PLANTING | GERMINATION | VEGETATIVE GROWTH | FLOWERING | SEED DEVELOPMENT | RIPENING | HARVESTING |
| Biophysical requirements | | | | | | | | |
| **spectral irradiance** | | | | | * | | | |
| **temperature** | | | * | | * | | | |
| **availability of water** | | * | * | * | * | * | * | |
| **availability of oxygen** | | | | | | | | |
| **availability of nutrients** | | | | | | | | |
| **trafficability of the land** | * | * | | | | | | * |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Management requirements | | | | | | | | |
| **availability of draft power** | * | | | | | | | |
| **availability of implements** | * | | | | | | | |
| **availability of pesticides** | | | | | | | | |
| **adequacy of infrastructure** | | | | | | | | |
| Conservation requirements | | | | | | | | |
| **resistance to erosion** | | | | | | | | |
| **resistance to compaction** | * | | | | | | | * |
| **resistance to slaking** | | | * | | | | | |
| Improvement requirements | | | | | | | | |
| **conditions for drainage** | | | | | | | | |
| **conditions for leaching** | | | | | | | | |
| **conditions for irrigation** | | | * | * | * | | | |
| **conditions for liming** | | | | | | | | |

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## 2.2 Rating of land qualities and classification of land suitability

Rating tables **for classing the adequacy with which a certain land quality meets a particular land-use requirement (the** 'sufficiency' **of the land quality) are formalized interpretations of selected land characteristics, i.e. of components of the land quality examined. Table 2.2 is an example of a rating table: the sufficiency of the land quality 'resistance to erosion' is rated with the soil erodability index (SEI) of Wischmeier & Smith (1978) as a reference. This index is based on an interpretation of the land characteristics 'soil texture', 'content of organic matter in soil', 'soil structure' and 'soil permeability'.**

**Table 2.2. Rating table expressing the sufficiency of the land quality 'resistance to erosion' (on a rating scale from 1 to 4), as a function of soil erodability index (SEI).**

| Rating | Designation | SEI (ordinal scale, 0-1) |
|---|---|---|
| **1** | **no risk** | **< 0.4** |
| **2** | **slight risk** | **0.4 - 0.6** |

| | | |
|---|---|---|
| 3 | moderate risk | 0.6 - 0.8 |
| 4 | strong risk | 0.8 - 1.0 |

Note that **the rating specifications in Table 2.2 are** not **cropspecific. Although basically incorrect, this practice is quite common. It avoids the need to make separate rating tables for each and every type of land utilization. The crop requirements are taken into account later, during the conversion of the collective land quality ratings to land suitability classes.**

Conversion tables **interpret the various ratings of land qualities and translate these into an indication of the (comparative) performance of a land-use system. The complexity of such conversion tables increases with the number of land-use requirements considered. Table 2.3 is an example of a simple conversion table. It was developed for classifying land units at medium and high altitudes in the Kindaruma area, Kenya, with respect to their suitability for smallscale mixed farming with intermediate technology (Nyandat & Muchena, 1978).**

**Table 2.3. Example of a simple conversion table.**

| Suitability class | Ratings | | | | | |
|---|---|---|---|---|---|---|
| | CL | MOI | FERT | ER | IMPLE | DRA |

| | IMATE | STURE | ILITY | OSION | MENTS | INAGE |
|---|---|---|---|---|---|---|
| S1 (highly suitable) | II+III | 1-2 | 2 | 2 | 2 | 2 |
| S2 (moderately suitable) | II+III | 3 | 3 | 3 | 2-3 | 3 |
| S3 (marginally suitable) | II+III | 3 | 4 | 3 | 3 | 3-4 |
| N (not suitable) | | 4-5 | 5 | 4-5 | 4-5 | 5 |

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## 2.3 Case study: The Bura West irrigation scheme, Kenya

Qualitative assessment of land suitability will be discussed by examining the Bura West irrigation scheme in the Tana River District of Kenya's Coast Province (Muchena, 1987). The area comprised some 15 000 ha of which 3 900 were proposed for irrigation. Figure 2.1 shows the site of the Bura West irrigation scheme.

Dominant land characteristics of selected land qualities were rated according to the 'Proposals for Rating Land Qualities' of the Kenya Soil Survey (2nd Approximation, 1977), modified by Muchena where necessary to suit the conditions of the study area. These rating criteria are listed in full in Appendix A1. The ratings of land qualities for each land unit in the area were translated into a land suitability class with LUT-specific conversion tables.

*Demand side: relevant types and requirements of land utilization*

The selection of land utilization types was based on the current irrigated land-use in the Bura West irrigation scheme. Sugarcane and rice were not being grown in the Bura West area but were examined as options for land-use.

Fig. 2.1. Site of the Bura West irrigation scheme, Kenya (Muchena, 1987).

The land utilization types considered and their land-use requirements are outlined in the following (after Muchena, 1987).

<u>LUTC: irrigated cotton</u>

*Management/technology*. Smallholder plots of 1.25 ha within a governmentowned, centrally managed settlement scheme. Surface irrigation with long furrows; anticipated cropping intensity 100%. Water supply on rotation at 14day intervals. Land preparation mechanized but all other operations by hand except aerial sprays. Inputs high: farm inputs (seed; 80 to 120 kg fertilizerN $ha^{-1}$; herbicides and pesticides) available on credit. Technical knowhow of the farmers low to moderate; frequent use of extension services required. Mainly family labour, occasionally hired labour for weeding and cotton picking.

*Crop requirements*: Cotton requires a frostfree growing season of 200 days. The optimum temperature for germination is 34 °C; seedling growth is best between 24 and 29 °C, at other stages it requires temperatures of about 32 °C. Cotton loves sun; reduced irradiance (overcast sky, shading by interplanted crops, too dense a stand) retards flowering and fruiting and increases boll shedding. Cotton is salttolerant: 0%, 50% and 100% yield reductions occur if the electrical conductivities of saturation extracts (ECe) are <8, 17 and 27 mS $cm^{-1}$, respectively. The crop tolerates 40% exchangeable sodium; stunted growth is noted if sodium occupies between 40 and 60% of the cation exchange capacity of the soil. Inadequate drainage or a pH lower than 5.5 reduce growth. Adequate supplies of N, P and K are essential for good yields.

<u>LUTM: irrigated maize</u>

*Management/technology.* Smallholder plots of 0.625 ha within a governmentowned, centrally managed settlement scheme. Surface irrigation with long furrows; cropping intensity 48%; irrigation intervals of 14 days. Land preparation mechanized but all other operations by hand. Inputs moderate: farm inputs available on credit. Production mainly subsistenceoriented. Knowledge of the farmers low to moderate. Supervision by extension officers. Mainly family labour.

*Crop requirements.* The maize varieties grown in the area require a frostfree growing period of 80 to 110 days. Germination is best between 18 and 21 °C, greatly reduced below 13 °C and failing at 10 °C. The optimum temperature at tasseling is between 21 and 30 °C. Maize requires a fertile soil and is sensitive to waterlogging. The crop does not tolerate much salt: yield reductions are 0%, 50% and 100% at electrical conductivity of <2, 6 and 10 mS $cm^{-1}$, respectively. Maize is sensitive to sodicity to the extent that yield reductions of up to 50% occur at sodium saturation values of 15% or less. The crop grows in soils with a pH between 5.0 and 8.0; the optimum is between 6.0 and 7.0.

<u>LUTR: irrigated rice</u>

*Management/technology.* Plot sizes 1 ha or more. Basin irrigation of two crops per year in a largescale commercial setup. Land preparation mechanized; transplanting, weeding and harvesting by hand. Inputs high (HYV seed, fertilizers and pesticides); technical knowhow moderate. Labour inputs high during transplanting, weeding and harvesting.

*Crop requirements*. Rice can be cultivated in regions where the average temperature is at least 20 to 25 °C (with a minimum of 10 °C) for 4 to 6 consecutive months. High humidity favours growth but low humidity is needed in the ripening stage. The best soils are finely textured, slowly permeable, with good fertility. The optimum pH is around 6.0 in dry soils and around 7.0 in flooded soils but rice will survive pH of 8 to 9. The crop is moderately sensitive to salinity: yield reductions are 0%, 50% and 100% at <2, 7 and 11 mS $cm^{-1}$, respectively. There are no yield reductions if the level of adsorbed sodium ions remains less than 20%; soils with more than 30% adsorbed sodium are considered marginal for rice growing.

LUTS: irrigated sugarcane

*Management/technology*. Largescale commercial production on plots of 1 ha or more. Surface irrigation; the anticipated cropping intensity is close to 100%. Land preparation mechanized; planting and harvesting by hand. Farm inputs high and technical knowhow moderate to high. Labour inputs high during planting and harvesting.

*Crop requirements*. Although sugarcane is a comparatively hardy crop, it needs a steady supply of soil moisture during growth (14 to 18 months, depending on the variety; 12 months for a ratoon crop). The germination of stem cuttings is best between 32 and 38 °C; growth is slow or fails at temperatures below 15 °C. Sugarcane can grow in soils with a pH between 5.0 and 8.0; a pH between 6.3 and 6.7 is required for optimum performance. The crop is moderately sensitive to salinity: yield is reduced by 0, 50 and 100% at electrical conductivity of <2, 8.5 and 12 mS $cm^{-1}$, respectively. Sugarcane is semitolerant to exchangeable sodium and can grow on soils with up to 40% adsorbed sodium ions.

LUTP: irrigated cowpea

*Management/technology*. Smallholder plots of 0.625 ha in a governmentowned, centrally managed settlement scheme. Surface irrigation with long furrows (irrigation supervised by extension officers); anticipated cropping intensity around 50%. Land preparation mechanized but all other operations by hand. Inputs of seeds, fertilizers and pesticides low to moderate, bought on credit. The grain mainly grown for subsistence; the green leaves used as a vegetable. The farmers relied on family labour; knowhow low to moderate.

*Crop requirements*: Cowpeas are sensitive to cold and killed by frost. The crop is intolerant to waterlogging and requires good drainage. Yield reduction due to salinity amounts to 0, 50 and 100% at electrical conductivity of <5, 9 and 13 mS $cm^{-1}$, respectively. The crop is sensitive to sodicity and affected if more than 10% of the cation exchange capacity is occupied by sodium ions.

<u>LUTG: irrigated groundnut</u>

*Management/technology*. Smallholder plots of about 0.625 ha in a centrally managed settlement scheme. Surface irrigation with long furrows; anticipated cropping intensity about 50%. Irrigation needs supervision. Land preparation mechanized but all other operations by hand. Inputs of seeds, fertilizers and pesticides low to moderate, bought on credit. Crop grown for subsistence and to generate a cash income. The farmers rely on family labour; technical knowhow low to moderate.

*Crop requirements*. Groundnut requires a warm climate and adequate moisture supply. A fertile, finely textured surface soil is needed. Groundnut is moderately sensitive to salinity: yield reductions are 0, 50 and 100% at saturated electrical conductivity of <3.2, 5 and 6.5 mS $cm^{-1}$, respectively. The crop is sensitive to sodicity and is affected if more than 10% of the cation exchange capacity of the soil is occupied by sodium ions.

**Fig.2.2. Soil map of the Bura West irrigation scheme (Muchena, 1987).**

***Supply side: land units and land qualities***

**The land utilization types, each with a specific set of land-use**

requirements, dictate which land qualities need to be examined for each land unit in the study area. The land units coincide with soil mapping units or associations thereof. Figure 2.2 presents a reduced version of the original 1:10 000 soil map of the Bura West irrigation scheme; the (generalized) key to this soil map is in Table 2.4.

**Table 2.4. Generalized key to the soil map of the Bura West irrigation scheme.**

| Symbol | $CaCO_3$ | Salinity | Sodicity |
|---|---|---|---|
| **P Plains** | | | |
| **Pf Sedimentary plains of large alluvial fans** | | | |
| Pf1 Slightly elevated land | | | |
| **Pf1.1 Well drained to moderately well drained, very deep, (dark) brown, firm sandy clay (loam) with clear hardpan.** | **0-90 cm limefree.** | **slightly to strongly saline at 70-115 cm.** | **moderately to strongly sodic at 5090 cm.** |
| **Pf1.2 Moderately well to imperfectly drained, very deep, dark (reddish) brown, firm, sandy clay to clay.** | **0-15/40 cm limefree.** | **strongly saline at 1540 cm.** | **moderately to strongly sodic at 1540 cm.** |
| **Pf1.3 The same as Pf1.2 but dark (greyish) brown.** | **0-10/15 cm limefree.** | **strongly saline at 1015 cm.** | **strongly sodic at 1015 cm.** |
| Pf2 Lowerlying land | | | |
| **Pf2.1 Well drained, very deep, dark (reddish) brown, friable, (sandy) clay.** | **015/50 cm limefree.** | **slightly saline at 100125 cm.** | **slightly to strongly sodic at 60125 cm.** |

| | | | | |
|---|---|---|---|---|
| Pf2.2 | The same as Pf2.1 but moderately friable to firm. | calcareous throughout. | moderately to strongly saline at 2040 cm. | moderately to strongly sodic at 2040 cm. |

continued on next page

| Symbol | | $CaCO_3$ | Salinity | Sodicity |
|---|---|---|---|---|
| Pf2.3 | The same as Pf2.2. | calcareous throughout. | moderately to strongly saline at 1020 cm. | moderately to strongly sodic at 1020 cm. |
| Pf2.4 | Well drained to mode-rately well drained, very deep, dark reddish brown, firm clay. | moderately to strongly calcareous >30 cm. | strongly saline at 6070 cm. | strongly sodic at 1530 cm. |
| Pf2.5 | The same as Pf2.4 but reddish brown to dark reddish brown. | As Pf2.4, but >15 cm. | moderately to strongly saline at 4050 cm. | strongly sodic at 1015 cm. |
| Pf3 | Low land | | | |
| Pf3.1 | Moderately well to imperfectly drained, dark reddish brown, firm cracking clay. | strongly calcareous throughout. | moderately to strongly saline at 2060 cm. | moderately to strongly sodic at 2030 cm. |
| Pf3.2 | The same as Pf3.1, but firm to very firm. | As Pf3.1. | moderately to strongly saline at 1530 cm. | moderately to strongly sodic at 1015 cm. |
| Pf3.3 | Imperfectly to poorly | As Pf3.1. | moderately | |

strongly
drained very deep, dark to strongly sodic at
(greyish) brown, firm, saline at 1525 cm.
cracking clay. 5070 cm.

A Floodplain

A1 Imperfectly drained, slightly to slightly to moderately
very deep, (dark) brown, moderately moderately to strongly
(very) firm, stratified, calcareous saline at sodic at
cracking clay. >20-30 cm. 70100 cm. 2030 cm.

---------------------------------------------------------------------------------------------------

Depth classes: 050 cm shallow; 5080 cm moderately deep; 80120 cm deep;
>120 cm very deep.
Salinity classes: electrical conductivity of saturation extract (ECe) 04 mS $cm^{-1}$ nonsaline; 48 mS $cm^{-1}$ slightly saline; 816 mS $cm^{-1}$ moderately
saline; >16 mS $cm^{-1}$ strongly saline.
Sodicity classes: exchangeable sodium percentage (ESP) 05% nonsodic; 510%
slightly sodic; 1015% moderately sodic; >15% strongly sodic.

*Land quality rating and classification of land suitability*

Each of the selected land qualities is rated for each land unit (i.e. for each of the legend units of Table 2.4) according to the rating specifications in Appendix A1. Table 2.5 summarizes the ratings given.

Table 2.5. Land quality ratings for the Bura West irrigation scheme. Rating specifications in Appendix A1.
*key*:
Awc, available water capacity; ASal, absence of salinity; ASod, absence of sodicity; Oxy, availability of oxygen; Ger, conditions for germination; Nut, nutrient availability; Rts, foothold for roots; Wrk, workability; Drain, drainability.

---------------------------------------------------------------------------------------------------

| Map unit | Land quality | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Awc | ASal | ASod | Oxy | Ger | Nut | Rts | Wrk | Drain |
| **Pf1.1** | **4** | **3** | **3** | **12** | **4** | **4** | **2** | **2** | **5** |
| **Pf1.2** | **13** | **4** | **4** | **23** | **4** | **4** | **4** | **2** | **4** |
| **Pf1.3** | **13** | **5** | **5** | **23** | **45** | **4** | **5** | **35** | **4** |
| **Pf2.1** | **2** | **1** | **2** | **1** | **2** | **23** | **12** | **2** | **2** |
| **Pf2.2** | **23** | **24** | **4** | **1** | **3** | **3** | **3** | **3** | **3** |
| **Pf2.3** | **2** | **34** | **4** | **1** | **3** | **3** | **4** | **3** | **3** |
| **Pf2.4** | **2** | **24** | **45** | **12** | **3** | **34** | **34** | **4** | **4** |
| **Pf2.5** | **2** | **24** | **45** | **12** | **4** | **4** | **45** | **5** | **4** |
| **Pf3.1** | **3** | **34** | **34** | **23** | **3** | **3** | **3** | **3** | **3** |
| **Pf3.2** | **3** | **34** | **3** | **23** | **3** | **3** | **3** | **4** | **3** |
| **Pf3.3** | **3** | **34** | **3** | **34** | **4** | **4** | **3** | **4** | **3** |
| **A1** | **3** | **13** | **3** | **3** | **34** | **4** | **2** | **4** | **4** |

**To arrive at a land suitability classification, the land quality ratings are compared ('matched') with boundary values; these are set for each land utilization type in the conversion table (Table 2.6). The boundary values reflect the compounded land-use requirements (*management & technology requirements* and *crop requirements*) of individual land utilization types. The most limiting land quality (rating) determines the final land suitability (class) in each land-use system.**

**Table 2.6. Conversion table: criteria for establishing the suitability (class) of land for selected types of land utilization.**
***key*:**
**S1, highly suitable; S2, moderately suitable; S3, marginally suitable; N2,**

**permanently not suitable; na, not applicable.**

| Land suitability class | Land quality | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **class** | Awc | ASal | ASod | Oxy | Ger | Nut | Rts | Wrk | Drain |
| LUTC: irrigated cotton | | | | | | | | | |
| **S1** | **1** | **2** | **2** | **2** | **1** | **2** | **1** | **2** | **1** |
| **S2** | **2** | **3** | **3** | **3** | **2** | **3** | **2** | **3** | **2** |
| **S3** | **3** | **4** | **4** | **4** | **3** | **4** | **3** | **4** | **3** |
| **N2** | **4** | **5** | **5** | **5** | **4** | **4** | **4** | **5** | **4** |
| LUTM: irrigated maize | | | | | | | | | |
| **S1** | **1** | **1** | **1** | **1** | **1** | **2** | **2** | **2** | **1** |
| **S2** | **2** | **2** | **2** | **2** | **2** | **3** | **3** | **3** | **2** |
| **S3** | **3** | **3** | **3** | **3** | **3** | **4** | **4** | **4** | **3** |
| **N2** | **4** | **4** | **4** | **4** | **4** | **4** | **5** | **5** | **4** |
| LUTR: irrigated rice | | | | | | | | | |
| **S1** | **2** | **1** | **1** | **2** | **na** | **2** | **2** | **2** | **2** |
| **S2** | **3** | **2** | **2** | **3** | **na** | **3** | **3** | **3** | **3** |
| **S3** | **4** | **3** | **3** | **4** | **na** | **4** | **4** | **4** | **4** |
| **N2** | **5** | **4** | **4** | **5** | **na** | **4** | **5** | **5** | **5** |
| LUTS: irrigated sugarcane | | | | | | | | | |
| **S1** | **1** | **1** | **1** | **2** | **na** | **2** | **2** | **2** | **1** |
| **S2** | **2** | **2** | **2** | **3** | **na** | **3** | **3** | **3** | **2** |
| **S3** | **3** | **3** | **3** | **4** | **na** | **4** | **4** | **4** | **3** |
| **N2** | **4** | **4** | **4** | **5** | **na** | **4** | **5** | **5** | **4** |
| LUTP: irrigated cowpea | | | | | | | | | |
| **S1** | **1** | **1** | **1** | **1** | **1** | **2** | **2** | **2** | **1** |
| **S2** | **2** | **2** | **2** | **2** | **2** | **3** | **3** | **3** | **2** |
| **S3** | **3** | **3** | **3** | **3** | **3** | **4** | **4** | **4** | **3** |
| **N2** | **4** | **4** | **4** | **4** | **4** | **4** | **5** | **5** | **4** |
| LUTG: irrigated groundnut | | | | | | | | | |
| **S1** | **1** | **1** | **1** | **1** | **1** | **2** | **2** | **1** | **1** |
| **S2** | **2** | **1** | **2** | **2** | **2** | **3** | **3** | **2** | **2** |
| **S3** | **3** | **2** | **3** | **3** | **3** | **4** | **4** | **3** | **3** |

| N2 | 4 | 3 | 4 | 4 | 4 | 4 | 5 | 4 | 4 |
|---|---|---|---|---|---|---|---|---|---|

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The results of the matching procedure are summarized in Table 2.7. Combination ratings, e.g. S3N2, indicate that half the area occupied has one rating and the remaining half has the other. Table 2.7 shows that mapping unit Pf2.1 represents a land unit with a moderate suitability for all uses considered. Mapping units Pf2.2, Pf3.1, Pf3.2 and Pf3.3 are marginally suitable for some uses; all other areas are permanently unsuitable for any of the land utilization types considered.

Table 2.7. Land suitability classes for the land utilization types considered.

| Land Unit | LUTC | LUTM | LUTR | LUTS | LUTP | LUTG |
|---|---|---|---|---|---|---|
| Pf1.1 | N2 | N2 | N2 | N2 | N2 | N2 |
| Pf1.2 | N2 | N2 | N2 | N2 | N2 | N2 |
| Pf1.3 | N2 | N2 | N2 | N2 | N2 | N2 |
| Pf2.1 | S2 | S2 | S2 | S2 | S2 | S2 |
| Pf2.2 | S3 | S3N2 | S3N2 | S3N2 | S3N2 | N2 |
| Pf2.3 | S3N2 | N2 | N2 | N2 | N2 | N2 |
| Pf2.4 | N2 | N2 | N2 | N2 | N2 | N2 |
| Pf2.5 | N2 | N2 | N2 | N2 | N2 | N2 |
| Pf3.1 | S3 | S3N2 | S3N2 | S3N2 | S3N2 | N2 |
| Pf3.2 | S3 | S3N2 | S3N2 | S3N2 | S3N2 | N2 |
| Pf3.3 | N2 | N2 | S3N2 | S3N2 | N2 | N2 |
| A1 | N2 | N2 | S3 * | N2 | N2 | N2 |

* would classify as N2 if risk of inundation were considered.

## 2.4 Strengths and weaknesses of qualitative methods

Qualitative methods of land suitability assessment find wide application, and for good reason. An entirely quantitative and comprehensive analysis of actual suitability of land would require a highly sophisticated

computer model and a host of accurate data on land and land-use. Even if such a model could be constructed, after years of methodological work by a multidisciplinary team, it would be doubtful whether the estimates generated would be sufficiently accurate for planners and decision makers.
Often, one has no option but to rely on the (partly intuitive) judgment of experts who can make a descriptive interpretation of 'the production environment' and translate their interpretation into a qualitative land suitability class. The fact that different experts interpret aspects of land-use systems differently explains the poor reproducibility of such assessments. Formalization of the interpretation procedure by the use of predefined rating and conversion tables mitigates this but it makes the procedure rigid and imposes restrictions on the expert whose unique local knowledge is the very strength of the approach.

There are situations, however, where qualitative classification of land suitability and descriptive accounts of the performance of land-use systems are simply 'not good enough', e.g. if quantitative information on (expected) production, and on the inputs needed to achieve this production, is required for costbenefit projections. This explains why developments in land evaluation are increasingly directed at measurement and calculation of aspects of land and land-use, and at mathematical description of processes and interactions.

# CHAPTER 3

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# TOWARDS MEASUREMENT AND CALCULATION:

# PARAMETRIC METHODS

## 3. TOWARDS MEASUREMENT AND CALCULATION: PARAMETRIC METHODS

**Parametric methods of land suitability assessment take the following steps:**
**-they consider a few key properties of a land-use system and assign a numerical value to each property (**'singlefactor valuation' **or** 'indexing'**)**
**-they combine all singlefactor valuations in one mathematical equation that produces a numerical expression of system performance or a relative index of performance (**'compounding'**)**
**-they use this output for** 'ranking' **different land-use systems according to their (agricultural) value.**
**The criteria for selection, valuation, and compounding of key properties are defined by 'experts'. The procedure of suitability assessment is fully formalized once these criteria have been set. Parametric methods are transitional between qualitative methods that are entirely based on expert judgment, and standard mathematical models.**

### 3.1 Singlefactor valuation and compounding

**Parametric methods are based on the notion that the suitability of land for a defined agricultural use is (often) conditioned by only a few** significant factors. Response functions **express the impact of individual significant factors on the performance of the land-use system.**

**An example: the single land characteristic 'depth of soil' is positively correlated with production, strongly so when the soil is shallow and tending to an asymptote when the depth approaches the rooting depth of the crop. An index which expresses the sufficiency of the significant factor 'depth of soil' on a scale from 0 to 1 could be as follows.**

$$SDI = (1 - \exp(-x * SD))$$

**where**
**SDI is soil depth index**
**$x$ is a cropspecific coefficient ($cm^{-1}$)**
**SD is depth of soil (cm).**

**The value of coefficient '$x$' would be 0.10 $cm^{-1}$ for shallowly rooting**

crops (e.g. vegetables) and 0.02 $cm^{-1}$ for forest trees (Riquier, 1974). All relations and the values of all coefficients must be established or validated by experiment.

Once all significant factors have been evaluated, the singlefactor indexes must be 'compounded' in such a way that (most of) the interaction between the selected significant factors is accounted for.

Singlefactor values are normally multiplied together but (complex) mathematical formulations are used as well. The multiplication method has the advantage that it observes the law of the minimum: if one factor inhibits production it is indexed 'zero' and the calculated performance of the whole system will also be zero. More complex equations add further sophistication. Simple addition and subtraction of singlefactor values is rarely satisfactory. The assumption that all favourable factors add together and all harmful ones are counterproductive without any mutual interference is simplistic.

multiplication method: $PI = f(A) * f(B) * f(C) \ ...* WF1$

complex function (example): $PI = WF2 * (1 - f(A)) * f(B)^2 \ ...$

where

| | |
|---|---|
| PI | is the final expression of system performance, |
| $f(A)$, $f(B)$, $f(C)$ | are significant factor valuations, |
| WF1, WF2 | are weighting factors. |

Most compounding equations generate a performance index or a productivity index (PI). Often, they express the actual level of performance as a fraction of the maximum performance of a land-use system, which would occur with all significant factors optimum. There are also equations that express production or some other aspect of land or land-use (e.g. soil loss by erosion) directly.

Note that a simple comparative evaluation of land-use systems results if different scenarios (i.e. different combinations of singlefactor values referring to different land-use systems with different crops, soils and weather conditions) are examined. The generated values of the performance index express the comparative success of each land-use system and are used for ranking the systems.

3.2 Indexing of soil productivity

**Indexing of soil productivity is a simple method to evaluate the suitability of** soil **(a component of land-use systems) as a substrate for root growth. The soilproductivity index is based on several physical and chemical factors that are examined for each layer in the soil. To minimize data collection, the least number of soil factors is used that still gives a reasonably credible or useful result.**
**As the soil is characterized by layer, the method could be used to evaluate the effect of progressive erosion on 'soil productivity', i.e. performance of land-use systems whose nonsoil properties are assumed 'not significant'.**

**'The selection of the significant soil factors that are included in the index and the specification of response curves for each factor are, of course, both the heart and the weak point of the approach. To represent the soil by only a few factors does not do justice to the complexity of soils and one set of factors can never hold for all soil types.' (Rijsberman & Wolman, 1984)**

**The sufficiency of each soil factor selected is judged by interpreting response curves that relate soil factors measured to (partial) relative sufficiency values between 0 and 1.0. The compounding equation suggested by Neill (1979) for calculating the soilproductivity index reads:**

$$PI_{soil} = \sum_{i=1}^{n} (A_i * B_i * C_i * D_i * E_i * WF_i) \qquad (3.1)$$

**where**

| | |
|---|---|
| $PI_{soil}$ | is soilproductivity index |
| $A_i$ | is sufficiency of available water capacity of layer i |
| $B_i$ | is sufficiency of aeration of layer i |
| $C_i$ | is sufficiency of bulk density of layer i |
| $D_i$ | is sufficiency of pH of layer i |
| $E_i$ | is sufficiency of electrical conductivity of layer i |
| $WF_i$ | is weighting factor for layer i |
| $n$ | is number of layers considered in calculation |
| $i$ | is a serial number, 1,2...$n$ |

**The weighting factor reflects the relative importance of a particular soil**

layer for crop performance. The $WF_i$ values substituted in the compounding equation are based on an 'ideal' root distribution pattern. The sum of all weighting factors for one profile equals 1.0. The meaning of the weighting factor is illustrated in Figure 3.1.

Fig. 3.1. Meaning of weighting factor (Rijsberman & Wolman, 1984).

Note that the weighting factor for a particular soil layer is the integral of the root distribution curve between the upper and lower boundary of the layer divided by the integral over the total rooting depth.

A general distribution function may describe root distribution satisfactorily in some (years in some) systems but it is bound to be grossly inaccurate in others. One might just as well use a generic function based on an assumed linear decrease in root density from the surface down to the maximum rooting depth of the crop. The weighting factor for a rooted layer with its upper boundary at depth $D_1$ and the lower boundary at $D_2$ would be described by

$$WF_i = ((RDm - D_1)^2 - (RDm - D_2)^2) / RDm^2 \qquad (3.2)$$

where

$WF_i$ is weighting factor for layer i

RDm is maximum depth of root system (cm)

$D_1$ is depth of the upper boundary of layer i (cm)

$D_2$ is depth of the lower boundary of layer i (cm).

## 3.3 Example: predicting the consequences of erosion

Srivastava et al. (1984) indexed soil productivity in a study aimed at estimating changes in productivity imposed by longterm erosion of black and red soils in the Hyderabad region of India. The compounding equation used was a modification of Equation 3.1 and reads:

$$PI_{soil} = \sum_{i=1}^{n} (A_i * C_i * D_i * G_i * WF_i) \quad (3.3)$$

where

$PI_{soil}$ is soilproductivity index
$A_i$ is sufficiency of waterholding capacity (Awc) of layer i
$C_i$ is sufficiency of bulk density (BD) of layer i
$D_i$ is sufficiency of pH of layer i
$G_i$ is sufficiency of gravel content of layer i
$WF_i$ is weighting factor for layer i
$n$ is number of layers distinguished in the soil
$i$ is a serial number, 1,2...n.

The response curves used to estimate the partial sufficiencies of 'available water capacity', bulk density, pH, and gravel content are presented in Figure 3.2.

Measured values for the 'significant factors' of four (shallow and deep, red and black) soils at the ICRISAT Centre in Patancheru, India, are presented in Table 3.1. Srivastava et al. (1984) assumed an 'ideal' root distribution over a rooting depth of 100 cm to calculate the weighting factor for each layer. The generic relation (Equation 3.2) will be used in the present text.

**Fig. 3.2 ad. Response curves of the single factors 'available water capacity' (Awc; Fig. 3.2a), bulk density (BD; Fig. 3.2b), pH (Fig. 3.2c) and gravel content (Fig. 3.2d).**

Indexing **of the 'significant soil factors' in Table 3.1 with Figures 3.2a through 3.2d will be demonstrated for the 'shallow black soil'. First, singlefactor values and weighting factors are determined for the upper (0-25 cm) layer:**

**$A_i$ (moisture sufficiency): measured value is 0.18 ---> $A_i = 0.90$**
**$C_i$ (bulk density sufficiency): measured value is 1.3 ---> $C_i = 1.00$**
**$D_i$ (pH sufficiency): measured value is 7.6 ---> $D_i = 0.90$**
**$G_i$ (gravel sufficiency): measured value is 14.6 ---> $G_i = 0.93$**
**$WF_1$ (weighting factor): $WF_{(0\text{-}25cm)} = ((100-0)^2 - (100-25)^2) / 100^2 = 0.438$**

**Substitution of these values in Equation 3.3 produces the partial soilproductivity index for the upper layer:**
**$PI_{(025cm)} = 0.90 * 1.00 * 0.90 * 0.93 * 0.438 = 0.33$**

**For the 2nd layer:**
**$PI_{(2550cm)} = 0.90 * 0.63 * 0.83 * 0.87 * 0.313 = 0.128$**

**The productivity index for the whole soil is the sum of all partial indexes:**
**$PI_{soil} = 0.33 + 0.128 = 0.458$**

**Table 3.1. 'Significant factors' measured for the soils studied according to layer.**
***key*: s, sandy; gr, gravelly; cl, clay(ey).**

| | Texture (class) | Awc | BD ($Mg\ m^{-3}$) | pH ($CaCl_2$) | Gravel (%) |
|---|---|---|---|---|---|
| Shallow black soil | | | | | |
| **0-25** | **clay** | **0.18** | **1.3** | **7.6** | **14.6** |
| **25-50** | **clay** | **0.18** | **1.4** | **8.0** | **18.6** |
| Deep black soil | | | | | |
| **0-20** | **clay** | **0.18** | **1.3** | **7.6** | **6.0** |
| **20-40** | **clay** | **0.18** | **1.4** | **8.0** | **6.0** |
| **40-60** | **clay** | **0.18** | **1.4** | **8.0** | **6.0** |
| **60-90** | **clay** | **0.18** | **1.4** | **8.0** | **6.0** |
| **90-130** | **clay** | **0.18** | **1.45** | **8.0** | **7.0** |
| **130-180** | **clay** | **0.18** | **1.45** | **8.0** | **9.0** |
| Shallow red soil | | | | | |
| **0-15** | **s. loam** | **0.15** | **1.55** | **5.5** | **8.6** |
| **15-27** | **gr.clloam** | **0.12** | **1.55** | **6.4** | **49.0** |
| Deep red soil | | | | | |
| **0-10** | **s. loam** | **0.15** | **1.55** | **5.5** | **4.0** |
| **10-20** | **s. loam** | **0.12** | **1.55** | **6.4** | **6.0** |
| **20-30** | **s. clloam** | **0.12** | **1.55** | **6.4** | **10.0** |
| **30-49** | **gr.s.loam** | **0.12** | **1.65** | **6.3** | **8.0** |
| **49-102** | **gr.s.loam** | **0.12** | **1.65** | **6.0** | **37.0** |
| **102-145** | **gr.s.loam** | **0.12** | **1.65** | **5.7** | **15.0** |

**Table 3.2 presents the partial and integral productivity indexes computed for the selected soils. The correlation between these productivity indexes and yields was established by plotting calculated $PI_{soil}$ against estimates of average yield for land-use systems with a maizepigeon pea intercrop on the selected black and red soils. The**

estimates were made by specialists and refer to land-use systems in which plant nutrients are not limiting and other aspects of management are 'at a normal value'.

Table 3.3 summarizes the estimates for intercropped maize and pigeon pea on the studied soils.

Table 3.2. Computed productivity indexes (Equation 3.3) of the soils studied.

| | $A_i$ | $C_i$ | $D_i$ | $G_i$ | $WF_i$ | $PI_{soil}$ |
|---|---|---|---|---|---|---|
| Shallow black soil | | | | | | |
| 0-25 cm | 0.90 | 1.00 | 0.90 | 0.93 | 0.438 | 0.330 |
| 25-50 cm | 0.90 | 0.63 | 0.83 | 0.87 | 0.313 | 0.128 |
| total | | | | | | 0.458 |
| Deep black soil | | | | | | |
| 0-20 cm | 0.90 | 1.00 | 0.90 | 1.00 | 0.360 | 0.292 |
| 20-40 cm | 0.90 | 0.63 | 0.83 | 1.00 | 0.280 | 0.132 |
| 40-60 cm | 0.90 | 0.63 | 0.83 | 1.00 | 0.200 | 0.094 |
| 60-90 cm | 0.90 | 0.63 | 0.83 | 1.00 | 0.150 | 0.071 |
| 90-130 cm | 0.90 | 0.20 | 0.83 | 1.00 | 0.100 | 0.015 |
| 130-180 cm | 0.90 | 0.20 | 0.83 | 1.00 | 0.000 | 0.000 |
| total | | | | | | 0.604 |
| Shallow red soil | | | | | | |
| 0-15 cm | 0.75 | 0.92 | 0.96 | 1.00 | 0.272 | 0.180 |
| 15-27 cm | 0.60 | 0.65 | 1.00 | 0.34 | 0.190 | 0.025 |
| total | | | | | | 0.205 |
| Deep red soil | | | | | | |
| 0-10 cm | 0.75 | 0.92 | 0.96 | 1.00 | 0.190 | 0.126 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 10-20 cm | 0.60 | 0.92 | 1.00 | 1.00 | 0.170 | 0.094 |
| 20-30 cm | 0.60 | 0.68 | 1.00 | 1.00 | 0.150 | 0.061 |
| 30-49 cm | 0.60 | 0.76 | 1.00 | 1.00 | 0.230 | 0.105 |
| 49-102 cm | 0.60 | 0.76 | 1.00 | 0.52 | 0.260 | 0.062 |
| 102-145 cm | 0.60 | 0.76 | 0.98 | 0.91 | 0.000 | 0.000 |
| total | | | | | | 0.448 |

**Table 3.3. Expected mean grain yield and total biomass production of intercropped rainfed maize and pigeon pea (kg $ha^{-1}$ $year^{-1}$).**

| | Grain yield | | Biomass production | | Total |
|---|---|---|---|---|---|
| | **Maize** | **Pigeon pea** | **Maize** | **Pigeon pea** | |
| **Shallow black soil** | **1 800** | **860** | **3 600** | **3 440** | **7 040** |
| **Deep black soil** | **3 200** | **1 580** | **6 400** | **6 320** | **12 720** |
| **Shallow red soil** | **1 420** | **640** | **2 840** | **2 560** | **5 400** |
| **Deep red soil** | **2 620** | **830** | **5 240** | **3 320** | **8 560** |

**Plotting calculated $PI_{soil}$ (Table 3.2) against independent estimates of yield and production (Table 3.3) and subsequent curvefitting produced approximate relationships between (calculated) $PI_{soil}$ and (estimated) yield and production potentials:**

$$Ym = 450.1 + 4\,221 * PI_{soil} \quad (r^2 = 0.76) \quad (3.4a)$$
$$Ypp = 63.4 + 2\,132 * PI_{soil} \quad (r^2 = 0.72) \quad (3.4b)$$
$$TBP = 1\,154 + 16\,971 * PI_{soil} \quad (r^2 = 0.79) \quad (3.4c)$$

**where**
**Ym is maize (grain) yield of the maizepigeon pea intercrop (kg $ha^{-1}$**

year$^{-1}$)
Ypp is pigeon pea (grain) yield (kg ha$^{-1}$ year$^{-1}$)
TBP is total biomass production of the maizepigeon pea intercrop (kg ha$^{-1}$ year$^{-1}$).

*Impact of surface erosion*

The impact of surface erosion on the productive capacity of land-use systems is evaluated by calculating $PI_{soil}$ for different scenarios (with different losses of surface soil). Substitution of the $PI_{soil}$values in Equations 3.4 generates estimates of yield and production for each scenario.

Table 3.4. Soilproductivity indexes (Equation 3.3) and corresponding yields (Ym, maize grain; Ypp, pigeon pea) and total biomass production (TBP) of intercropped maize and pigeon pea on 'shallow black soils' with various losses of surface soil by erosion (after Srivastava et al., 1984).

| | $A_i$ | $C_i$ | $D_i$ | $G_i$ | $WF_i$ | $PI_{soil}$ | Ym | Ypp | TBP | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | (kg ha$^{-1}$ year$^{-1}$) | | | | | |
| no erosion | | | | | | | | | | | | |
| 0-25 cm | | | | 0.90 | 1.00 | 0.90 | 0.93 | 0.438 | 0.330 | | | |
| 25-50 cm | | | 0.90 | 0.63 | 0.83 | 0.87 | 0.313 | 0.128 | | | | |
| | | | | | | 0.458 | | 2 383 | 1 040 | 8 927 | | |
| assuming removal of 5 cm topsoil | | | | | | | | | | | | |
| 0-20 cm | | | | 0.90 | 1.00 | 0.90 | 0.93 | 0.360 | 0.271 | | | |
| 20-45 cm | | | 0.90 | 0.63 | 0.83 | 0.87 | 0.338 | 0.138 | | | | |
| | | | | | | 0.409 | | 2 176 | 935 | 8 095 | | |
| assuming removal of 10 cm topsoil | | | | | | | | | | | | |
| 0-15 cm | | | | 0.90 | 1.00 | 0.90 | 0.93 | 0.278 | 0.209 | | | |
| 15-40 cm | | | 0.90 | 0.63 | 0.83 | 0.87 | 0.363 | 0.149 | | | | |
| | | | | | | 0.358 | | 1 961 | 827 | 7 230 | | |
| assuming removal of 20 cm topsoil | | | | | | | | | | | | |
| 0-5 cm | | | | 0.90 | 1.00 | 0.90 | 0.93 | 0.098 | 0.074 | | | |
| 5-30 cm | | | | 0.90 | 0.63 | 0.83 | 0.87 | 0.433 | 0.177 | | | |
| | | | | | | 0.251 | 1 510 | 599 | 5 414 | | | |
| assuming removal of 30 cm topsoil | | | | | | | | | | | | |
| 0-20 cm | | | | 0.90 | 0.63 | 0.83 | 0.87 | 0.360 | 0.147 | 1 071 | 377 | 3 649 |

-------------------------

Table 3.4 presents a calculated example of $PI_{soil}$ and the corresponding yields and productions for land-use systems with 'shallow black soils'. Figure 3.3 shows the projected relative productions of total biomass of intercropped maize and pigeon pea on shallow and deep, black and red soils with various losses of surface soil by erosion. (Figure 3.3 is constructed by substituting calculated $PI_{soil}$ in Equation 3.4c; the values of TBP were then divided by the values of TBP calculated for uneroded soil.)

Fig. 3.3. Relative total production of biomass by land-use systems with intercropped maize and pigeon pea on shallow and deep, red and black soils, with various losses of surface soil by erosion.

## 3.4 Strengths and weaknesses of parametric methods

Parametric methods have a long history in land evaluation. The first documented application stems from 1928 when a simple parametric method was developed as a reference for land taxation in Bavaria. The best known method is perhaps the 'Storie Index' for the comparative grading of soils, a multiplication method with the soil series, the slope and several other properties of soil and land as significant factors. The method suffers from several shortcomings that are common to most parametric methods. Firstly, it uses compound factors such as the soil series, which include single characteristics that are again introduced in indexes of other significant factors. Secondly, it uses functions developed and tested for application in a particular region and it may not be assumed that these functions hold equally well elsewhere. Tests must be done anew before each application (but are often 'forgotten').

Some authors claim that parametric methods eliminate subjectivity because response curves or functional relations are used for indexing and compounding. The results of parametric methods are indeed reproducible once the method is developed, tested and standardized. But the same holds for the use of tested rating and conversion tables. It is also claimed that parametric methods are 'quantitative' methods. It is true that parametric methods produce numeric values but it remains to be seen how good these are. Parametric methods consider only the most significant factors and normally 'account for' interactions between significant factors by simple multiplication of singlefactor indexes. Such simplifications are paid for by lost precision. On the other hand, the very simplicity of parametric methods makes them useful in situations where there is a paucity of basic data and in situations where the system under analysis is poorly understood. The Universal Soil Loss Equation, which claims to produce an estimate of surface erosion, is an example.

In summary, parametric methods may reveal orders of magnitude or trends in (components of) land-use systems. As such, they have their value. Simple parametric methods will continue to be applied, particularly in broad regional surveys in countries where the available information on land and land-use is so limited that more sophisticated procedures cannot be used. Parametric methods that select and evaluate significant factors with minimum subjectivity, observe the interactions between the different factors, and interpret correctly the impact of all singlefactor values on land-use system performance, are still far away.

# CHAPTER 4

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# AGROECOLOGICAL ZONING

# 4. AGROECOLOGICAL ZONING

'Agroecological zoning' (AEZ) is a procedure of smallscale land suitability assessment. It was developed by the Food and Agriculture Organization of the United Nations with the objective 'to assess the potential agricultural use of the world's resources' (FAO, 1978). The immediate goal of the project was to investigate whether the world population could still be fed by the year 2000. The project had to be completed in only a few years, which forced the team to accept a number of restrictions:
-Land was described on the basis of the 1:5 000 000 Soil Map of the World (FAOUnesco, 1974) and an inventory of climate data, initially limited to some 700 meteorological stations in Africa (FAO, 1978).
-Land-use alternatives were restricted to those involving the world's major (annual) food and fibre crops, selected on the basis of the area occupied, the total production and the financial value they represent. Eleven 'major crops' were selected. In descending order of importance: wheat, paddy rice, maize, pearl millet, sorghum, soya, cotton, phaseolus bean, white potato, sweet potato, and cassava. All other 'key attributes of land-use' were lumped together and merely signify whether cropping is practised with low input (of management and technology) or with high input.

Note that the management/technology aspects of land-use are considered at a much higher level of aggregation than the crop aspects. Land-use requirements in the AEZ study are *defacto* climaterelated and soilrelated crop requirements.

### *Steps in agroecological zoning*

Several preparatory steps must be taken before land suitability classes can be established. These steps will be listed hereafter and shown in their relational context in Figure 4.1.

<u>Step</u> 1:Soilrelated requirements of the 'major crops' selected are matched against the characteristics of all soil units distinguished on the Soil Map of the World. Soilunit ratings for rainfed cropping with 'high' and 'low' input are thus obtained.
<u>Step</u> 2:Records of individual climate stations are evaluated to delineate major climatic divisions. The temperature specifications of the major climatic divisions are matched against the temperature requirements of

the selected 'major crops' to identify those broad climatic regions that are 'not suitable' (N) for growing a particular 'major crop'. Further analysis is restricted to regions with 'suitable' (S) climate.
Step 3:Precipitation, potential evapotranspiration and temperature data of stations are analysed to determine beginning and end of a possible growing season and the length of the growing period (LGP). Sites with comparable LGP are aggregated to LGP zones.

Step 4:Radiation and temperature data of stations are matched against relevant climaterelated crop requirements in a model of net biomass production and constraint-free yield.
Step 5:The step from a potential ('constraintfree') yield to a more practical anticipated yield is made by making yield deductions for likely agro-climatic constraints in a given LGP zone, under consideration of the available technology (i.e. the 'input').
Step 6:The anticipated yield is then matched against a reference yield (different for 'highinput' and 'lowinput' cropping). The outcome of this matching is the agroclimatic suitability.
Step 7:The soilunit rating and the agroclimatic suitability determine the (preliminary) land suitability class for highinput and lowinput rainfed farming. The final land suitability class is obtained by correcting the preliminary land suitability class by a set of phase, slope and texture rules.

LANDUSE SYSTEM

LAND

LANDUSE

Data on: Soil/terrain Weather/climate Crop requirements Inputs

Step 1: Soil unit

rating

Step 2: phase, Major climatic
slope, division
texture

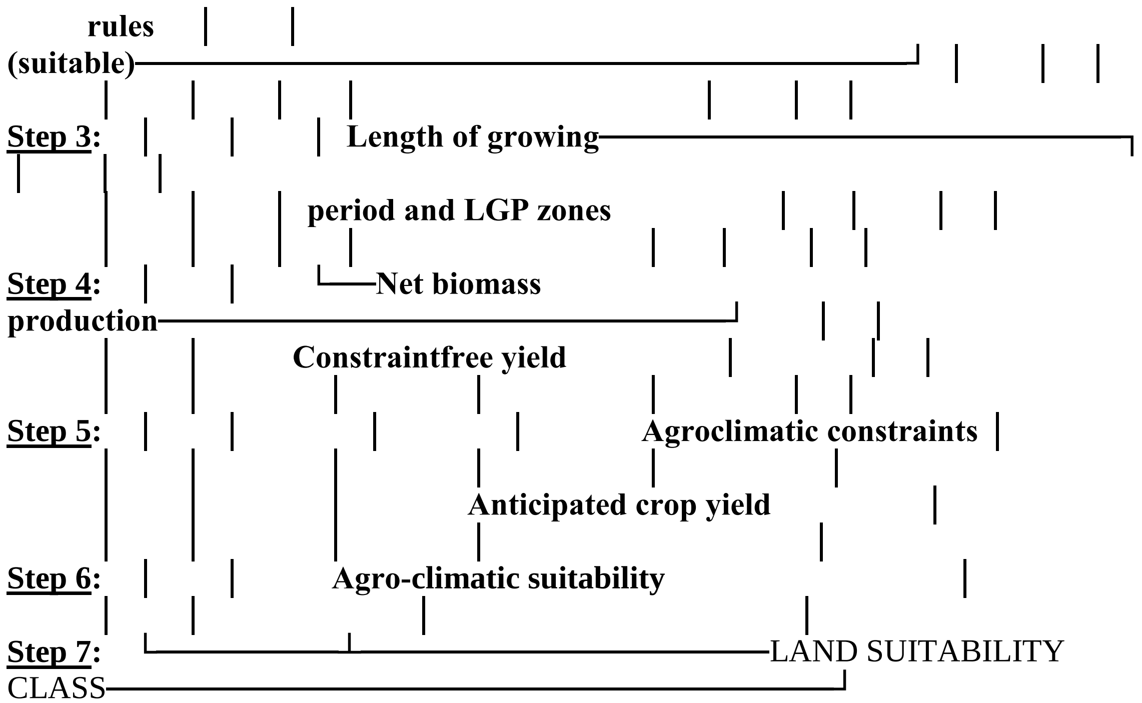


**Fig. 4.1. All AEZ matching procedures in their relational context.**

## 4.1 Soilrelated crop requirements and soilunit ratings

### *Soilrelated crop requirements*

**Each soil unit in the legend of the FAOUnesco Soil Map of the World (1974) is characterized by its 'internal properties' (depth, drainage class, texture class, inherent fertility, electrical conductivity, pH, $CaCO_3$ content, and gypsum content), and by the 'external property' slope angle. Experts have defined the corresponding (soilrelated) requirements of each of the 'major crops'. The requirements of maize, soya and rice are presented in Table 4.1 as an illustration. The tabulated values are to be regarded as 'required soil properties' for optimum and marginal** soil **suitability.**

**Table 4.1. Soilrelated requirements of maize, soya and rice. Source: FAO, 1978.**
***key*:**

**vp, very poorly drained; i, imperfectly drained; w, well drained; sed, somewhat excessively drained; mw, moderately well drained; MC, (smectite) clay; KC, (kandite) clay; LS, loamy sand; SL, sandy loam; SiL, siltloam; CL, clayloam.**

------------------------------------------------------------------------------------------------------

Slope Soil depth Drainage Texture
**Crop** (%) **(cm)** class class
**opt.marg. opt. marg. opt. range opt. range**
maize **0-8 8-15** >**50 10-50 mww ised SiL-CL SLMC**
soybean **0-8 8-20** >**75 50-75 mww ised SiL-CL LSKC**
rice **0-4 4-8** >**50 25-50 imw vpw SiL-CL SLMC**

Fertility Salinity pH $CaCO_3$ Gypsum
**(level) (mS/cm)** (1:2.5) (%) (%)
**opt.marg. opt. range opt. marg. opt. marg.**
maize **moderate 0-4 4-6 5.5-8.2 5.28.5 0-15 15-25 0-.2 .2-2**
soya **moderate 0-4 4-6 5.5-7.3 5.28.2 015 15-25 0-.2 .2-2**
rice**low 0-2 2-4 5.5-7.5 5.28.2 0-15 15-25 0-.2 .2-2**

------------------------------------------------------------------------------------------------------

*Soilunit ratings*

**A comprehensive** rating table **was constructed by matching all tabulated soil-related crop requirements against the properties specified for each soil unit in the Soil Map of the World. The rating table indicates the comparative suitability of the various soil units for highinput and lowinput rainfed production of each of the selected major crops.**

Note that **the tabulated ratings apply to the current soil units, i.e. without major land improvements.**

**Four (suitability) ratings were used:**
**S1 'very suitable' or 'suitable'**
**S2 'marginally suitable'**
**N1 'not suitable but limitations ameliorable'**
**N2 'not suitable with limitations of a permanent nature'.**

**Where combination ratings, e.g. S2N2, are given for a soil unit it is**

considered that half the area occupied has one rating and the remaining half the other. Appendix A2 contains the full rating instructions for the eleven 'major crops' and for sugarcane. Table 4.2 presents an excerpt from the comprehensive rating table.

Table 4.2. Example of soilunit ratings (based on internal properties only). Source: FAO, 1978.

| | Maize | | Soya | | Rice | |
|---|---|---|---|---|---|---|
| | low input | high input | low input | high input | low input | high input |
| Ferric Acrisol: | S2N2 | S2 | S2N2 | S2 | S2N2 | S2N2 |
| Orthic Ferralsol: | S2 | S2 | S2 | S2 | S2 | S2 |
| Ferric Luvisol: | S2 | S1S2 | S2 | S1S2 | S2N2 | S2N2 |

### *Phase, slope and texture rules*

The tabulated ratings of soil units are modified for individual mapping units if limitations are imposed by the slope of the land or by an unfavourable texture (certain soil units only), or by unfavourable conditions which are marked as a 'phase' on the Soil Map of the World. Detailed phase, slope and texture rules can be found in Appendix A3. Limitations imposed by conditions indicated as phases on the Soil Map of the World are accounted for by downgrading the rating for all or part of the mapping unit, at one or at both levels of input, in accordance with the severity of the limitation. Twelve phases are recognized on the Soil Map of the World (1974): 'stony', 'lithic', 'petric', 'petrocalcic', 'petrogypsic', 'petroferric', 'phreatic', 'fragipan', 'duripan', 'saline', 'sodic' and 'cerrado'.

Note that phase definitions introduced in the legend of the Soil Map of the World after termination of the AEZ project are not included in Appendix A3.

If the slope of the land is between 8 and 30%, the tabulated ratings are

**modified as follows.**

**-If input is low, a third of the ratings remain unchanged, a third are downgraded by one class and the remaining third are downgraded to N2**
**-If input is high, a third of the ratings remain unchanged and the remaining two-thirds are downgraded to N2.**
**(All ratings are downgraded to N2, regardless of input, if the crop is rice.)**

**If the slope of the land is** steeper than 30%, **85% of all ratings are downgraded to N2 and the remaining 15% are treated as if their slope were between 8 and 30%. (This implies that 5% of the lands with a slope of more than 30% are considered suitable for cultivation at both levels of input, if other considerations are satisfactory.)**

Coarsely textured **soil units whose initial suitability ratings do not already reflect the coarseness of the soil material are downgraded by one class.**

4.2 Major climatic divisions and LGP zones

***Climaterelated crop requirements***

**The biophysical production potential of crops is determined (within limits set by the crop's physiological properties) by the irradiance of** photosynthetically active radiation **that the crop can intercept, and the** temperature **regime of the production environment. The AEZ study distinguishes four** cropadaptability groups, **each with specific temperature and radiation requirements. Table 4.3 lists the climatic requirements of 'major crops' in each cropadaptability group.**

**Table 4.3. Indicative climaterelated crop requirements by cropadaptability group. Source: FAO, 1978.**
-------------------------------------------------------------------------------------------------

| | Cropadaptability group | | | |
|---|---|---|---|---|
| | **I** | **II** | **III** | **IV** |

Optimum temperature range (°C) 15-20 25-30 30-
35 20-30
Operative range (°C) 5-30 15-35 15-45
10-35
Irradiance for maximum
photosynthesis (cal $cm^{-2}$ $min^{-1}$)* 0.20.6 0.30.8 > 1.0 > 1.0

Crops in each
cropadaptability wheat bean millet maize
group potato soya sorghum
sorghum
bean rice maize
cotton (sugarcane)
cassava
sw. potato

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* data as published by FAO (1978); 1 cal $cm^{-2}$ $min^{-1}$ = 697.8 W $m^{-2}$

Note that cultivars suited to temperate regions and high altitudes in the tropics belong to cropadaptability groups I ('C3 crops') and IV ('C4 crops'). Tropical (lowland) cultivars belong to cropadaptability groups II ('C3 crops') and III ('C4 crops'). The terms 'C3 crops' and 'C4 crops' and the differences between these two types will be discussed in Chapter 8.

*Major climatic divisions*

A first grouping of (station) temperature data suffices to delineate thermal zones; further separation of subtropical regions with winter rainfall from those with summer rains produces major climatic divisions. Table 4.4 presents the major climatic divisions of Africa and shows that a simple agroclimatic suitability assessment can be made at the level of suitability order (i.e. a division into 'suitable' (S) and 'not suitable' (N)) by matching the climatic requirements of each cropadaptability group against the boundary specifications of major climatic divisions.
Table 4.4 demonstrates that tropical mountain areas and cold subtropical regions in Africa are considered unsuitable for rainfed production of 'major crops'. These climatic divisions are not examined any further in the AEZ study.

**Table 4.4. Major climatic divisions (descriptive names) of Africa and their order of suitability. Source: FAO, 1978.**

| Major climatic division | suitable (S) for cropadaptability group | mean 24hour temperature in growth cycle (°C) | total area in Africa ($ha*10^3$) |
|---|---|---|---|
| **Warm tropics/trop. lowlands** | **II, III** | **>20** | **2 029 975** |
| **Cool tropics/trop. highlands** | **I, IV** | **<20** | **96 604** |
| **Cold tropics/trop. mountains** | **not suitable (NS)** | **<6.5** | **2 903** |
| **Warm subtropics (summer rain)** | **II, III** | **>20** | **291 894** |
| **Cool subtropics (summer rain)** | **I, IV** | **<20** | **39 900** |
| **Cold subtropics (summer rain)** | **not suitable (NS)** | **<6.5** | **193** |
| **Cool subtropics (winter rain)** | **I** | **>6.5** | **543 198** |
| **Cold subtropics (winter rain)** | **not suitable (NS)** | **<6.5** | **6 663** |

**Fig. 4.2. Generalized survey of climatic resources of Africa: LGP zones and major climatic divisions. Source: FAO (1978).**

*LGP zones*

The availability of water and the temperature regime determine the 'length of the possible growing period' (LGP) of crops at a particular place. LGP is simple to calculate.
-The beginning of the possible growing period is arbitrarily set at the moment when the precipitation rate (PREC) first equals half the rate of potential evapotranspiration (0.5 * ET0) after a dry spell. A 'humid period' occurs whenever the precipitation rate exceeds the full rate of potential evapotranspiration.
-The possible growing period ends when the precipitation rate has become equal to or less than half the potential evapotranspiration rate unless a humid period occurs. The possible growing period then extends into the dry season and ends only after all available stored soil moisture has been depleted. The amount of available moisture is assumed equal to the precipitation surplus during the humid period, with a maximum of 100 mm for all soils and crops.
-In practice, the 'possible growing period' is not determined solely by availability of water but also by temperature. To estimate the period when both water and temperature permit crop growth, the AEZ team excluded from the calculated period of water availability all days with a 24hour mean temperature of less than 6.5 °C.

Regional aggregation of sitespecific LGP produces LGP zones. Figure 4.2 presents a generalized map of the major climatic divisions and the LGP zones of Africa (source: FAO, 1978).

## 4.3 Net production of biomass, constraintfree yield and anticipated yield

*Net biomass production and constraintfree crop yield*

The production potential in an LGP zone is determined by matching climate-related crop requirements against climatic land characteristics. The procedure generates estimates of net biomass production (i.e. the maximum possible production of dry matter) and constraint-free crop yield (the maximum possible economically useful production) in an LGP zone.

The average rate of net biomass production over the whole growth cycle is estimated by plotting a typical cumulative growth curve against the

time elapsed. The result is a 'growth over time curve' from which an equivalent growth rate for the whole growth cycle is derived.
The cumulative growth curve is (assumed to be) sigmoid and symmetrical; the value of the equivalent rate of biomass production is then half the slope of the growth curve at the inflection point (i.e. 0.5 * $b_{nm}$ as in Figure 4.3).

Fig. 4.3. Symmetrical cumulative growth curve.

The areic mass of dry matter produced ($B_n$) is the product of the overall rate of biomass production (0.5 * $b_{nm}$) and the length of the growth cycle ($Ng$).

$$B_n = 0.5 * b_{nm} * Ng \qquad (4.1)$$

where
$B_n$ is areic mass of dry matter produced in a growing cycle (kg ha$^{-1}$)
$b_{nm}$ is slope of (symmetrical) growth curve at inflection point, i.e. average rate of biomass production by a field crop (kg ha$^{-1}$ d$^{-1}$)
$N_g$ is length of growth cycle (d).

The potential growth rate of a crop is described by
-defining the gross assimilate production as a function of solar irradiance, temperature, and physiological properties of the crop
-correcting for losses of assimilates due to maintenance respiration
-correcting for losses of assimilates due to growth respiration.

(Maintenance respiration and growth respiration will be described in detail in Chapter 8. Suffice it here that losses by maintenance respiration are incurred because plants 'burn' some of the assimilates to obtain energy for, *inter alia*, maintenance of plant matter formed earlier. Losses by growth respiration are incurred in the conversion of primary assimilates to structural plant matter.)

Gross production of assimilates

The gross production of assimilates is calculated by matching measured global radiation against theoretically required (interception of) photosynthetically active radiation (PAR) for uninhibited production of assimilates (de Wit, 1965). Table 4.5 presents the theoretical irradiance of PAR on clear days ($A_c$, in cal cm$^{-2}$ d$^{-1}$), and the gross rate of assimilate production by a hypothetical reference crop (kg ha$^{-1}$ h$^{-1}$) on clear days ($b_c$) and on overcast days ($b_o$).
It is generally assumed that some 50% of the measured incoming global radiation ($R_g$, in cal cm$^{-2}$ d$^{-1}$) is photosynthetically active. Table 4.5 demonstrates that the amount of incoming radiation on a clear day depends on the time of year and on position on the globe. Irradiance on a cloudy day is further determined by the fraction of the day that the sky is overcast.

Table 4.5. Theoretical irradiance of photosynthetically active radiation on clear days ($A_c$, cal cm$^{-2}$ d$^{-1}$), and daily gross assimilation rate (areic mass rate of $CH_2O$, kg ha$^{-1}$ d$^{-1}$) of the crop canopy on clear ($b_c$) and overcast ($b_o$) days for a reference crop with a closed canopy and a maximum assimilation rate of 20 kg ha$^{-1}$ h$^{-1}$.

| | | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| N. hemisphere | | Ja | Fe | Ma | Ap | My | Jn | Jl | Au | Se | Oc | No | De |
| S. hemisphere | | Jl | Au | Se | Oc | No | De | Ja | Fe | Ma | Ap | My | Jn |
| 0° | $A_c$ | 343 | 360 | 369 | 364 | 349 | 337 | 342 | 357 | 368 | 365 | 349 | 337 |
| | $b_c$ | 413 | 424 | 429 | 426 | 417 | 410 | 413 | 422 | 429 | 427 | 418 | 410 |
| | $b_o$ | 219 | 226 | 230 | 228 | 221 | 216 | 218 | 225 | 230 | 228 | 222 | 216 |
| 10° | $A_c$ | 299 | 332 | 359 | 375 | 377 | 374 | 375 | 377 | 369 | 345 | 311 | 291 |
| | $b_c$ | 376 | 401 | 422 | 437 | 440 | 440 | 440 | 439 | 431 | 411 | 385 | 370 |
| | $b_o$ | 197 | 212 | 225 | 234 | 236 | 235 | 236 | 235 | 230 | 218 | 203 | 193 |
| 20° | $A_c$ | 249 | 293 | 337 | 375 | 394 | 400 | 399 | 386 | 357 | 313 | 264 | 238 |
| | $b_c$ | 334 | 371 | 407 | 439 | 460 | 468 | 465 | 451 | 425 | 387 | 348 | 325 |
| | $b_o$ | 170 | 193 | 215 | 235 | 246 | 250 | 249 | 242 | 226 | 203 | 178 | 164 |
| 30° | $A_c$ | 191 | 245 | 303 | 363 | 400 | 417 | 411 | 384 | 333 | 270 | 210 | 179 |
| | $b_c$ | 281 | 333 | 385 | 437 | 471 | 489 | 483 | 456 | 412 | 356 | 299 | 269 |
| | $b_o$ | 137 | 168 | 200 | 232 | 251 | 261 | 258 | 243 | 216 | 182 | 148 | 130 |
| 40° | $A_c$ | 131 | 190 | 260 | 339 | 396 | 422 | 413 | 369 | 298 | 220 | 151 | 118 |
| | $b_c$ | 218 | 283 | 353 | 427 | 480 | 506 | 497 | 455 | 390 | 314 | 241 | 204 |
| | $b_o$ | 99 | 137 | 178 | 223 | 253 | 268 | 263 | 239 | 200 | 155 | 112 | 91 |

**The** time fraction of cloud cover **can be directly measured or it can be inferred by comparing the irradiance measured with the theoretical irradiance. If it is assumed that the irradiance of PAR under an overcast sky amounts to 20% of that under a clear sky, the measured incoming PAR (taken as 50% of the total radiation measured) can be conceived as divided as follows.**

$$f0 * 0.2 * A_c + (1 - f0) * A_c = 0.5 * R_g$$

**where**

f0 is time fraction of cloud cover (d $d^{-1}$)
$A_c$ is theoretical photosynthetically active radiation on a clear day (cal $cm^{-2}$ $d^{-1}$)
See Table 4.5.
$R_g$ is measured total incoming radiation (cal $cm^{-2}$ $d^{-1}$)

Isolating the cloud fraction (f0) in the above relation yields

$$f0 = (A_c - 0.5 * R_g) / 0.8 * A_c \qquad (4.2)$$

The gross rate of assimilate production by a hypothetical reference crop (with a permanently closed canopy and growing in the optimum temperature range) is

$$b_{gm} = f0 * b_o + (1 - f0) * b_c \qquad (4.3)$$

where
$b_{gm}$is gross assimilation rate of reference crop (kg $ha^{-1}$ $d^{-1}$)
(Values of $b_o$ and $b_c$ are suggested in Table 4.5.)

Real field crops differ from the hypothetical reference crop. Their maximum assimilation rate ($P_{max}$) is not a steady 20 kg $ha^{-1}$ $h^{-1}$, as in Table 4.5, but is different for different cropadaptability groups and is also temperaturedependent. See Table 4.6.

Table 4.6. Maximum assimilation rate ($P_{max}$, in kg $ha^{-1}$ $h^{-1}$) as a function of the crop adaptability group and the daytime temperature ($T_{day}$). Source: Kassam et al., 1982.

| Cropadaptability group | Maximum assimilation rate | | | | | |
|---|---|---|---|---|---|---|
| | Daytime temperature (°C) | | | | | |
| | 10 | 15 | 20 | 25 | 30 | |
| I | | 15 | 20 | 20 | 15 | 5 |
| II | | 0 | 15 | 32.5 | 35 | 35 |
| III | | 0 | 5 | 45 | 65 | 65 |
| IV | | 5 | 45 | 65 | 65 | 65 |

-------------------------

This difference must be taken into account in calculations of the gross assimilation rate of real field crops ($b_{gma}$). The relation used by the AEZ team to describe $b_{gma}$ is a modification of Equation 4.3.

$$b_{gma} = (f0 * b_o) * (1 + 0.2 * y) + (1 - f0) * b_c * (1 + 0.5 * y) \qquad (4.4)$$

with

$$y = (P_{max} - 20) / 20 \qquad (4.4.1)$$

where

$b_{gma}$ is gross assimilation rate of field crop with closed canopy at maximum growth and constant assimilation rate $P_{max}$ (kg $ha^{-1}$ $d^{-1}$)

$y$ is a factor for the difference between the momentary maximum assimilation rate of a field crop ($P_{max}$) and the fixed maximum assimilation rate of the reference crop (20 kg $ha^{-1}$ $h^{-1}$)

$P_{max}$ is maximum assimilation rate of field crop (kg $ha^{-1}$ $h^{-1}$). See Table 4.6.

Total respiration losses

The net rate of assimilate production by a field crop (with a closed canopy at the time of maximum growth) is found by reducing $b_{gma}$ by the rate at which assimilates are lost by maintenance respiration.

Losses by maintenance respiration differ among crops and are temperature-dependent. The AEZ team set $C_{30}$, the rate of maintenance respiration at 30 °C, to 0.0283 kg $kg^{-1}$ $d^{-1}$ for leguminous crops and at 0.0108 kg $kg^{-1}$ $d^{-1}$ for nonlegumes. They suggested a quadratic relation to describe the temperature dependence of the maintenance respiration rate:

$$C_t = C_{30} * (0.044 + (0.0019\ °C^{-1}) * T_{24h} + (0.001\ °C^{-1}) * T_{24h}^2) \qquad (4.5)$$

where

$C_t$ is mass fraction rate of gross assimilate production (as $CH_2O$) lost through maintenance respiration with respect to dry crop mass at temperature $T_{24h}$ (kg $kg^{-1}$ $d^{-1}$)

$C_{30}$ is rate of loss of gross assimilate production by maintenance respiration at 30 °C, set to 0.0283 kg $kg^{-1}$ $d^{-1}$ for leguminous crops and 0.0108 kg $kg^{-1}$ $d^{-1}$ for other crops

$T_{24h}$ is average temperature (24hour mean) over the growth cycle (°C).

The cumulative maintenance respiration over an entire growth cycle amounts to $C_t * Ng * B_n$. Recall that Equation 4.1 described $B_n$ as

$$B_n = 0.5 * b_{nm} * Ng \quad (4.1)$$

The average rate of maintenance respiration losses over the growth cycle can now be described as:

$$b_{mr} = C_t * 0.5 * b_{nm} * Ng \quad (4.6)$$

where
$b_{mr}$ is average loss rate of assimilates by maintenance respiration over the growth cycle (kg ha$^{-1}$ d$^{-1}$)
$C_t$ is mass fraction rate of gross assimilate production lost by maintenance respiration at temperature $T_{24h}$ (kg kg$^{-1}$ d$^{-1}$)
$b_{nm}$ is average rate of biomass production by field crop (kg ha$^{-1}$ d$^{-1}$)
$Ng$ is length of growing cycle (d).

Losses of assimilates by growth respiration are estimated at 0.28 kg kg$^{-1}$ for all crops and at any temperature: the production of structural plant matter amounts to 72% of the net production of assimilates. In other words, the conversion efficiency ($E_c$) is assumed to be 0.72.

Net biomass production

The average net rate of biomass production over the growth cycle can be calculated by correcting the gross rate of assimilate production for losses by maintenance respiration and growth respiration.

$$b_{nm} = (b_{gma} - b_{mr}) * \mathrm{Ec}$$
or
$$b_{nm} = \mathrm{Ec} * b_{gma} / (1 + \mathrm{Ec} * C_t * Ng / 2) \quad (4.7)$$

where
$b_{nm}$ is average net rate of biomass production by a field crop with closed

canopy at the time of maximum growth (kg $ha^{-1}$ $d^{-1}$)
Ecis conversion efficiency (= 0.72 kg $kg^{-1}$)
$b_{gma}$is gross rate of assimilate production by crop with maximum assimilation rate $P_{max}$ (kg $ha^{-1}$ $d^{-1}$)
$C_t$is rate of loss of gross assimilate production by maintenance respiration at temperature $T_{24h}$ (kg $kg^{-1}$ $d^{-1}$)
$Ng$is length of growth cycle (d).

Equation 4.7 differs slightly from the relation suggested in the original FAO publication (FAO, 1978), which corresponds to

$b_{nm} = 0.72 * b_{gma} / (1 + 0.25 * C_t * Ng)$

Equation 4.7 will be used in the rest of this text.

Combination of Equations 4.1 and 4.7 yields the following expression of the total net production of biomass:

$$B_n = 0.36 * b_{gma} * Ng / (1 + 0.36 * C_t * Ng) \qquad (4.8)$$

where
$B_n$is areic mass of dry matter produced in a growing cycle (kg $ha^{-1}$)

Note that Equation 4.8 holds for crops with a closed canopy at the time of maximum growth. A fully closed canopy corresponds to a 'leaf surface to ground surface ratio' of 5.0 or greater. The 'leaf surface to ground surface ratio' is known as the leaf area index (LAI) and will be discussed in some detail in Chapter 8. If the canopy of the field crop does not fully cover the ground surface at the time of maximum growth (e.g. because of a low sowing or planting density), the calculated net biomass production needs correction. Figure 4.4 presents a correction factor ($L_m$) to adjust calculated net biomass production for incomplete ground cover (i.e. LAI less than 5.0) at the time of maximum growth.

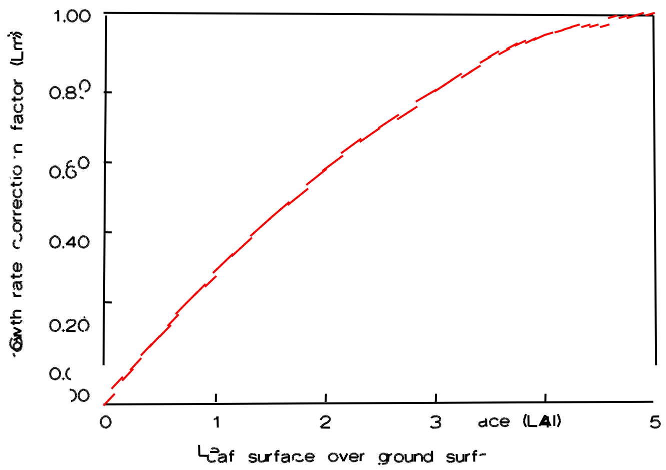


**Fig 4.4. Correction factor for incomplete ground cover ($L_m$) as a function of the leaf area index (LAI) at the time of maximum growth.**

**A generally applicable expression of the potential net biomass production of 'major crops' ($B_{na}$) would thus be**

$$B_{na} = 0.36 * b_{gma} * Ng * L_m / (1 + 0.36 * C_t * Ng) \qquad (4.9)$$

where
$B_{na}$ is potential net production of dry matter by field crop (kg $ha^{-1}$)
$b_{gma}$ is overall gross rate of assimilate production (kg $ha^{-1}$ $d^{-1}$)
$Ng$ is length of growing cycle (d)
$L_m$ is correction factor for incomplete ground cover
$C_t$ is rate of loss of $b_{gma}$ by maintenance respiration at actual temperature (kg $kg^{1}$ $d^{-1}$)
0.36 is half the conversion efficiency (= 0.5 * Ec).

Only part of the total net biomass production is economically interesting (harvested) produce. The constraintfree crop yield ($B_{ya}$) is calculated by simply multiplying the net biomass production by a tabulated harvest index (hi) (Table 4.7).

Table 4.7. Indicative harvest index (hi) of highyielding varieties of major crops under rainfed conditions.

| Crop adaptability group | Crop | Harvest index (hi) |
| --- | --- | --- |
| I | wheat (bread and durum wheat) | 0.40 |
| | white potato | 0.60 |
| | phaseolus bean (temperate and trop. highland. cvv.) | 0.30 |
| II | phaseolus bean (tropical cvv.) | 0.30 |
| | soya | 0.35 |
| | rice | 0.30 |
| | cotton | 0.07 |
| | sweet potato | 0.55 |
| | cassava | 0.55 |
| III | pearl millet | 0.25 |
| | sorghum (tropical cvv.) | 0.25 |
| | maize (tropical cvv.) | 0.35 |
| | sugarcane (sugar at 10-12% of fresh cane) | 0.25 |
| IV | sorghum (temperate and trop. highland cvv.) | 0.25 |

maize (temperate and trop. highland cvv.) 0.35
------------------------------------------------------------------------------------------------------

The constraintfree crop yield amounts to

$$B_{ya} = B_{na} * \text{hi} \tag{4.10}$$

where
$B_{ya}$ is constraintfree yield (kg $ha^{-1}$)
hi is harvest index (0 - 1).

*Agroclimatic constraints and anticipated crop yield*

The net biomass production and constraintfree crop yield indicate the potential performance of crops because they are determined solely by the average temperature and radiation regimes of the site during cropping. No consideration was given to agroclimatic constraints imposed by rainfall variability, climaterelated pests and diseases, and impeded workability or harvesting. Such constraints need to be considered if one wishes to establish anticipated crop yields for the various LGP zones.

Groups of agroclimatic constraints are expressed in terms of reduction ratings on an ordinal scale to reflect the severity of constraints in each LGP zone for each level of input. Four groups of constraints are recognized.
(a) constraints result from moisture stress during the growing period
(b) constraints concern yield losses due to pests, diseases and weeds
(c) constraints concern factors affecting yield formation and quality
(d) constraints arise from difficult workability and handling of produce.

The severity of a particular group of constraints is rated as follows.
rating 0: slight constraint, if any, causing no significant yield losses
rating 1: moderate constraint, resulting in yield losses of 25%
rating 2: severe constraint, resulting in yield losses of 50%.

The anticipated crop yield is obtained with a relative loss inventory to a reference yield level. The calculated constraintfree crop yield can serve as a reference but represents the highinput situation only; the yield

**reference for lowinput farming was set to an arbitrary 25% of the calculated constraintfree yield.**

Note that **the reductions from reference yield to anticipated yield are made** consecutively **according to the presence (or absence) of constraints and the severity of their occurrence for each crop, in each LGP zone and at each level of input.**

**Table 4.8 is an excerpt from the comprehensive inventory of likely agro-climatic constraints to maize in the major climatic division of tropical and subtropical (summer rainfall) areas, differentiated by LGP zone and level of input. (The complete table for rating agroclimatic constraints is given in Appendix A4.)**

**Table 4.8. Severity of agroclimatic constraints to maize in tropical and subtropical areas with summer rainfall. Source: FAO, 1978.**

| LGP (d) | Ratings lowinput (abcd) | Ratings highinput (abcd) | |
|---|---|---|---|
| 75-89 | 2120 | 2020 | Rainfall variability |
| 90-119 | 2110 | 2010 | Silk drying |
| 120-149 | 1100 | 1000 | |
| 150-179 | 0000 | 0000 | |
| 180-209 | 0000 | 0000 | |
| 210-239 | 0100 | 0001 | |
| 240-269 | 0101 | 0002 | |
| 270-299 | 0101 | 0102 | Borers |
| 300-330 | 0101 | 0102 | Leafspot, leafblight |
| 330-364 | 0112 | 0112 | Streak virus, wet produce |
| 365 | 0222 | 0222 | Workability |

4.4 Classification of land suitability

*Agroclimatic suitability*

**The ratio of the anticipated crop yield and the reference crop yield is an expression of the impact of agroclimatic constraints on cropping (at high or low input). Four** Agro-climatic suitability classes **are distinguished.**

VS very suitable **the anticipated yield amounts to 80% or more of the reference yield at the specified input**

S suitable **the anticipated yield is between 40 and 80% of the reference yield**

MS marginally suitable **the anticipated yield is between 20 and 40% of the reference yield at the specified input**

NS not suitable **the anticipated yield amounts to 20% or less of the reference yield at the specified input.**

**Figure 4.5 presents the generalized agroclimatic suitability map of Africa for rainfed maize (FAO, 1978).**

Fig. 4.5. Generalized agroclimatic suitability map of Africa for rainfed maize. Source: FAO (1978).

### *Land suitability classification*

The agroclimatic suitability classification is extended to a (preliminary) land suitability classification by combining it with information on individual soil units in each LGP zone (cropspecific and inputspecific as in Table 4.2 and Appendix A2). The following rules apply.

-The land suitability class is the same as the agroclimatic suitability class if the (tabulated) soilunit rating is S1.

-The land suitability class is one class less than the agroclimatic suitability class if the (tabulated) soilunit rating is S2.
-Soilunit ratings N1 and N2 imply that the land suitability class is NS.

Once the modifications for soilunit rating have been made, the land suitability assessment is further adjusted to account for limitations imposed by the slope of the land, the texture or the phase designation of the mapping unit according to the rules discussed in Section 4.1 (also Appendix A3).

Note that phase, slope and texture rules are applied only after the agro-climatic suitability classes have been converted to tentative land suitability classes. Although phase, slope and texture rules are used to modify soilunit ratings for individual soil mapping units, unmodified soilunit ratings are used to establish the final land suitability class.

There are two exceptions to this procedure of land suitability assessment. These exceptions were necessary to deal with the particular circumstances of
-the suitability of Fluvisols (for all crops)
-the suitability for rice (all soils).
"Cultivation of Fluvisols is generally governed by the depth, intensity and duration of flooding which occurs in the low lying areas of these soils. In turn these flooding attributes are generally controlled, not by the quantity of 'on site' precipitation but by external factors such as river flood regime and catchment/site ratio. Additionally, with the exception of rice, cultivation of these soils is normally confined to post flood periods, the crops being grown on moisture remaining in the soil after the rainy season." (FAO, 1978).
Special rules for assessing the land suitability for rice production were deemed necessary because
-rice yields in climatically suited areas are, to a large degree, dependent on complete water control. This is considered impossible under purely rainfed conditions and therefore no 'very suitable' (VS) land should be recognized for this crop from the climatic viewpoint.
-lengths of growing periods in excess of 180 days approach rainfall regimes of 1000 mm/year or more. These, in turn, may be assumed to provide three consecutive months with more than 200 mm precipitation each, which is the minimum acceptable distribution for cultivation of paddy rice on bunded fields.
-difficulties of land preparation may be expected to preclude rice cultivation in all regions with yearround humid growing periods, i.e.

where LGP is 365 days.

Note that **the special rules suggested for land-use systems with Fluvisols or rice are of an *adhoc* nature. The rationale of these rules will not be discussed in this text; those interested may consult World Soil Resources Report 48 (FAO, 1978, p.105106) for a detailed description.**

A broad inventory of land suitability **is obtained if all areas with the same land suitability class in each LGP zone are summed. Table 4.9, as an example, lists the extents of 'warm tropical lowlands' in Africa variously suited to the production of rainfed maize.**

**Table 4.9. Land suitability of warm tropical lowlands in Africa for rainfed maize production; areas in $10^3$ ha. (FAO, 1978).**

| LGP (d) | Suitability at high input | | | | Suitability at low input | | | |
|---|---|---|---|---|---|---|---|---|
| | **VS** | **S** | **MS** | **NS** | **VS** | **S** | **MS** | **NS** |
| **365** | | | | | **147381** | | | **147381** |
| **330-364** | | | **8038** | **67434** | | **346** | **13791** | **61335** |
| **300-329** | | | **8083** | **65582** | | **715** | **26369** | **46581** |
| **270-299** | | **7527** | **26558** | **93755** | | **2307** | **38634** | **86899** |
| **240-269** | | **20578** | **36229** | **77241** | | **3672** | **41853** | **88523** |
| **210-239** | **9624** | **29122** | **19862** | **71901** | **1986** | **23165** | **27338** | **78020** |
| **180-209** | **30433** | **58624** | **11118** | **125921** | **7626** | **57122** | **29408** | **131940** |
| **150-179** | **42825** | **37146** | **6083** | **88964** | **11763** | **46691** | **18734** | **97830** |
| **120-149** | | **23726** | **28794** | **61934** | | **9577** | **20880** | **83997** |
| **90-119** | | | **2001** | **13535** | **56644** | **2001** | **2644** | **67535** |
| **75- 89** | | | **1200** | **57038** | | **1200** | | **57038** |
| **1- 74** | | | **7637** | | **361830** | **7637** | | **361830** |
| **0** | | | | | **183660** | | | **183660** |
| **Yield range (t/ha)** | 7.1-5.7 | 5.7-2.8 | 2.8-1.4 | <1.4 | 1.8-1.4 | 1.4-0.7 | 0.7-0.4 | <0.4 |

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4.5 Calculated example

**The AEZ procedure of land suitability assessment will be demonstrated for a land-use system with lowland maize at Ulongue, in the Angonia District of Mozambique. The basic data stem from Voortman & Spiers (1986) and from Kassam et al. (1982).**

Site **Ulongue, Mozambique**
**Coordinates: 14°44' S and 34°22' E**
**Altitude: 1270 m.**

Land unit **SMW mapping unit: Af22/3b (FAOUnesco, 1974)**
**soils: 70% of area is Ferric Acrisol**
**20% of area is Orthic Ferralsol**
**10% of area is Ferric Luvisol**
**texture: medium to heavy**
**slope: between 8 and 30%**
**phases: none**
**climate: Table 4.10.**

**Table 4.10. Monthly climatic data (20 years averages) of Ulongue, Angonia District, Mozambique.**

----------------------------------------------------------------------------------------------------------

Month

---------------------------------------------------------------------------------------------

| | J | F | M | A | M | J | J | A | S | O | N | D |
|---|---|---|---|---|---|---|---|---|---|---|---|---|

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $T_{24h}$ (°C) | 24.4 | 24.2 | 24.0 | 23.3 | 20.9 | 18.8 | 18.4 | 20.3 | 23.0 | 25.7 | 25.6 | 24.7 |
| $T_{day}$ (°C) | 24.9 | 24.7 | 24.7 | 24.4 | 22.3 | 20.6 | 20.1 | 21.8 | 24.4 | 27.0 | 26.4 | 25.2 |
| PREC (mm) | 235 | 184 | 130 | 39 | 15 | 6 | 5 | 5 | 10 | 20 | 71 | 216 |
| ET0 (mm) | 116 | 106 | 111 | 100 | 93 | 86 | 88 | 119 | 145 | 168 | 143 | 122 |
| $R_g$ *) | 425 | 455 | 421 | 398 | 403 | 361 | 372 | 440 | 512 | 510 | 504 | 418 |

----------------------------------------------------------------------------------------------------

*) data in cal $cm^{-2}$ $d^{-1}$ (Voortman & Spiers, 1986); 1 cal $cm^{-2}$ $min^{-1}$ = 697.8 W $m^{-2}$.

Land-use **Crop: maize (cropadaptability group III)**

**harvest index:** hi = 0.35 (Table 4.7)
**growting cycle:** $Ng$ = 120 d
**maximum LAI:** 5.0 ($L_m$ = 1.0)
**germination:** on first day of possible growing period
**level of inputs:** high

The analytical pathway follows the seven steps discussed in this chapter. The functional relations used to calculate net biomass production and constraintfree yield are those derived in this text; the production estimates obtained are therefore slightly different than the ones published by Kassam et al. (1982).

**Step 1. Soilunit rating**

The tabulated soilunit ratings for Ferric Acrisols, Orthic Ferralsols and Ferric Luvisols under maize are as follows (Table 4.2; Appendix A2).

| Soil unit | Input: low | Input: high |
|---|---|---|
| Ferric Acrisol | S2N2 | S2 |
| Orthic Ferralsol | S2 | S2 |
| Ferric Luvisol | S2 | S1S2 |

**The phase, slope and texture rules (Appendix A3) might be applied to the above soilunit ratings to establish a** soil **suitability rating for individual mapping unit components. This is, however, irrelevant to the present calculation.**

<u>**Step 2. Major climatic division**</u>

**The temperature data for Ulongue show that the mean daytime temperature is above 20 °C throughout the year. This places Ulongue in the major climatic division of the warm tropics, suitable for the production of maize cultivars in cropadaptability group III.**

<u>**Step 3. Length of growing period**</u>

**To determine the beginning and end of the possible growing period, one must divide the monthly values of PREC, ET0 and $T_{day}$ in the basic data set by the number of days in the month, and assign the (approximate) daily values obtained to the 15th day of the month. Plotting the monthly PREC and ET0 over the year, as in Figure 4.6, quickly shows whether a growing period occurs and, if so, when.**

**-After a dry winter, PREC first exceeds 0.5 * ET0 on 15 November. The** start of the possible growing period is 15 November

**-The** end of the rainy period, with PREC > 0.5 * ET0, is 11 April

**-A** humid period, with PREC > ET0, extends from 28 November until 22 March, **with a cumulative surplus of PREC of 288 mm. Accordingly, the quantity of soil moisture available to the crop on 11 April is set to 100 mm.**

**-The cumulative deficit of PREC after 11 April exceeds 100 mm on 19 May;** the end of the possible growing period is 19 May.

**As the daily temperature is well over 6.5 °C throughout the growing period, correction for unfavourable temperatures is not needed. The length of the possible growing period (LGP) amounts to 184 days.**

Fig. 4.6. Distribution of precipitation (PREC) and potential evapotranspiration (ET0) over the year and the beginning and end of the possible growing period.

Step 4. Net biomass production and constraintfree yield

The basic data set stipulates that the growth cycle of the maize variety sown in Ulongue is 120 days if the crop cycle starts on the first day of the possible growing period (i.e. on 15 November). The average temperatures and irradiances over the growth cycle can be approximated with the data listed for 15 November to 15 March in Table 4.10.

$T_{24h}$ = (25.5 / 2 + 24.7 + 24.4 + 24.2 + 24.0 / 2) / 4 = 24.5 °C
$T_{day}$ = (26.4 / 2 + 25.2 + 24.9 + 24.7 + 24.7 / 2) / 4 = 25.1 °C
$R_g$ = (504 / 2 + 418 + 425 + 455 + 421 / 2) / 4 = 440 cal $cm^{-2}$ $d^{-1}$

The average irradiance of photosynthetically active radiation ($A_c$) and the daily gross assimilation rates ($b_c$ and $b_o$) over the period from 15 November till 15 March at Ulongue (latitude 14°44' S) are estimated by interpolating the appropriate values in Table 4.5:

$A_c$ = (385 / 2 + 386 + 386 + 381 + 364 / 2) / 4 = 382 cal $cm^{-2}$ $d^{-1}$
$b_c$ = (449 / 2 + 452 + 451 + 444 + 428 / 2) / 4 = 448 kg $ha^{-1}$ $d^{-1}$
$b_o$ = (240 / 2 + 242 + 242 + 238 + 228 / 2) / 4 = 239 kg $ha^{-1}$ $d^{-1}$

**The following series of calculations can now be made.**

-Maximum assimilation rate at 25.1 °C: $P_{max}$ = **65 kg ha$^{-1}$ h$^{-1}$ (Table 4.6)**
-Correction factor for $P_{max}$ <> 20 kg ha$^{-1}$ h$^{-1}$: $y$ = **(65 - 20) / 20** = **2.25 (Equation 4.4.1)**
- Time fraction of cloud cover: **f0** = **(382 - 0.5 * 440) / 0.8 * 382** = **0.53 (Equation 4.2)**
-Gross assimilation rate:
$b_{gma}$ = **0.53 * 239 * (1** + **0.2 * 2.25)** + **(1 - 0.53) * 448 * (1** + **0.5 * 2.25)** =
**631 kg ha$^{-1}$ d$^{-1}$ (Equation 4.4)**
-Relative maintenance respiration losses at $T_{24h}$:
$C_t$ = **0.0108 * (0.044** + **0.0019 * 24.5** + **0.001 * 24.5 * 24.5)** =
**0.00746 kg kg$^{-1}$ d$^{-1}$ (Equation 4.5)**
- Accumulated net biomass production:
$B_{na}$ = **0.36 * 631 * 120 * 1.0 / (1** + **0.36 * 0.00746 * 120)** =
**20 615 kg ha$^{-1}$ (Equation 4.9)**
- Constraintfree yield:
$B_{ya}$ = **20 615 * 0.35** = **7 215 kg ha$^{-1}$. (Equation 4.10).**

<u>Step 5. Anticipated yield</u>

**The anticipated yield is obtained by making deductions for likely agroclimatic constraints. Table 4.8 and Appendix A4 indicate no constraint for maize in the LGP zone of 180209 days. Consequently, the anticipated yield is assumed equal to the constraintfree yield.**

<u>Step 6. Agroclimatic suitability</u>

**The agroclimatic suitability criteria discussed in Section 4.4 stipulate that the** agroclimatic suitability class is 'very suitable' (VS) **because the anticipated yield is greater than 80% of the constraintfree yield (the reference yield for highinput farming).**

<u>Step 7. Land suitability class</u>

**The land suitability class is established by adjusting the agroclimatic suitability class for possibly limiting properties of soil and terrain.**

**The effect of all internal soil properties is expressed in the rating of the** soil **suitability of individual mapping units (Step 1). Recall that the ratings for mapping unit Af22/3b and highinput farming are:**

-S2 (marginally suitable) for the Ferric Acrisols, the Orthic Ferralsols and half the Ferric Luvisols, together covering 95% of the mapping unit
-S1 ((very) suitable) for the remaining half of the Ferric Luvisols (5% of the mapping unit).

The rules discussed in Section 4.4 stipulate that the land suitability of mapping unit Af22/3b is tentatively set to 'S' (suitable) for 95% of the mapping unit, and 'VS'(very suitable) for the remaining 5%.

The tentative land suitability assessment must now be adjusted for any limitations marked on the soil map as phases and it must be adjusted for unfavourable slope and soil texture.
-There are no phase designations for the mapping unit Af22/3b near Ulongue
-The slope of Af22/3b land is between 8 and 30%. According to the slope rules (Section 4.1 and Appendix A3), a third of the ratings remain unchanged and the remaining twothirds are downgraded to 'NS' (not suitable)
-This assessment is not changed any further because texture rules do not apply. (The soil texture is not 'coarse').

This brings the final land suitability classification of Af22/3b land near Ulongue for highinput maize production at

2% very suitable (VS)
32% suitable (S)
66% not suitable (NS)

## 4.6 Strengths and weaknesses of the AEZ approach

Recall that the AEZ approach was developed for the purpose of making a global inventory of land resources in a short period of time. That implies that interpretation procedures are simple and few data are needed.
The simplicity of the approach is both its strength and its weakness: the interpretation procedures are formalized and universally applicable, and produce estimates of potential and actual production and yield. But the accuracy of the yield estimates is low and definitely insufficient for regional planning (unless one is prepared to found a development policy on crude assumptions such as 'yield potential with low input is 25% of

**that with high input').**

**The simplifications made in the interpretation procedure can of course be criticized. Why is the** actual **(gauged) precipitation matched against the** potential **evapotranspiration? Why are soil properties not considered in calculations of LGP? Why is the amount of stored moisture in soil the same for all crops? And so on. The answer to these questions is simple. The AEZ project spent its modest means on its first objective: making a reconnaissance survey of the land resources of the world.**

**The accuracy of the generated land suitability indications would improve considerably if the AEZ methodology were (made) fully land-usesystemspecific and dynamic. However, that would lead to sharply increased needs for data and higher running costs, which would not be justified in the light of the project's original objective.**

**The AEZ study is a milestone in the history of land evaluation, in spite of its limitations. It introduced a promising new approach to land suitability assessment and sparked the development of quantified methods of land-use systems analysis.**

# CHAPTER 5

# DYNAMIC ANALYSIS OF LANDUSE SYSTEMS: AN INTRODUCTION

# 5. DYNAMIC ANALYSIS OF LANDUSE SYSTEMS: AN INTRODUCTION

**The procedure for agroecological zoning was custom-built to support FAO's global survey of land resources. Two limitations of the AEZ procedure must be removed if one seeks to develop the approach into a more generally applicable analytical tool:**
**-the analysis must be made** land-use system specific
**-the analysis must be made** dynamic.
**It is the purpose of this chapter to demonstrate the principles of dynamic analysis of land-use systems. Emphasis will be on 'how it is done' rather than on the measure of analytical complexity that can be handled. The problem to be tackled is simple:**
'***Does the land quality 'water availability during the growing season' permit to successfully grow a known annual crop at a known site with traditional rainfed cultivation?***
**It will be assumed that the selected site belongs to a land unit with deep homogeneous and adequately draining soils in flat and level terrain (no lateral flow of water and no waterlogging), and it will be assumed that the rainfall pattern over the year is unimodal. The land utilization type concerns a crop that is already grown in the area (no problems with temperature or photoperiodicity requirements) by farmers who have adequate resources (labour, physical means). It is furthermore assumed that basic data are available as needed.**

**Recall that the study of agro-ecological zones made the following assumptions. The possible growing season begins when the precipitation rate (PREC) exceeds half the potential evapotranspiration rate (0.5 * ET0) after a dry period. If waterlogging or flooding are ruled out as possible constraints to crop production, crop growth is possible as long as the precipitation rate remains greater than half the potential evapotranspiration rate. When this condition ceases, crops need not immediately perish if they can draw water from the soil (with a maximum of 100 mm for all soils and crops). The possible growing season ends when the accumulated precipitation deficit exceeds the amount of stored soil moisture.**

**The AEZ concept of a 'possible growing season' could perhaps be adopted when dealing with the problem tackled in this chapter but not all of the simplifications made should be followed. Availability of moisture varies over time as a function of the net influx of water into the**

system, the compounded water losses from the system, and the characteristics of the rooted surface layer in which water is stored. To be absolutely sure that planting or germination occurs under conditions of precipitation surplus (no 'false start'), the start of the crop season will be set to the moment when PREC first exceeds full ET0 (after a dry period) rather than 0.5 * ET0. From that moment on, the field has an establishing crop cover and consumptive needs for water amount to the maximum evapotranspiration rate (ETm) rather than the potential rate (ET0) as used by the AEZ team.

An outline of plant production, and of the role of water in this process, will be given in the following. Functional relations or 'transfer functions', which relate dependent variables to measured or estimated system characteristics, will be identified as we go along.

## 5.1 Consumptive use of water by plants

Crop production is possible thanks to the unique capability of green plants to reduce atmospheric $CO_2$ to carbohydrates. Plants take in $CO_2$ through minute openings in their leaves, the stomata. Each stoma gives access to a substomatal cavity with moist walls. Intake of $CO_2$ is a diffusion process, driven by a mass fraction gradient of $CO_2$ between the atmosphere (with a constant mass fraction of $CO_2$ of some $350 * 10^{-6}$) and the substomatal cavities with a lower concentration of $CO_2$. The concentration of water vapour in the air inside the cavities is close to saturation; the relative humidity of the atmosphere is normally less than that. Inward diffusion of $CO_2$ is (nearly) always accompanied by outward diffusion of water vapour. This process of water loss is called transpiration.
There is strong correlation between the rate of transpiration and the rate of assimilation of $CO_2$, which is amply available from a huge and turbulent atmosphere. Availability of water can be a problem, when uptake of water by the roots cannot fully replenish transpiration losses. This happens when the crop cannot compensate the combined osmotic, capillary and adsorptive forces with which water is retained by the soil. Plants actively curb their water consumption (i.e. the rate of transpiration) when exposed to drought; they close their stomata.

Doorenbos et al. (1979) express the moisture content of soil at which stomata start to close (the critical volume fraction of moisture in soil, SMCR), as a function of the total available soil moisture (TASM). A depletion fraction (*p*, between 0 and 1) indicates the relative depletion of TASM, which corresponds with a critically low volume fraction of soil moisture. The depletion fraction is a function of the physiological tolerance to drought of the crop and the maximum rate of water loss from the rooted soil to the atmosphere (ETm).
The maximum amount of 'available' moisture that can be stored in the rooting zone is often defined as the amount of water present at field capacity diminished by the amount which is still present at permanent wilting point.

TASM = (SMFC  SMPWP) * RD (5.1)

where
TASM is maximum possible amount of available moisture (cm)
SMFC is volume fraction of moisture in soil at field capacity ($cm^3$ $cm^{-3}$)
SMPWP is volume fraction of moisture at permanent wilting point ($cm^3$ $cm^{-3}$)
RD is equivalent depth of a homogeneously rooted surface layer (cm).

The amount of moisture actually available for uptake at any moment (AASM) is defined by:

AASM = (SMPSI  SMPWP) * RD (5.2)

where
AASM is actual (i.e. momentary) amount of available moisture (cm)
SMPSI is actual volume fraction of moisture in the root zone ($cm^3$ $cm^{-3}$).

Equation 5.2 holds as long as SMPSI is greater than SMPWP; if SMPSI is less than SMPWP, there is no 'available' moisture. The condition of adequate internal drainage implies that SMPSI cannot become greater than SMFC (and AASM cannot exceed TASM).

if AASM>TASM then AASM = TASM (5.2a)

and
if SMPSI<SMPWP then AASM = 0 (5.2b)

Water is consumed at the maximum rate as long as the actual volume fraction of moisture in the rooting zone (SMPSI) is greater than or equal to the critical volume fraction of moisture (SMCR), with

SMCR = (1  *p*) * (SMFC  SMPWP) + SMPWP (5.3)

where
SMCR is critical volume fraction of moisture in soil ($cm^3\ cm^{-3}$)
*p* is depletion fraction (Tables 5.2).

*Actual rate of evapotranspiration (ET)*

The compounded losses of water vapour from the rooted surface soil can now be described for three ranges of soil moisture:
-If SMPSI >= SMCR, water is consumed at the maximum rate (ETm)
-If SMPSI drops to a value =< SMPWP, transpiration ceases altogether. Further loss of water from the root zone is entirely by evaporation, arbitrarily set to 0.05 * ET0
-If SMPWP < SMPSI < SMCR, the rate of loss of water from the rooted surface soil decreases proportionally to the decrease in moisture content, i.e. from ETm (at SMPSI = SMCR) to 0.05 * ET0 (at SMPSI = SMPWP).

This schematized ETSMPSI relation is described by Equations 5.4 and shown in Figure 5.1.

**Fig. 5.1. Approximate relation of ET to SMPSI.**

if **SMPSI** >= **SMCR then ET** = **ETm** **(5.4a)**

else if **SMCR** > **SMPSI** > **SMPWP then** **(5.4b)**
**ET** = **(SMPSISMPWP) * (ETm0.05 * ET0) / (SMCRSMPWP)** + **0.05 * ET0**

else **ET** = **0.05 * ET0** **(5.4c)**

**where**
**SMPSI** is momentary volume fraction of moisture in soil ($cm^3$ $cm^{-3}$)
**SMCR** is critical volume fraction of moisture in soil ($cm^3$ $cm^{-3}$)
**SMPWP** is volume fraction of moisture at permanent wilting point ($cm^3$ $cm^{-3}$)
**ET** is actual rate of evapotranspiration (cm $d^{-1}$)
**ETm** is maximum rate of evapotranspiration (cm $d^{-1}$)
**ET0** is potential rate of evapotranspiration (cm $d^{-1}$).

*Maximum rate of evapotranspiration (ETm)*

**The maximum rate of evapotranspiration (ETm) depends on both the evaporative demand of the atmosphere, expressed by the** potential rate of evapotranspiration **(ET0), and the properties of the crop, expressed by a** crop coefficient **(kc).**

Doorenbos & Pruitt (1977) suggest

$$ETm = kc * ET0 \qquad (5.5)$$

where

kc is the crop coefficient

ET0 is potential rate of evapotranspiration (cm $d^{-1}$).

The value of the crop coefficient varies with development stage and morphology of the crop and, according to Doorenbos et al. (1979), to some extent also with wind speed and humidity. Actual kc increases from a low value at the time of crop emergence to a maximum when the crop reaches full development. It then declines as the crop matures. Table 5.1A presents generic kcranges for various crops and crop development stages. Table 5.1B presents indicative values for the lengths of individual development stages in a crop cycle. (In practice, development rates depend on varietal properties and temperature; exact figures can be found in agronomic literature.)

Table 5.1A. Indicative crop coefficients (kc) for some common crops. Source: Doorenbos et al. (1979).

| Crop | Development stages | | | | |
|---|---|---|---|---|---|
| | initial | vegetative | mid season | late season | harvest |
| green bean | 0.300.40 | 0.650.75 | 0.951.05 | 0.900.95 | 0.850.95 |
| cabbage | 0.40-0.50 | 0.70-0.80 | 0.95-1.10 | 0.90-1.00 | 0.80-0.95 |
| cotton | 0.400.50 | 0.700.80 | 1.051.25 | 0.800.90 | 0.650.70 |
| groundnut | 0.400.50 | 0.700.80 | 0.951.10 | 0.750.85 | 0.550.60 |
| maize | 0.300.50 | 0.700.85 | 1.051.20 | 0.800.95 | 0.550.60 |
| onion | 0.400.60 | 0.700.80 | 0.951.10 | 0.850.90 | 0.750.85 |
| pea | 0.400.50 | 0.700.85 | 1.051.20 | 0.650.75 | 0.250.30 |
| peppers | 0.400.50 | 0.700.80 | 0.951.10 | 0.901.00 | 0.800.90 |

| | | | | | |
|---|---|---|---|---|---|
| potato | 0.400.50 | 0.700.80 | 1.051.20 | 0.850.95 | 0.700.75 |
| rice | 1.101.15 | 0.101.15 | 1.101.30 | 0.951.05 | 0.951.05 |
| safflower | 0.300.40 | 0.700.80 | 1.051.20 | 0.650.70 | 0.200.25 |
| sorghum | 0.300.40 | 0.700.75 | 1.001.15 | 0.750.80 | 0.500.55 |
| soya | 0.300.40 | 0.700.80 | 1.001.15 | 0.700.80 | 0.400.50 |
| sugarbeet | 0.400.50 | 0.750.85 | 1.051.20 | 0.901.00 | 0.600.70 |
| sugarcane | 0.400.60 | 0.751.20 | 1.051.30 | 0.801.05 | 0.600.75 |
| sunflower | 0.300.40 | 0.700.80 | 1.051.20 | 0.700.80 | 0.350.45 |
| tobacco | 0.300.40 | 0.700.80 | 1.001.20 | 0.901.00 | 0.750.85 |
| tomato | 0.400.50 | 0.700.80 | 1.051.25 | 0.800.95 | 0.600.65 |
| watermelon | 0.40-0.50 | 0.70-0.80 | 0.95-1.05 | 0.80-0.90 | 0.65-0.75 |
| wheat | 0.300.40 | 0.700.80 | 1.051.20 | 0.650.75 | 0.200.25 |

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**Table 5.1B. Indicative values for the duration of the various development stages of some common crops (d). Source: Doorenbos et al. (1979).**

| Crop | Development stages | | | |
|---|---|---|---|---|
| | **initial** | **vegetative** | **midseason** | **late season** |
| **green bean** | **1520** | **1520** | **2030** | **520** |
| **cabbage** | **20-30** | **30-35** | **20-30** | **10-20** |
| **cotton** | **2030** | **4050** | **5060** | **4055** |
| **groundnut** | **1535** | **3045** | **3050** | **2030** |
| **maize** | **1530** | **3045** | **3045** | **1030** |
| **onion** | **1520** | **2535** | **2545** | **3545** |
| **pea** | **1025** | **2530** | **2530** | **2030** |
| **peppers** | **2535** | **30** | **3060** | **30** |
| **potato** | **2030** | **3040** | **3060** | **2035** |
| **rice** | **30** | **30** | **40** | **30** |
| **safflower** | **2035** | **3575** | **4565** | **2540** |

| | | | | |
|---|---|---|---|---|
| sorghum | 2025 | 3040 | 4045 | 30 |
| soya | 2025 | 2535 | 4565 | 2030 |
| sugarbeet | 2530 | 3560 | 5070 | 3050 |
| sugarcane | 3060 | 90120 | 180330 | 3060 |
| sunflower | 2025 | 3540 | 4050 | 2530 |
| tobacco | 10 | 2030 | 3035 | 3040 |
| tomato | 1015 | 2030 | 3040 | 3040 |
| watermelon | 10-20 | 15-20 | 35-50 | 10-15 |
| wheat | 1520 | 2530 | 5065 | 3040 |

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Several procedures for calculating ET0 have been published, e.g. the Penman method, the radiation method, and pan evaporation methods; most weather stations publish (approximate) daily or monthly ET0.

*Depletion fraction (p)*

The depletion fraction (*p*) of moisture can be established once ETm is known. Some crops, e.g. potato and sweet pepper, have great difficulty in coping with moisture stress and wilt quickly, whereas others such as cotton and sisal, close their stomata only at much higher moisture potential (i.e. at lower volume fraction of moisture in soil). Doorenbos et al. (1979) distinguish four droughttolerance classes, or 'crop groups', and suggest indicative values for *p*, for combinations of crop group and ETm. The crop groups are listed in Table 5.2A; values for *p* are presented in Table 5.2B for the entire range of combinations of crop group and ETm.

Table 5.2A. Groups of crops with similar drought tolerance.

| Crop group | Representative crops |
|---|---|
| 1 | onion, peppers, potato |
| 2 | cabbage, pea, tomato |
| 3 | phaseolus bean, groundnut, rice, sunflower, watermelon, wheat |
| 4 | cotton, maize, sorghum, soya, sugarbeet, sugarcane, tobacco. |

**Table 5.2B. Depletion fraction (*p*) as a function of crop group and maximum rate of evapotranspiration (ETm). Source: Doorenbos et al. (1979).**

| Crop group | ETm (cm $d^{-1}$) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | <0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | >=1.0 |
| 1 | 0.50 | 0.425 | 0.35 | 0.30 | 0.25 | 0.225 | 0.20 | 0.20 | 0.175 |
| 2 | 0.675 | 0.575 | 0.475 | 0.40 | 0.35 | 0.325 | 0.275 | 0.25 | 0.225 |
| 3 | 0.80 | 0.70 | 0.60 | 0.50 | 0.45 | 0.425 | 0.375 | 0.35 | 0.30 |
| 4 | 0.875 | 0.80 | 0.70 | 0.60 | 0.55 | 0.50 | 0.45 | 0.425 | 0.40 |

The land-use requirement 'unconstrained consumptive water use' (ETm) can now be calculated from Equation 5.5; the sufficiency of the land quality 'water availability' can be judged by matching the actual volume fraction of moisture (SMPSI) against SMCR, SMPWP and SMAD (Equations 5.4).

-if SMPSI remains greater than SMCR throughout the crop cycle, there is no water stress at all (Class S1 land)

-if SMPSI becomes less than SMPWP, the land is unsuitable for rainfed cultivation of the selected crop (Class N land)

- in the intermediate situation (ET less than ETm but the crop survives) land suitability for the defined use is marginal (Class S2 land).

## 5.2 Dynamic simulation

### *Statevariables*

Water enters the rooted surface soil as precipitation (PREC) and leaves as actual evapotranspiration (ET) and possibly as deep percolation. The rate of loss from the root zone depends partly on the volume fraction of moisture, which changes over time in response to precipitation and losses by evapotranspiration and deep percolation. There is one obvious way of breaking this vicious circle: AASM (or rather SMPSI and RD; Equation 5.2) must be fixed. However this is exactly the sort of action one would want to avoid. Recall that the AEZ approach was deemed 'not

LUSspecific' earlier in this chapter, inter alia because it fixed AASM at a maximum 100 mm for all soils and crops!

The solution to this problem is simple after all. Consider the basic data set: suppose that it contains, say, daily PREC and ET0. That implies that it is impossible to detect any variation in PREC or ET0 over periods of less than one day. In the parlance of the modeller, the temporal resolution of the available data is one day. The values of the variables PREC and ET0 are fixed for the duration of time intervals of, in this example, one day, after which new values for PREC and ET0 are called from the data base for calculations over the next time interval.
Apply the same reasoning to AASM: consider the values of SMPSI and RD invariant for the duration of one time interval, use the value of SMPSI to calculate ET with Equations 5.4, and then update the value of AASM by adding the water influx (PREC) and subtracting the (calculated) water losses in the interval. The updated value of AASM and the updated value of RD can be used to calculate an updated value of SMPSI which is then considered invariant over the next interval, and so on.

Note that the dependent variable AASM is calculated anew for each interval in the crop cycle and signifies the state of the system during an interval. AASM is a state variable. The statevariable technique allows description of availability and consumptive needs for water in a dynamic way.

*Choice of time interval (DT)*

The statevariable technique views a crop cycle as a concatenation of time intervals; intervals have a userdefined length. The choice of interval is a matter of importance. Good results can only be expected if the difference between the temporarily fixed state variable(s) and the true variable(s) is kept small. This implies that state variables must be frequently updated: the interval must be chosen short enough to handle the dynamics of the system. Certainly not longer, preferably not shorter. This somewhat cryptic statement becomes understandable if one compares the analysis of one time interval with the taking of a photograph. If one photographs a snail with a shutter time of $1/30^{th}$ of a second (DT), the result might be a sharp picture of the snail. If the same shutter time is used to photograph a passing motorcycle, the result will most likely not be a sharp image but an undifferentiated blur that cannot be used for analysis in any way. The speed at which the motorcycle travels makes it necessary to reduce the exposure time from 1/30th to, say, 1/500th of a second for a sufficiently undistorted picture. The choice of DT depends on the dynamics of the system (snail, motorcycle) under analysis.

Of course, one could photograph any object, including snails, with a short time of exposure. Likewise, one could simulate any process using short intervals but there are good reasons to select the longest interval that is still satisfactory. A choice of, say, DT = 1 d implies that 10 times as much data must be collected (and 10 times as many calculations made) as in a run with 10days intervals.

The choice of DT is dictated by the analytical accuracy pursued and the dynamics of the system under study but also by the resolution of the available data and the computation capacity at hand. Computer models are now being developed that use variable intervals selected by the model itself in response to variations in system dynamics.

A set interval of 10 d will be used in this chapter, where calculations will be done by hand. A shorter interval is often required for good results. The interval used in the rest of this book (and in most practical analyses of land-use systems) is 1 d.

## 5.3 Adjustment of state variables

### *Adjusting the equivalent rooting depth (RD)*

Most annual food and fibre crops have an initial rooting depth of 4 to 10 cm upon emergence (depending on seed size and depth of planting or sowing); the roots are assumed to grow at fixed rates to reach their maximum depth (RDm) early in the midseason development stage (EMS). Normally, the roots are not evenly distributed over the rooted surface soil. So, the rooting depth used in the calculations (RD) is not the true rooting depth but represents an equivalent depth of rooting, over which roots are (thought to be) uniformly distributed.

Depth of rooting increases during a crop cycle from the initial value (RDint) to a maximum value, reached at EMS and arbitrarily set to 0.7 * RDm. The value of the factor (=0.7) was chosen on the supposition that plotting root mass against soil depth produces a pattern with an amplitude RDm and an equivalent depth of 0.7 times the amplitude. Another value may be substituted for 0.7 if there is evidence of a different distribution pattern of roots.

Figure 5.2 shows in a schematized way how RD increases in the course of the growing season. The horizontal axis in Figure 5.2 is a time axis; it runs from emergence or planting time to GD, the moment at which a full cycle is completed. This horizontal axis is divided into time intervals, each labeled with a sequential number, *L*.

An example: if EMS is reached after 5 intervals have elapsed (since germination), and the length of the intervals (DT) is 10 d, then the midseason stage of crop development starts after *L* * DT = 50 d.

**Fig. 5.2. Equivalent rooting depth (RD) over the growing season.**

**The RD pattern of Figure 5.2 is mathematically described as follows.**

if $L$ < **EMS then RD** = **RDint** + **(0.7 * RDm RDint) *** $L$ / **EMS** **(5.6a)**

else **RD** = **0.7 * RDm** **(5.6b)**

**where**
$L$**is number of intervals elapsed since emergence**
**EMSis number of intervals between emergence and beginning of midseason stage of crop development**
**RDis equivalent rooting depth (cm)**
**RDmis maximum rooting depth (cm)**
**RDintis rooting depth at planting or emergence (cm).**

**Table 5.3 suggests (ranges for) initial rooting depth (RDint) and maximum rooting depth (RDm). These are substitute values which might be used if observed values are not available. Approximate EMS and total duration of growth (GD) can be inferred from Table 5.1B (divide daysums by DT).**

**Table 5.3. Indicative values for the initial rooting depth (RDint, cm) and the maximum rooting depth (RDm, cm) of common crops. Sources: Doorenbos et al. (1979); Landon (1991); van Keulen & Wolf (1986).**

| Crop | Rooting depth (cm) initial | Rooting depth (cm) maximum | Crop | Rooting depth (cm) initial | Rooting depth (cm) maximum |
|---|---|---|---|---|---|
| **bean** | **7-10** | **100150** | **safflower** | **5-10** | **100200** |
| **cabbage** | **10** | **4060** | **sorghum** | **5-10** | **100200** |
| **cotton** | **5-10** | **100170** | **soya** | **7-10** | **60130** |
| **groundnut** | **7-10** | **50100** | **sugarbeet** | **7-10** | **70120** |
| **maize** | **10** | **100170** | **sugarcane** | **15-25** | **150250** |

| | | | | | |
|---|---|---|---|---|---|
| onion | 4-10 | 3050 | sunflower | 5-10 | 80150 |
| pea | 7-10 | 60100 | tobacco | 3-8 | 50100 |
| peppers | 7-10 | 90 | tomato | 5-10 | 70150 |
| potato | 10-15 | 4060 | watermelon | 7-10 | 100150 |
| rice | 10-15 | 80100 | wheat | 7-10 | 125 |

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*Adjusting the momentary soil moisture content (SMPSI)*

The amount of available moisture in the rooting zone at the time of germination can be established using Equation 5.2 if the value of the initial soil moisture content (SMPSIint) is substituted for SMPSI and RDint for RD.

Water may enter or be lost from the rooting zone in any time interval in the crop cycle and the rooting depth (RD) increases as long as EMS is not reached. Hence, the value of AASM is likely to change in the course of an interval and needs to be recalculated after each set of interval calculations:

(new)AASM = (SMPSI  SMPWP) * RD + PREC * DT  ET * DT      (5.7)

where
SMPSI is soil moisture content during the interval (cm$^3$ cm$^{-3}$)
SMPWP is volume fraction of soil moisture at permanent wilting point (cm$^3$ cm$^{-3}$)
RD is equivalent rooting depth at the end of the interval (cm)
PREC is rate of precipitation during the (past) interval (cm d$^{-1}$)
ET is calculated actual rate of evapotranspiration (cm d$^{-1}$)
DT is length of interval (d).

Recall from the discussion of Equation 5.2 that AASM cannot be negative nor can it exceed TASM (Equation 5.1; substitute the adjusted rooting depth for RD).

if AASM > TASM then AASM = TASM      (5.2a)
and
if SMPSI < SMPWP then AASM = 0      (5.2b)

Note that the stipulation of 'adequate internal soil drainage' in the definition of the land-use system implies that water percolates out of the rooted surface layer whenever Equation 5.2a applies.
One can now establish the value of SMPSI at the end of the time interval, and valid for the entire next interval, with

$$(new)SMPSI = AASM / RD + SMPWP \quad (5.8)$$

Equations 5.1 to 5.8 allow to match the requirement 'consumptive water needs' against the land quality 'water availability' by considering measurable system characteristics.

## 5.4 Pathway of calculation and data needs

Functional relations were identified in the previous sections in a sequence that is not necessarily the sequence in which they are used in the computations. Consider, for instance, the soil moisture depletion fraction (*p*, in Equation 5.3) which cannot be established unless ETm is known; ETm follows from Equation 5.5.
A proper sequence of calculation instructions and transfer functions is an 'algorithm'. The internal structure of an algorithm can be depicted in a 'flow chart'. In a notation that can be understood by a calculating device, the algorithm becomes a 'program'. It is beyond the scope of this text to discuss principles of computer programming but the construction of simple flow charts deserves some attention.

### *Flow charts*

A flow chart is essentially a diagram in which the calculation procedure is presented in discrete steps. The order in which these steps are taken is indicated by arrow signs; the steps themselves are represented by symbols. The shape of a symbol indicates the type of action that it represents. In this text, only four types of symbol will be used:

terminals mark the beginning and end of the calculations

operations indicate the use of functional relations decisions indicate which step to take if there are alternatives

I/O indicates input of basic information or output of calculation results.

Figure 5.3 presents the flow chart of a simple routine to determine the annual sum of all oneday intervals with a precipitation surplus.

Fig. 5.3. Flow diagram of a procedure to count the annual number of days with a precipitation surplus (*S*).

1. The procedure depicted in Figure 5.5 begins at terminal START.
2. The first operation initializes the analysis by stating that the calculations start with interval #1 ($L$ = 1) and with zero surplus intervals ($S$ = 0).
3. Next, PREC and ET0 for interval $L$ are input from the basic data set.
4. If PREC > ET0, the decision is taken to carry on with an operation in which the value of the 'surplus intervals counter' is adjusted (new$S$ = old$S$ + 1).
5. If the decision is taken to continue the analysis after this interval ($L$ < 365?; yes), the next operation is to adjust the 'intervals counter' ($L$ = $L$ + 1). Matching of PREC against ET0 can now be done for that interval.
6. This procedure goes on until $L$ = 365 when the value of $S$ is output.
7. The calculations are terminated as indicated by terminal END.

Each symbol in Figure 5.3 represents a straightforward instruction; a computer program results if these instructions are listed from terminal START to terminal END. In BASIC language:

```
1   REM Start
2   LET L=1: LET S=0
3   PRINT "Specify PREC and ET0values for interval nr "; L;: INPUT
PREC, ET0
4   IF PREC>ET0 THEN LET S=S+1
5   IF L<365 THEN LET L=L+1: GOTO 3
6   PRINT "The number of days with a precipitation surplus is "; S
7   END
```

*Analysis of land suitability*

Figure 5.4 presents the flow diagram of an algorithm to analyse the problem tackled in this chapter. The diagram comprises two matching procedures, enframed for easy recognition.
-Interval values of PREC and ET0 must be compared to determine the interval in the year (running number) in which the growing period begins.
-Generated values of SMPSI, SMCR and SMPWP are used to calculate the actual consumptive water use (ET) in each interval. ET is compared with the required water consumption (ETm).

The routine to identify the beginning of a possible growing season is based on repeated matching of PREC against ET0. The outcome of this routine can be one of three alternatives:

-if the maximum number of consecutive surplus intervals is counted ($S >= 365$ / DT? --> yes), the procedure is abandoned (OUTPUT: suitability
CLASS S1; WS = 0)
-if a deficit interval is found (PREC >= ET0? --> no), the surplus interval counter is reset ($S = S$ 1), a 'dryinterval counter' is set at $D = 1$ and the number of consecutive deficit intervals is counted. Should the value of $D$ become equal to or greater than 365/DT, the land is dry throughout the year (OUTPUT: suitability CLASS N; WS = 0)
-else the crop cycle starts with the first interval of the wet season, i.e. WS = ($S + D$) = NR. The 'growthcycle interval counter' ($L$) assumes the value $L = 1$.

Once the beginning of the growing period has been established, the analysis proceeds with matching SMPSI against SMCR. If SMPSI is greater than or equal to SMCR, an 'ET = ETm counter' is activated: $Y = Y + 1$. Subsequently, the equivalent rooting depth (RD), the actual amount of stored soil moisture (AASM) and the maximum moisture storage (TASM) are calculated.

Fig. 5.4. Flow diagram of an analysis which (1) identifies the beginning of a growing season, and (2) determines the land suitability class as conditioned by the availability of soil moisture.

Adjusting the value of the volume fraction of moisture in the rooted soil layer (SMPSI) concludes each set of calculations for an interval.
-if the adjusted SMPSI is less than or equal to SMPWP, the land is considered unsuitable for rainfed cultivation of the crop under analysis and the procedure is abandoned (OUTPUT: suitability CLASS N; WS = NR).
-if SMPSI remains greater than SMPWP, the routine checks whether the crop has completed its growing cycle. If not, the 'growingcycle interval counter'($L$) is adjusted ($L = L + 1$) and a new cycle of interval calculations started.
Once all intervals in the growing cycle of the crop are processed, the land

**is either classified as CLASS S1 land (ET = ETm in all intervals), or as CLASS S2 land.**

***Data needs***

Recall that **four categories of data are needed to describe a land-use system:**
-soil and terrain data
-weather or climate data
**These typify the land unit.**
-crop data
- management/technology data.
**These describe the land utilization type.**

**The data items in each category are listed hereafter.**

**<u>Soil and terrain data</u>:**
**SMFC volume fraction of moisture in soil at field capacity ($cm^3\ cm^{-3}$)**
**SMPWP volume fraction of moisture in soil at pF=4.2 ($cm^3\ cm^{-3}$).**

**<u>Weather/climate data</u>:**
**PREC rate of precipitation ($cm\ d^{-1}$; meteorological reports)**
**ET0 rate of potential evapotranspiration ($cm\ d^{-1}$; meteorological reports).**

**<u>Crop data</u>:**
**Crop group (see Table 5.2A)**
**EMS early midseason stage (time intervals; Table 5.1B)**
**GD duration of growing cycle (time intervals; Table 5.1B)**
**RDm maximum rooting depth (cm; Table 5.3)**
**kc crop coefficient for each interval in the crop cycle (Tables 5.1).**

**<u>Management/technology data</u>:**
**SMPSIint initial volume fraction of moisture in soil ($cm^3\ cm^{-3}$; consult Extension Service)**
**RDint initial rooting depth (cm; Table 5.3 and Extension Service)**
**Planting or sowing date (crop calendar; consult Extension Service).**

## 5.5 Calculated example

**Once the algorithm is made, analysis of a practical case becomes a matter of collecting basic data and conscientious following of the flow diagram from terminal START to terminal END. The calculations in this chapter will still be done with a handcalculator. Hence the chosen (long) time interval of DT = 10 d. A working sheet is used which specifies the various steps in an interval calculation (decisions, operations, I/O) in separate columns and in their proper sequence; calculations for different intervals are accommodated on different lines. Table 5.4 summarizes the analysis of a land-use system with rainfed maize grown on a loam soil with 'traditional' management. The basic data are recorded on the working sheet for easy reference (the weather data being entered in columns 2 and 3).**

Note that **Table 5.4 has the structure and clarity of an electronic spreadsheet; the calculation procedure could indeed conveniently be run with any of the commercially available computerized accounting packages. However the intention of this chapter was not to present a practical application but 'merely' to illustrate the philosophy of quantitative analysis of a land-use system, to introduce the state variable approach, and to explain the importance of a correct choice of time interval.**

***First routine: determining the start of the wet season (WS)***

**The diagram in Figure 5.4 shows that the first interval in the year is tentatively assumed to have a precipitation surplus ($S = S + 1$). When the first matching of PREC against ET0 results in a deficit for this first interval (Column 6: PREC>=ET0? > no), the postulate is withdrawn ($S = S\ 1 = 0$) and a deficit interval is counted instead (Column 7: $D = 1$). The next interval in the year (NR = 2) is tentatively assumed to be dry as well ($D = D + 1$), which appears to be correct (Column 9: PREC < ET0? --> yes), so that the procedure is repeated for the 3rd interval, and so on. Precipitation first exceeds full potential evapotranspiration in the 5th interval in the year (PREC < ET0? --> no). It is therefore concluded that germination or planting can take place in the 5th time interval of 10 days (Column 10: WS = 5).**

***Second routine: interval calculations and adjustment of state variables***

**Analysis continues with the first interval in the crop cycle (Column 11:**

*L* = 1). PREC, ET0 and kc for this interval are called from the basic data set (Columns 2, 3 and 12) after which ETm can be calculated from Equation 5.5. Column 13: ETm = kc * ET0 = 0.132 cm $d^{-1}$.
The depletion fraction (*p*) is now determined with Tables 5.2A and 5.2B (Column 14: *p* = 0.875).
The critical volume fraction of soil moisture (SMCR) is calculated with Equation 5.3: SMCR = (1 0.875) * (0.35 $cm^3$ $cm^{-3}$ 0.10 $cm^3$ $cm^{-3}$) + 0.10 $cm^3$ $cm^{-3}$ = 0.131 $cm^3$ $cm^3$. This value is entered in Column 15.

Table 5.4. Calculated example of water availability to maize on loam soil. The columns of this working sheet list all steps in a calculation sequence; each line accommodates one time interval.

**SMPSI** >= **SMCR (Column 16); the actual rate of evapotranspiration is equal to the maximum rate (Column 17: ET=0.132 cm $d^{-1}$).**
**The 'ET=ETm counter' is activated accordingly (Column 18: *Y*=1).**

**This concludes the assessment of water availability for the first interval in the crop cycle;** all state variables must now be adjusted **to the value that they hold in calculations for the second interval.**

**First, the running number of the interval under analysis is matched against (system constant) EMS: (Column 19: *L* < EMS? --> yes).**
**As long as *L* < EMS, Equation 5.6a describes how to adjust the value of the equivalent rooting depth RD (Column 20: RD = 7 cm + (0.7 * 130 cm 7 cm) * 1/6 = 21 cm).**
**Once RD is updated, AASM can be calculated from Equation 5.7. See Column 21: AASM = (0.26 $cm^3$ $cm^{-3}$ 0.10 $cm^3$ $cm^{-3}$) * 21 cm + 5.6 cm 1.32 cm = 7.64 cm.**
**The maximum amount of available soil moisture is calculated from Equation 5.1. See Column 22: TASM = (0.35 $cm^3$ $cm^{-3}$ 0.10 $cm^3$ $cm^{-3}$) * 21 cm = 5.25 cm.**
**The calculated actual and possible quantities of available moisture in the rooting zone are now compared (Column 23: AASM > TASM? --> yes).**
**Equation 5.2a indicates that the final AASM must assume the value of TASM (Column 24: AASMcorr = 5.25 cm).**

Note that **the difference (AASM - AASMcorr = 2.39 cm water) percolated from the root zone to deeper layers in this first interval.**

Finally, SMPSI is calculated from Equation 5.8.
Column 25: SMPSI = 5.25 cm / 21 cm + 0.1 $cm^3$ $cm^{-3}$ = 0.35 $cm^3$ $cm^{-3}$ (i.e. field capacity).

This concludes the adjustment of variable values. It must now be decided whether another cycle of interval calculations is to follow. If the adjusted value of SMPSI, i.e. SMPSI calculated for the end of the first interval, is less than SMPWP, it is assumed that the crop has wilted permanently; further interval calculations are then pointless. In the example, the crop survives the first interval (Column 26: SMPSI =< SMPWP? > no).

*Calculations needed for more intervals ?*

The end of the growing cycle has not yet been reached after only one interval (Column 27: $L$ < GD? --> yes). Hence, the sequence of interval calculations continues (loop to Column 11 where $L$ = 2).
The interval calculations proceed as described until the 6th interval in the growing cycle ($L$ = 6) when the decision $L$ < EMS? (Column 19) is 'no'. RD remains steady at 91 cm from that moment on (Equation 5.6b).
In the 11th interval in the growing cycle, SMPSI becomes less than SMCR (Column 16), so that the actual rate of evapotranspiration becomes less than ETm due to drought stress.
ET is calculated from Equation 5.4b. See Column 17: ET = (0.145 $cm^3$ $cm^{-3}$ 0.1 $cm^3$ $cm^{-3}$) * (0.33 cm $d^{-1}$ 0.05 * 0.44 cm $d^{-1}$) / (0.158 $cm^3$ $cm^{-3}$ 0.1 $cm^3$ $cm^{-3}$) + 0.05 * 0.44 cm $d^{-1}$ = 0.261 cm $d^{-1}$.
Counter $Y$ is not activated (Column 18: $Y$ = 10) because ET is less than ETm in this interval.

The growing cycle is completed after 12 intervals (Column 27: $L$ < GD ? --> no).

*Output of results*

In this example, the crop reached maturity even though not all intervals in the growing cycle were free from water stress. See Column 28: $Y$ = GD ? --> no. Therefore, the suitability of this particular land is rated 'CLASS S2' (marginally suitable) for rainfed maize which germinates in the $5^{th}$ interval in the year.

Note that even a simple problem like the one treated here requires many

**calculations. Although one scenario involving a single land-use system could still be analysed 'by hand', a computer becomes indispensible if more (or more complex) situations are to be analysed.**

## 5.6 Strengths and weaknesses of dynamic analysis of land-use systems

**Even though this chapter is only a first introduction to dynamic analysis of land-use systems, it demonstrates that dynamic analysis adds an extra dimension to assessment of land suitability: it takes the temporal variability of land-use requirements and land qualities into account. The use of well documented functional relations based on generally accepted physical, chemical and biological laws reduces reliance on (claimed) expertise.**

**An alleged weak point of the approach is its dependence on accurate and quantitative data on land and land-use. Admittedly, such data are scarce. However... .**
**Land-use system analysis needs basic data on land and land-use to generate information on the performance of actual or projected land-use systems under defined conditions. This generated information is not 'new'; it was always there, hidden in the basic data. If this basic information is poor, the results of the analysis cannot be better. But that holds for qualitative and quantitative methods alike. The frankness with which procedures for quantitative analysis demand good basic information is indeed one of their strong points.**

# CHAPTER 6

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# CALCULATING SUFFICIENCY: SINGLEFACTOR RATINGS

# 6. CALCULATING SUFFICIENCY: SINGLEFACTOR RATINGS

**Dynamic modelling seems to offer an alternative to partly intuitive rating of static (tabulated) single factors. The following problem will be studied to examine this supposition.**

***'Quantify the sufficiency of the land quality 'water availability' in a land-use system with a known annual crop that germinates at a known site and at a known time.'***

**To keep analytical complexity at a minimum, it will be assumed that the crop is grown on nonsaline, flat and level land with a deep water table, and on homogeneous soils with adequate internal drainage. The crop choice will be restricted to varieties that are already grown in the area and there are no management/technology restrictions.**

## 6.1 Land-use requirement: maximum transpiration

**Recall that unhindered transpiration is a precondition for maximum plant production. The 'relevant' land-use requirement is thus: 'let water availability be adequate for maximum transpiration at all times'.**
**Total consumptive water use by a cropped field is composed of** transpiration **from the crop canopy and** evaporation **from the soil surface:**

$$ETm = TRM + EM \qquad (6.1)$$

**where**
**ETm is maximum rate of evapotranspiration (cm $d^{-1}$)**
**TRM is maximum rate of transpiration (cm $d^{-1}$)**
**EM is maximum rate of evaporation (cm $d^{-1}$).**

**Recall that Doorenbos et al. (1979) approximate ETm with:**

$$ETm = kc * ET0 \qquad (5.5)$$

**where**
**kc is the crop coefficient**
**ET0 is potential rate of evapotranspiration (cm $d^{-1}$).**

**The relevant land-use requirement (TRM) can be quantified if**
- **the crop coefficient (kc) can be established**

**-the total consumptive water use (ETm) can be divided into its transpiration and evaporation components.**

***Crop development***

**Table 5.1A suggests that the maximum rate of evapotranspiration (ETm) of common annual food and fibre crops is about onethird of the potential rate (ET0) at the moment of germination, when transpiration is still negligible. ETm is greater than ET0 during the midseason development stage but falls again to, say, two-thirds of ET0 at maturity. Table 5.1B suggests lengths of crop development stages. Be aware that these cannot be accurate because the rate of crop development is determined by the physiological properties of the crop (variety)** and **the temperatures at the site.**
**Crops cannot develop below their** threshold temperature for development; **development accelerates as the temperature rises. The positive difference between the average daily temperature ($T_{24h}$) and the threshold temperature (T0) is the** effective daily temperature sum. **If all effective daily temperature sums in a growing cycle, i.e. from emergence until maturity, are summed, the result is a variety specific** heat requirement for full development **(Tsum, in °C d).**

**For example, if a variety 'A', with a tabulated threshold temperature of 10 °C and a tabulated Tsum of 1500 °C d, were grown in an environment where the average temperature remains at a steady 25 °C, the time required for full development (i.e. the length of the growing cycle) would amount to 1500 °C d / (25-10) °C = 100 d.**

**Table 6.1 presents indicative values for threshold temperature and heat requirement for some common crops.**

**Table 6.1. Indicative values for threshold temperature for development (T0, in °C) and heat requirement for full development (Tsum, in °C d). Source: Van Heemst, 1988.**

| Crop | T0 | Tsum | Crop | T0 | Tsum |
|---|---|---|---|---|---|

| | | | | | |
|---|---|---|---|---|---|
| barley | 2 | 2 700 | pigeon pea | 11 | 1 350 |
| cassava | 10 | 4 820 | rice (HYV) | 10 | 1 600 |
| chick pea | 7 | 1 280 | rice (trad.) | 11 | 2 080(?) |
| cotton | 10 | 1 450 | sesame | 10 | 1 380 |
| cowpea | 8 | 1 350 | sorghum | 10 | 1 600 |
| groundnut | 10 | 1 350 | soya | 5 | 1 750 |
| lentil | 0 | 2 350(?) | sugarcane | 10.5 | 6 325(?) |
| maize | 10 | 1 600 | sunflower | 5 | 1 700 |
| millet | 10 | 1 380 | sweet potato | 10 | 2 000 |
| mung bean | 10 | 1 200 | tobacco | 0 | 1 450 |
| potato | 0 | 2 000 | wheat | 0 | 2 110 |

The relative development stage (RDS) of a crop at any moment in the crop cycle can be calculated by simply dividing the cumulative effective daily temperature until that moment by the varietyspecific Tsumvalue.

For example, after 10 days of growth at 20 °C and another 10 days at 25 °C, the RDS of crop 'A' is: (10 d * 10 °C + 10 d * 15 °C) / 1500 °C d = 0.17.

The relative development stage increases in the course of a time interval of DT days.

$$DRDS = (T_{24h} - T0) * DT / Tsum \qquad (6.2)$$

where
DRDS is increase in relative development over the time interval
$T_{24h}$ is average daily temperature during the interval (°C)
T0 is threshold temperature for development (°C)
Tsum is heat requirement for full development (°C d)
DT is length of interval (d).

A crop is fully mature (and the growing cycle ends) when RDS = 1.0. The relative development stage at the end of a time interval is calculated from Equation 6.3.

$$(new)RDS = (old)RDS + DRDS \qquad (6.3)$$

*Calculating the crop coefficient*

Table 5.1A suggests that a hypothetical, short, 'reference' field crop, adequately supplied with water and not exposed to turbulent air, has a crop coefficient value ($kc_{ref}$) of 0.33 at germination when RDS = 0. The maximum $kc_{ref}$value of 1.0 is reached in the midseason period when the RDS is between 0.6 and 0.7. The reference crop would complete its development with $kc_{ref}$ = 0.6 to 0.67 at RDS=1.0. This $kc_{ref}$RDS pattern is described by

$$kc_{ref} = 0.33 + 0.73 * RDS + 1.93 * (RDS)^2 - 2.33 * (RDS)^3 \qquad (6.4)$$

where
$kc_{ref}$ is crop coefficient of a short green reference crop
RDS is relative development stage.

A real field crop differs from the reference crop because its canopy is less smooth and (can be) exposed to turbulent air. The effects of turbulence will be expressed by a turbulence coefficient (TC) which varies from TC = 1.0 (laminar flow) when RDS = 0 to a maximum value (TCM) reached when RDS = 0.67.

$$TC = 1 + (kc_{ref} - 0.33) * (TCM - 1) / 0.67 \qquad (6.5)$$

where
TC is momentary turbulence coefficient
$kc_{ref}$ is momentary referencecrop coefficient
TCM is (tabulated) maximum turbulence coefficient.

Note that the value of TCM is identical with the value of kc suggested in Table 5.1A for the midseason development stage of adequately watered crops.

The crop coefficient of a field crop (kc) is approximated by multiplying the reference crop coefficient by the turbulence coefficient.

$$kc = kc_{ref} * TC \qquad (6.6)$$

where
kc is momentary crop coefficient of a field crop.

*Transpiration and evaporation components of ETm*

**Transpiration is negligible at the time of germination, when there is (almost) no canopy and kc is close to 0.33. The transpiration rate is close to TCM * ET0 in the midseason stage, when kc has its highest value. Interpolation between these values results in:**

$$TRM = ET0 * TC * (kc_{ref} - 0.33) / 0.67 \qquad (6.7)$$

**where**
**TRM is maximum transpiration rate of a field crop (cm $d^{-1}$).**

**The evaporation component of ETm, i.e. the maximum rate of evaporation (EM) from a soil 'not short of water', amounts to:**

$$EM = ETm - TRM \qquad (6.8)$$

## 6.2 Land quality: moisture supply to the transpiring crop

**Daily uptake of water by a crop is far greater than needed for its production of plant matter. Consider a row crop which produces a total of, say, 15 000 kg $ha^{-1}$ during its crop cycle of 100 d. The plant matter contains 12 to 15 percent moisture at harvest time, equivalent to some 2 000 kg (water) $ha^{-1}$. The total** dry **matter production would thus amount to some 13 000 kg $ha^{-1}$.**
**With one mole of water needed to synthesize one mole of $CH_2O$, a mass of 13,000 kg dry matter incorporates (18/30) * 13 000 = 8 000 kg water. The total water mass which is structurally a part of the produced plant matter amounts, in this example, to some 2 000 + 8 000 = 10 000 kg $ha^{-1}$, taken up over a period of 100 days.**
**Transpiration from a closed crop canopy on a clear sunny day may proceed at a rate of, say, 0.4 cm $d^{-1}$, so that 40 000 kg (water) $ha^{-1}$ must be taken up from the rooted surface soil to replenish the transpiration losses incurred on that one sunny day!**
**In view of the disparity between water loss by transpiration and water built in plant matter, one might as well ignore the latter and consider the rate of water uptake from the rooting zone equal to the transpiration rate.**

**The rate at which plant roots** can **absorb water from the soil is determined by the difference in moisture potential between the root**

tissue and the rooting medium ($PSI_{root}$ PSI) and by the resistance to water flow ($R_{root}$).

$$MUR = (PSI_{root} \ \ PSI) / R_{root}$$

where
MUR is maximum rate of water uptake by roots (cm $d^{-1}$).

Water taken up flows to the leaves whence it is transpired. This flow is driven by the difference in potential between the transpiration sites ($PSI_{leaf}$) and the intake sites ($PSI_{root}$). The flow rate is further determined by the resistance to flow posed by the plant tissue ($R_{plant}$):

$$TR = (PSI_{leaf} \ \ PSI_{root}) / R_{plant}$$

where
TR is rate of transpiration (cm $d^{-1}$).

The rate of water uptake is (nearly) equal to the rate of transpiration; the above relations can be combined to an expression of the possible rate of water uptake.

$$MUR = (PSI_{leaf} \ \ PSI) / (R_{plant} + R_{root}) \qquad (6.9a)$$

$$\text{if } MUR < 0 \text{ then } MUR = 0 \qquad (6.9b)$$

where
MUR is maximum rate of water uptake by the root system (cm $d^{-1}$)
$PSI_{leaf}$ is 'critical leaf water head' (cm)
PSI is matric suction of rooted soil (cm)
$R_{plant}$ represents resistance to flow in the plant (d)
$R_{root}$ represents resistance to flow to the roots (d).

Note that the resistance terms, $R_{plant}$ and $R_{root}$ in Equation 6.9a, represent the specific resistance to flow (in d $cm^{-1}$) over the distance of flow (in cm); $R_{plant}$ and $R_{root}$ have the dimension 'd'.

Many authors express soil suction by a negative number. This convention will NOT be followed in this text: suction (the common situation in soils) will be expressed by a positive number, and pressure by a negative number.

Soil scientists and hydrologists often express the soil moisture potential as energy per unit weight of water, with the dimension of length (van Bakel, 1981). This practice WILL be followed in the rest of this text. (1 cm suction corresponds with 0.1 J $kg^{-1}$ or 1 hPa)

### *Critical leaf water head ($PSI_{leaf}$)*

Equation 6.9 makes clear that $PSI_{leaf}$ = PSI if MUR = 0, i.e. if transpiration is nil. In other words, $PSI_{leaf}$, the critical leaf water head, is equal to the matric suction at permanent wilting point. Indicative critical leaf water heads of common crops are presented in Table 6.2.

Table 6.2. Critical leaf water heads ($PSI_{leaf}$, in cm) of some common crops; all values are determined on fieldgrown plants. Source: Reinds (1988).

| Crop | $PSI_{leaf}$ | Crop | $PSI_{leaf}$ |
|---|---|---|---|
| green pepper | 3 500 | soya | 15 000 |
| potato | 7 000 | maize | 17 000 |
| tobacco | 13 000 | sorghum | 20 000 |
| sunflower | 14 000 | cotton | 25 000 |
| wheat | 14 000 | | |

Note that the values in Table 6.2 confirm, by and large, the distribution of the same crops over the four (drought tolerance) 'Crop groups' suggested by Doorenbos et al. (1979). See also Table 5.2A.

Note further that $SMPSI_{leaf}$, the water content of a soil (layer) with a matric suction of $PSI_{leaf}$ cm, is conceptually a better expression of the soil moisture content at permanent wilting point than SMPWP, the moisture content at PSI = 16 000 cm. SMPWP is merely a soil constant whereas $SMPSI_{leaf}$ is determined by soil properties and crop properties.

### *Resistance terms ($R_{plant}$ and $R_{root}$)*

The resistance terms in Equation 6.9a are difficult to quantify and approximations suggested in literature are rather general.

$R_{plant}$ represents the compounded effects of all resistances to water flow between the root surface (intake point) and the leaf surface. $R_{plant}$ can be estimated from multiple measurements of water head gradients and associated water fluxes. Experimental data examined by Reinds (1988) suggest that $R_{plant}$ although variable over the growing cycle and decreasing when transpiration increases (Monteith, 1973) is in practice a constant and conditioned by the plant's physiological tolerance of drought. $R_{plant}$ and $PSI_{leaf}$ are strongly correlated.

$$R_{plant} = 680 + 0.53 * PSI_{leaf} \quad (r^2 = 0.94) \qquad (6.9.1)$$

Equation 6.9.1 is entirely empirical. It seems satisfactory at present but might well need adjustment when more experimental results become available.

$R_{root}$ represents all resistances to water flowing to and entering the roots. $R_{root}$ is influenced by the geometry of the rooting system and by the hydraulic conductivity of the rooted soil (with a matric suction PSI). Feddes & Rijtema (1971) suggest the following approximation of $R_{root}$ for crops with a homogeneous root distribution.

$$R_{root} = 13 / (RD * KPSI) \qquad (6.9.2)$$

where
RD is equivalent rooting depth (cm)
KPSI is hydraulic conductivity of soil with matric suction PSI (cm $d^{-1}$).

Parameters RD and KPSI will be discussed later (in paragraph 6.4 on "Auxiliary Relations") so as not to interrupt the train of thought.

## 6.3 Matching: calculating sufficiency

Actual transpiration (TR) proceeds at the maximum rate (TRM) as long as the possible water uptake by the roots (MUR) is equal to or greater than

**TRM cm $d^{-1}$. The rate of transpiration is limited to MUR cm $d^{-1}$ whenever MUR < TRM cm $d^{-1}$.**
**Equation 6.9b stipulates that negative water uptake from the rooted surface soil and negative transpiration are considered impossible.**

if **MUR >= TRM then TR = TRM** **(6.10a)**

else **TR = MUR** **(6.10b)**

**The sufficiency of water availability in a particular interval can be seen as the degree to which transpiration needs (TRM) are met by the momentary rate of water supply to the roots:**

**INTSUFF = TR / TRM** **(6.11)**

**where**
**INTSUFF is sufficiency of water availability.**

## 6.4 Auxiliary relations

**Matching demand against supply in a singleland-use system yields a quantitative expression of the momentary sufficiency of water availability. Equations 6.1 to 6.11 describe TRM (the land-use requirement, i.e. the demand side), and MUR (the land quality, i.e. the supply side). Some terms in these Equations need attention.**
-equivalent depth of the rooting zone **(RD, in Equation 6.9.2) is still to be described**
-hydraulic conductivity **of the soil (KPSI, in Equation 6.9.2) is still to be described.**
**SMPSIPSI relations are used to convert soil moisture content into matric suction and vice versa. Several theoretical SMPSIPSI relations have been published (e.g. Brooks & Corey, 1964; van Genuchten & Nielsen, 1985; Li Yunzhu, 1987; Vereeken et al., 1989). The relations suggested in this**

**section are as good, or bad, as any of these.**

***Equivalent depth of the rooting zone (RD)***

**Equation 5.6 describes the momentary depth of a uniform rooting zone (RD) as a function of the initial rooting depth (RDint) and the maximum rooting depth (RDm). It assumes that RD reaches its maximum of 0.7 * RDm early in the (tabulated) midseason development stage. This assumption can now be refined.**
**Annual plants use a certain fraction of all newly formed assimilates for growing roots. They do so from germination (when RDS = 0) until a plant-specific relative development stage at which root growth stops ($RDS_{root}$). Table 6.3 suggests indicative values for $RDS_{root}$.**

**Table 6.3. Indicative values for $RDS_{root}$. Source: Van Heemst, 1988 (modified).**

| Crop | $RDS_{root}$ | Crop | $RDS_{root}$ |
|---|---|---|---|
| **barley** | **0.59** | **pigeon pea** | **0.89** |
| **cassava** | **0.26** | **rice (HYV)** | **0.75** |
| **chick pea** | **0.48** | **rice (trad.)** | **0.75** |
| **cotton** | **0.87** | **sesame** | **0.76** |
| **cowpea** | **0.63** | **sorghum** | **0.61** |
| **groundnut** | **0.86** | **soya** | **0.61** |
| **lentil** | **0.60** | **sugarcane** | **0.90** |
| **maize** | **0.70** | **tobacco** | **0.50** |
| **millet** | **0.84** | **wheat** | **0.56** |

**The equivalent depth of the rooting zone (RD) can be found by interpolation between the rooting depth at germination (RDint) and the maximum rooting depth, as a function of RDS / $RDS_{root}$. It is assumed that the root density decreases linearly from a maximum density at the soil surface to nil at the maximum rooting depth (RDm).**

if **RDS =< $RDS_{root}$ then**
**$RD = RDint + RDS * (0.5 * RDm - RDint) / RDS_{root}$ (6.12a)**

else $RD = 0.5 * RDm$ (6.12b)

where

RD is momentary equivalent rooting depth (cm)

RDint is equivalent rooting depth at germination or planting (cm; see Table 5.3)

RDm is maximum rooting depth (cm; see Table 5.3)

RDS is momentary relative development stage

$RDS_{root}$ is (tabulated) RDS at which root growth ceases (see Table 6.3).

Note that drought stress depresses assimilation. Consequently, water shortage may result in less root mass. However that does not necessarily cause a shallower rooting depth.

*Hydraulic conductivity (KPSI)*

Paucity of reliable (measured) KPSIvalues explains the frequent use of theoretical or semi-empirical KPSIPSI relations to calculate hydraulic conductivity of soil as a function of matric suction and geometry. The latter is assumed rigid and correlated with texture class.
If matric suction is very low, KPSI is (still) equal to the saturated conductivity (K0) because no pores are wide enough to drain at such low suction. The suction at which the first pores empty is the air entry point. The condition of water saturation below air entry point will be disregarded in this text; its effect is only slight. Instead, it will be assumed that relative hydraulic conductivity (KPSI / K0) decreases with increasing PSI as a function of matrix geometry (expressed by an empirical constant, ALFA; see Equation 6.13a).
The average diameter of pores that (still) conduct water becomes ever narrower as PSI increases; hydraulic conductivity becomes increasingly determined by other than capillary forces. Rijtema (1965) suggests an empirical KPSIPSI relation for PSI greater than a soilspecific boundary value ($PSI_{max}$).

if $PSI =< PSI_{max}$ then $KPSI = K0 * \exp(-ALFA * PSI)$ (6.13a)

else $KPSI = AK * PSI^{-n}$ (6.13b)

where

$PSI_{max}$ is texturespecific suction boundary (cm)

KPSI is hydraulic conductivity of soil with a matric suction PSI (cm $d^{-1}$)

K0 is saturated hydraulic conductivity (cm $d^{-1}$)
ALFA is texturespecific geometry constant ($cm^{-1}$)
AK is texturespecific empirical constant ($cm^{-2.4}$ $d^{-1}$)
*n* is empirical constant; in practice $n = 1.4$ for all soil materials.

Figure 6.1 presents a KPSIPSI curve for sandy clayloam; indicative values for KPSI can be calculated for the relevant PSIrange with the parameter values suggested in Table 6.4.

Fig. 6.1. Indicative KPSIPSI curve for sandy clayloam.

Table 6.4. Indicative values for soil constants SM0, GAM, $PSI_{max}$, K0, ALFA and AK for reference soil texture classes. Source: Rijtema (1969).

| Texture | SM0 | GAM | $PSI_{max}$ | K0 | ALFA | AK |
|---|---|---|---|---|---|---|
| | ($cm^3$ $cm^{-3}$) | ($cm^{-2}$) | (cm) | (cm $d^{-1}$) | ($cm^{-1}$) | ($cm^{-2.4}$ $d^{-1}$) |
| coarse sand | | 0.395 | | 0.1000 | 80 | 1120 |
| 0.2440.08 | | | | | | |
| loamy sand | | 0.439 | | 0.0330 | 200 | 26.5 |
| 0.0398 16.4 | | | | | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| fine sand | 0.364 | 0.0288 | 175 | 50 | 0.0500 | 10.9 |
| fine sandy loam | 0.504 | 0.0207 | 300 | 12.0 | 0.0248 | 26.5 |
| silt loam | 0.509 | 0.0185 | 300 | 6.5 | 0.0200 | 47.3 |
| loam | 0.503 | 0.0180 | 300 | 5.0 | 0.0231 | 14.4 |
| loess loam | 0.455 | 0.0169 | 130 | 14.5 | 0.0490 | 22.6 |
| sandy clayloam | 0.432 | 0.0096 | 200 | 23.5 | 0.0353 | 33.6 |
| silty clayloam | 0.475 | 0.0105 | 300 | 1.5 | 0.0237 | 36.0 |
| clayloam | 0.445 | 0.0058 | 300 | 0.98 | 0.0248 | 1.69 |
| light clay | 0.453 | 0.0085 | 300 | 3.5 | 0.0274 | 2.77 |
| silty clay | 0.507 | 0.0065 | 50 | 1.3 | 0.0480 | 28.2 |
| heavy clay | 0.540 | 0.0042 | 80 | 0.22 | 0.0380 | 4.86 |
| peat | 0.863 | 0.0112 | 50 | 5.3 | 0.1045 | 6.82 |

*SMPSIPSI relation*

pFcurves of Dutch reference soil materials (singlegrain material with rigid geometry) are reasonably well described with one generic SMPSIPSI relation.

$$SMPSI = SM0 * PSI^{-GAM*\ln(PSI)} \qquad (6.14a)$$

where
SMPSI is volume fraction of moisture in soil with suction PSI ($cm^3$ $cm^{-3}$)
SM0 is total pore fraction ($cm^3$ $cm^{-3}$; see Table 6.4)
GAM is texturespecific constant ($cm^{-2}$; see Table 6.4).

Conversely:

$$PSI = \exp((1/GAM * \ln(SM0/SMPSI))^{0.5}) \qquad (6.14b)$$

## 6.5 Adjustment of state variables

The moisture content of the rooted soil (SMPSI) changes in the course of an interval as precipitation enters the soil from above (TRICKLE) and water is lost by evapotranspiration (TR + EA).

(new)SMPSI = (old)SMPSI + (TRICKLE - TR - EA) * DT / RD    (6.15)

where

| | |
|---|---|
| SMPSI | is volume fraction of moisture in soil ($cm^3\ cm^{-3}$) |
| TRICKLE | is rate of precipitation trickling down into the soil ($cm\ d^{-1}$) |
| TR | is actual rate of transpiration ($cm\ d^{-1}$) |
| EA | is actual rate of evaporation ($cm\ d^{-1}$) |
| RD | is equivalent rooting depth (cm) |
| DT | is length of interval (d). |

*Gauged precipitation rate (PREC) and effective precipitation rate (TRICKLE)*

Not all of the gauged precipitation (PREC * DT) reaches the soil surface; a part may be intercepted by a canopy and evaporate from there. This interception is a function of the morphology of the canopy and of distribution and intensity of precipitation over time. Interception reduces the efficiency of low intensity precipitation in particular. On the other hand, 'fog drip' and 'steered drip' might actually improve the suppply of water to a crop.
The uncertain effect of interception, the low confidence level of interception estimates, and Penman's statement that 'the rain gauge, though it is not vegetation, is probably the most important interceptor in quantitative hydrology', are good reasons to use gauged precipitation rates in water balance calculations, without further correction.
The specifications of the land-use system under study stipulate that the infiltration capacity of the soil is adequate to prevent surface runoff. So, the precipitation which actually enters the rooted surface soil (TRICKLE * DT) is the gauged precipitation diminished by the quantity absorbed by a surface mulch (if any).

*Evaporation of water from a field (EA)*

Watersaturated soils lose water by evaporation. The rate of evaporation (EA) is maximum (EM) as long as all water lost is replenished. Ever less water flows to the evaporation site (the soil surface) as the soil dries out; a surficial mulch layer forms when upward flow of water becomes less than EM.
Water (vapour) from the rooted soil has to pass the mulch layer before it reaches the atmosphere. The properties of the mulch layer and the water

(vapour) supply at the lower boundary of the mulch determine whether the actual rate of evaporation (EA) is less than EM.

Formation of a mulch layer

The equivalent matric suction of the mulch layer (PSIMUL) is between PSI (the suction of the underlying rooting zone) and PSIATM (the suction of soil material in equilibrium with atmospheric air). An approximation:

PSIMUL = (PSI + PSIATM) / 2 (6.16)

Campbell (1985) describes the relative humidity of air in (equilibrium with) airdry soil material.

RHA = exp(Mw * PSIatu / $R_g$ * $K_x$)

where
RHA is relative humidity of the atmosphere (0 - 1)
Mw is mass of water (kg $mole^{-1}$)
PSIatu is moisture potential of soil in equilibrium with the atmosphere (J $kg^{-1}$)
$R_g$ is gass constant (J $mole^{-1}$ $K^{-1}$)
$K_x$ is temperature of environment 'x' (K).

Recall that matric suction of soil is expressed by a positive value in cm rather than a negative value in J $kg^{-1}$, and temperatures are expressed in $^oC$ rather than K. With 1 cm suction equivalent to 0.1 J $kg^{-1}$, the molar mass of water equal to 0.018 kg $mole^{-1}$, and the gass constant equal to 8.3143 J $mole^{-1}$ $K^{-1}$, the above relation can be rewritten to:

PSIATM = (273 + $T_{24h}$) * $10^4$ * ln(RHA) / -2.1649 (6.16.1)

where
PSIATM is matric suction of airdry soil (cm)
$T_{24h}$ is average daily temperature ($^oC$).

Campbell (1985) uses a default RHAvalue of 0.5 in his calculations; the corresponding matric suction of 'airdry' soil material amounts to $10^6$ cm.

The moisture flux to the surface of the soil equals the maximum rate of evaporation (EM) as long as a mulch layer does not form. The rate of flow is proportional with the driving force (ratio of hydraulic head and flow distance) and inversely proportional with the resistance of water-filled soil pores. In a steady state notation, the generic flow equation reads:

$F$ = KPSI * (PSI + $G$) / $L_x$ (6.17)

where
$F$ is water flow over a distance $L_x$ (cm $d^{-1}$)
KPSI is hydraulic conductivity (cm $d^{-1}$)
PSI is matric suction, i.e. the matric component of the hydraulic head (cm)
$G$ is gravity component of the hydraulic head, equal to the negative value of
the vertical distance between the points of flow (cm)
$L_x$ is distance of flow (cm).

Substituting EM for $F$, KMUL for KPSI, and equivalent mulch depth (DMMUL, in cm) for flow distance ($L_x$) and for $G$, produces an expression of the equivalent mulch depth.

DMMUL = KMUL * (PSIATM - PSI) / (EM + KMUL) (6.18)

where
DMMUL is equivalent depth of the mulch layer (cm)
KMUL is hydraulic conductivity of the mulch layer (cm $d^{-1}$).

The hydraulic conductivity of the mulch layer (KMUL) can be calculated in the same way as the hydraulic conductivity of any other soil material (see Equation 6.13).

if PSIMUL < $PSI_{max}$ then KMUL = K0 * exp(-ALFA * PSIMUL)(6.19a)

else KMUL = AK * $(PSIMUL)^{-n}$ (6.19b)

where
PSIMUL is equivalent matric suction of the mulch layer (cm)
$PSI_{max}$ is texturespecific suction boundary (cm; see Table 6.4)
KMUL is hydraulic conductivity of the mulch layer (cm $d^{-1}$)
K0 is saturated hydraulic conductivity (cm $d^{-1}$; see Table 6.4)
ALFA is texturespecific geometry constant ($cm^{-1}$; see Table 6.4)

AK is texturespecific empirical constant ($cm^{-2.4}$ $d^{-1}$; see Table 6.4)
$n$ is an empirical constant; for practical applications $n$ = 1.4.

The moisture in the mulch layer at the end of a time interval (MULWAT) amounts to DMMUL * SMMUL cm, plus any precipitation which the layer received in the course of the interval.

MULWAT = DMMUL * SMMUL + PREC * DT (6.20)
with
SMMUL = SM0 * $PSIMUL^{(-GAM*\ln(PSIMUL))}$ (6.20.1)

where
MULWAT is water in the mulch layer at the end of the interval (cm)
DMMUL is equivalent thickness of the mulch layer (cm)
SMMUL is moisture content of the mulch at the beginning of the interval ($cm^3$ $cm^{-3}$)
PREC is rate of precipitation during the interval (cm $d^{-1}$)
DT is length of the interval (d).

If precipitation in any one interval makes the mulch layer wetter than the underlying soil, i.e. wetter than SMPSI $cm^3$ $cm^{-3}$, all water in excess of DMMUL * SMPSI cm is discharged to the rooting zone (TRICKLE, in cm $d^{-1}$).

if MULWAT > DMMUL * SMPSI then
TRICKLE = (MULWAT - DMMUL * SMPSI) / DT (6.21a)

else TRICKLE = 0 (6.21b)

where
TRICKLE is rate at which surface water enters the rooting zone (cm $d^{-1}$).

Note that the mulch layer has ceased to exist when TRICKLE becomes greater than nil.

Maximum (vapour) flux through the mulch layer

Rijtema (1971) describes the maximum flux of water vapour through a mulch layer (VAPFLUX).

$VAPFLUX = AIRDIFF * DMDA * SVAP * (RHMUL - RHA) / DMMUL$
(6.22)

where

VAPFLUXis maximum vapour flux through the mulch layer (cm $d^{-1}$)

AIRDIFF is vapour diffusion coefficient in air ($cm^2$ $d^{-1}$ $mbar^{-1}$)

DMDA is ratio of diffusion coefficients of mulch layer and air

SVAP is saturated vapour pressure (mbar)

RHMUL is relative humidity of air in equilibrium with soil material with suction PSIMUL

$T_{24h}$ is average daily temperature (°C).

Transfer functions to describe AIRDIFF and DMDA were obtained by curve fitting through AIRDIFF and DMDAvalues supplied by Rijtema (1971).

$$AIRDIFF = 2.38 + 0.0192 * T_{24h} \quad (6.22.1)$$

$$DMDA = 0.9 * (SM0 - SMMUL) - 0.1 \quad (6.22.2)$$

The saturated vapour pressure (SVAP) is described by Penning de Vries & Van Laar (1982).

$$SVAP = 6.11 * \exp(17.4 * T_{24h} / (239 + T_{24h})) \quad (6.22.3)$$

The humidity of air in the mulch layer is a function of the moisture potential of the mulch (after Campbell, 1985).

$$RHMUL = \exp(-2.1649 * 10^{-4} * PSIMUL / (273 + T_{24h})) \quad (6.22.4)$$

<u>Actual rate of evaporation</u>

A mulch layer poses an obstacle to evaporation if its permeability to water vapour (VAPFLUX) is less than the rate at which water is supplied at the upper boundary of the rooted surface soil (i.e. at the lower boundary of the mulch layer). If it is assumed that this supply stems wholly from the rooting zone, the rate of water supply can be estimated from the generic flow equation (Equation 6.17).

$$WATSUPPLY = KPSI * ((PSIMUL - PSI) / (RD - DMMUL) - 1) \quad (6.23)$$

where
WATSUPPLYis rate of upward water flow to the lower boundary of the mulch layer (cm $d^{-1}$)
RDis equivalent rooting depth (cm).

Calculating the actual rate of evaporation (EA) is now a matter of matching supply (i.e. WATSUPPLY or VAPFLUX, whichever has the smaller value) against demand (EM).

if WATSUPPLY > VAPFLUX then VAPSUPPLY = VAPFLUX (6.24a)

else VAPSUPPLY = WATSUPPLY (6.24b)
and
if VAPSUPPLY > EM then EA = EM (6.25a)

else EA = VAPSUPPLY (6.25b)

where
VAPSUPPLYis maximum rate at which water vapour is transmitted to the upper boundary of the mulch layer (cm $d^{-1}$).

*Percolation to deeper layers (INTPERC)*

It is thinkable that precipitation exceeds evapotranspiration (TR + EA) to the extent that the adjusted soil moisture content (Equation 6.15) exceeds field capacity. The stipulation of 'adequate internal soil drainage' implies that all water in excess of the soil moisture equivalent (SMEQ) is discharged to deeper layers (INTPERC, in cm $d^{-1}$).

if SMPSI > SMEQ then INTPERC = (SMPSI - SMEQ) * RD / DT
and
SMPSI = SMEQ (6.26a)

else INTPERC = 0 (6.26b)

where
SMEQ is soil moisture content at PSI=333 cm or pF 2.52 ($cm^3$ $cm^{-3}$)
INTPERC is rate of percolation from the rooted surface soil (cm $d^{-1}$)

**RD** **is equivalent depth of the rooting zone (cm)**
**DT** **is length of interval (d).**

**The soil moisture equivalent (SMEQ) is the volume fraction of moisture which remains if a watersaturated soil is allowed to drain.**

$$SMEQ = SM0 * 333^{-GAM*\ln(333)} \qquad (6.26.1)$$

**where**
**SM0 is total pore fraction ($cm^3\ cm^{-3}$; see Table 6.4)**
**GAM is texturespecific constant ($cm^{-2}$; see Table 6.4).**

## 6.6 Pathway of calculation and data needs

### *Flow diagram*

**Figure 6.2 presents the flow diagram of the entire procedure for assessing the sufficiency of the land quality 'water availability to a crop'. The numbers between brackets refer to specific functional relations. The pathway of calculation passes through the following stages.**
-initialization, **i.e. input of system constants and initial variables**
-interval calculations **culminating in matching of TRM against MUR and calculation of the actual rate of transpiration (TR) and the momentary sufficiency of the land quality 'water availability' (INTSUFF). Subsequently, all state variables are adjusted.**
-output of the generated sufficiencies.

**Fig. 6.2. Flow diagram of a procedure to assess the sufficiency of water supply.**

### *Data needs*

The data needed to assess the sufficiency of water availability over a

**growing cycle are arranged in five categories: General data, Management data, Crop data, Weather data and Soil data.**

**General data:**

| | |
|---|---|
| **DT** | **(=<10 d; typically DT = 1 d).** |

**Management data:**

| | |
|---|---|
| **PSIint** | **(consult local Extension Service)** |
| **RDint** | **(see Table 5.3)** |
| **Germination date** | **(consult crop calendar).** |

**Crop data:**

| | |
|---|---|
| **$PSI_{leaf}$** | **(consult agronomic literature; Table 6.2)** |
| **$RDS_{root}$** | **(consult agronomic literature; Table 6.3)** |
| **RDm** | **(consult agronomic literature; Table 5.3)** |
| **Tsum** | **(consult agronomic literature; Table 6.1)** |
| **T0** | **(consult agronomic literature; Table 6.1)** |
| **TCM** | **(depends on canopy morphology; typically between 1.0 and 1.2).** |

**Weather data:**

| | |
|---|---|
| **PREC** | **(meteorological reports)** |
| **ET0** | **(meteorological reports)** |
| **$T_{24h}$** | **(meteorological reports).** |

**Soil data:**

| | |
|---|---|
| **KPSIPSI relation** | **(soil reports; hydrology reports)** |
| **SMPSIPSI relation** | **(soil reports)** |
| **SMFC** | **(soil reports; SMPSIPSI relation).** |

Note that **it is good practice to use basic data 'as they come'. If you must, you may process the results of calculations; never tamper with input data.**

## 6.7 Calculated examples

The diagram in Figure 6.2 shows the procedure for calculating the momentary sufficiency of the land quality 'water availability to a crop'. Possibilities and limitations of the procedure are perhaps best demonstrated by examining some (hypothetical) land-use systems. The land units and land utilization types of these systems are defined as follows.

The land units are described with daily weather data (Tmax, Tmin, PREC, RHA and ET0) recorded in Xuzhou, in the North China Plain (P.R.C.), in 1986, 1987 and 1988. The soil data (SM0, GAM, PSIMAX, K0, ALFA and AK) have the values suggested for loess loam (see Table 6.4). The land utilization types differ in crop choice. Green peppers have a low critical leaf water head, maize is moderately tolerant to drought, and cotton is very well equipped to cope with severe drought. The crops germinate on the $150^{th}$ day in the year and on soil with an initial moisture potential of 1000 cm. Crop specifications are listed in Table 6.6.

Note that the soil specifications used assume default values which are likely to differ from the actual specifications of Xuzhou soils. The crop specifications in Table 6.6 are default values too. This practice is permissible only because the calculations have no other purpose than to illustrate the method of assessment. Practical analysis of land-use systems MUST be founded on information of good quality.

Table 6.6. Crop specifications used in the calculated examples.

| Crop | peppers | maize | cotton |
|---|---|---|---|
| Threshold temperature (T0) | 10 | 10 | 10 |
| Heat requirement (Tsum) | 1 600 | 1 650 | 1 950 |
| Maximum Turbulence Coefficient (TCM) | 1.05 | 1.15 | 1.15 |
| Root growth until ($RDS_{root}$) | 1.00 | 0.70 | 0.87 |
| Maximum rooting depth (RDm) | 90 | 130 | 130 |
| Initial rooting depth (RDint) | 6 | 10 | 10 |
| Critical leaf water head ($PSI_{leaf}$) | 3 500 | 17 000 | 25 000 |

**All sample calculations are done with WATSUF, a computer program of the algorithm depicted in Figure 6.2.**

***Calculated sufficiency of water availability***

**Sufficiency is traditionally expressed by a single rating for the entire growing period. A numerical expression of the single factor 'water availability' is obtained by dividing the cumulative** actual **transpiration losses by the cumulative** maximum **transpiration (the requirement for unconstrained growth).**
**Figure 6.3 demonstrates that simple numerical ratings can be misleading: the calculations confirm that 1987 was a wetter year than 1988 but the considerable fluctuations in water supply over the growing period are not expressed.**
**Dynamic analysis (the curves in Figure 6.3) suggests that rainfed maize germinating on 1 June on loess loam in Xuzhou was successful in 1987 but very poor in 1988.**

**Fig. 6.3. Sufficiency of the land quality 'water availability' in land-use**

systems with rainfed maize on loess loam near Xuzhou, P.R. of China. In both scenarios (1987 and 1988) the crop germinates on 1 June and on soil with a moisture potential of 1000 cm.

Note that a systemdependent rate of water supply (MUR) was matched against the transpiration needs of a constraintfree crop (TRM). The growth of a real crop would slow down in times of water stress and its transpiration needs would be less than those of a permanently stressfree crop, even after the period of stress had long passed. The sufficiencies calculated in the previous section are likely to be too pessimistic.

Singlefactor analyses are conceptually weak; they ignore the effects of interactions between 'relevant factors' in land-use systems. This causes loss of accuracy and misinterpretation. Conversion tables or 'compounding equations' cannot help.
Singlefactor ratings can perhaps indicate major differences between dry and wet years and between droughtsensitive and tolerant crops. However they must not be used for other than comparative studies of an exploratory nature.

# CHAPTER 7

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# CALCULATING PRODUCTION POTENTIALS

## 7. CALCULATING PRODUCTION POTENTIALS

**Production is a reflection of the compounded sufficiency of all land characteristics and land qualities in a land-use system. Most established procedures for assessing land suitability are based on this principle.**
**-They relate observed or inferred properties of soil and land to observed production**
**-They identify cause-effect relationships of assumed general validity**
**-They apply these to situations that are basically unknown.**
**Such 'quick and easy' procedures may work just fine in their place of birth where the rating tables, conversion tables, response curves or weighting factors were established but indiscriminate use of such 'models' in other regions leads to gross misinterpretation.**
**A realistic, quantitative model of land-use systems cannot be simple. It must make dynamic descriptions of relevant land-use requirements and corresponding land qualities, and it must take account of all direct and indirect interactions. It must describe processes, not just symptoms. Construction of a comprehensive model would take years of methodological work and the model would have very limited operational value because of its massive data needs and high running costs.**
**There is an alternative: a model which, instead of being fit to handle the actual performance of land-use systems, describes only the** possible **production in a rigidly defined** production situation **could be considerably simpler than a comprehensive model and would still be useful to land evaluators and planners.**

### 7.1 Production situations

**A production situation is a hypothetical land-use system, with one or only a few relevant land qualities. Land qualities not considered in the definition of a production situation are assumed not to constrain the performance of the system. Land-use is defined by the choice of crop and a fixed set of management attributes.**
**A production situation is** not an actual land-use system **and the production calculated is not the actual production but the** production potential.

Note that **production situations resemble the situations in which** agricultural research stations conduct experiments. For example, fertilizer experiments are conducted in production situation PS3. All plots receive the same amount of solar radiation and have the same temperature and water supply; weeding and plant protection are optimum and there are no harvest losses. How much of the production potential is realized depends solely on the sufficiency of the land quality 'nutrient availability' (which is manipulated).

Models of production situations are composed of a number of submodels, each matching one land-use requirement against one land quality and translating the outcome of the matching into realized or lost production potential.

*Hierarchy of production situations*

The simplest production situation (PS1) quantifies crop performance, within the physiological possibilities of the crop, as a function of the only land qualities that a farmer cannot modify, viz. the availability of solar radiation and the temperature. All other land qualities are assumed to fully satisfy the corresponding land-use requirements. Production situation PS1 constitutes the highest level in the hierarchy of production models. The production calculated is the highest that can be realized on an experimental field; it is the biophysical production potential.
At the second highest level (PS2), the assumption of optimum water supply is waived and the land quality 'moisture availability' is quantified and matched against the consumptive water needs. The result of this matching is incorporated in the calculation of the production potential. In other words, crop production in production situation PS2 is determined by the amount of intercepted radiation, the temperature and the availability of water. All other land qualities or limitations that influence production in normal farming (availability of nutrients, competition by weeds, occurrence of pests and diseases, harvest losses) are assumed not to constrain crop performance. The outcome of a PS2 analysis is the water-limited production potential.
At the third hierarchical level (PS3), the availability of nutrients is additionally taken into account. And so on.

The above suggests that production and yield are dependent variables, i.e. variables that can be calculated from the properties of the land unit and the land utilization type, the processes that take place and the rates

at which they proceed and interact. However, models become more complex and more difficult to manage as more land-use requirements are included. Inevitably a point will be reached where so many system properties, processes and interactions are involved that high data needs, internal complexity and error propagation make the model impracticable.
Models of production situation PS1 are still simple; simulation of production situation PS2 is already quite difficult. Calculating production potential as a function of temperature(s), available radiation, water, and nutrients (PS3) is not really practicable. A change in strategy is needed.
From PS3 onward, production and yield are treated as independent quantities. A target production is set (usually the calculated water-limited production potential, sometimes less but never more) and the physical means, labour and management inputs needed to produce the target are calculated. Thus, one obtains a 'nutrient requirement' or a 'fertilizer requirement' (PS3), an additional 'herbicide requirement' (PS4), and so forth, in addition to the calculated water-limited production potential.

Note that only production situations PS1, PS2 and PS3 will be discussed in this book.

Figure 7.1 presents a relational diagram of (sub)models of production situations. The modular setup has the advantage that submodels can be replaced (by another version); the overall structure remains intact.

**Fig. 7.1. Relational diagram of production situations.**

**The hierarchical arrangement of submodels has another advantage: interactions between combinations of land-use requirement and land quality are accounted for automatically, even if these combinations are examined at different levels. Consider, for example, a scenario in which water stress  quantified at the 2nd highest level in the model  forces a crop to reduce its water consumption. As the crop closes its stomata to curb transpiration losses, its intake of $CO_2$ is also reduced. This affects (leaf) growth and hence the interception of solar radiation  quantified at the highest level in the structure  in later intervals.**

## 7.2 Analysing farming systems

**Most farms comprise several land-use systems. The more land-use requirements and land qualities are considered in analyses of farming systems, the closer the resemblance between the simulated and the real system. However it is unlikely that analytical models will ever be fit to describe the full complexity of a small farmer's** actual **production environment.**

**Onfarm production is not solely determined by biophysical factors. The norms and values observed by the farm household and by the farming community in the area, and the nonagricultural sector are just as important. Studies of farming systems** must **consider the socio-economic constraints to farming.**

**A twostage analysis of onfarm production possibilities results if objective(s) and constraints identified in socioeconomic studies are combined with (sets of) activities, physical constraints, inputs and production figures generated in multiple analysis of production situations. Interactive multiplegoal 'linear programming' models are being developed for the purpose. The construction of an analytical structure which allows to introduce relevant sets of 'stage 1' biophysical information in the 'stage 2' socioeconomic optimation model has proven to be particularly difficult.**

# CHAPTER 8

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# PS1: BIOPHYSICAL PRODUCTION POTENTIAL

## 8. PS1: BIOPHYSICAL PRODUCTION POTENTIAL

**Production situation PS1 represents a land-use system with the least possible analytical complexity; all land qualities which can be influenced by a farmer through irrigation and drainage, use of fertilizers, weeding and control of pests and diseases are assumed to be optimum. The production calculated for production situation PS1 is the highest production possible on a farmer's field. It is the** 'biophysical production potential'. **The biophysical production potential is determined by the solar radiation and temperature during the growing period and by the physiological characteristics of the crop. Analysis of production situation PS1 is based on the same principles as calculation of net biomass production for agroecological zoning but the procedure is dynamic and considerably more detailed.**

### 8.1 Production of biomass by plants

**The fundamental process behind plant growth is** assimilation, **i.e. reduction of atmospheric $CO_2$ to carbohydrates, $(CH_2O)_n$. Assimilation requires energy; it is a unique capability of green plants that they can capture solar energy and use it in assimilation:**

$$CO_2 + H_2O + \textit{solar energy} > {}^1/_n(CH_2O)_n + O_2 \qquad (8.1a)$$

**Conversion of $(CH_2O)_n$ to $CO_2$ and $H_2O$ occurs also. This process is known as** respiration; **it releases chemical energy which can be used by the plant.**

$$^1/_n(CH_2O)_n + O_2 > CO_2 + H_2O + \textit{chemical energy} \qquad (8.1b)$$

**Van Heemst (1986) estimates that up to 40 percent of all primary photosynthates is burnt again in respiration.**

***Pathways of photosynthesis***

**The rate of assimilation under conditions of light saturation and optimum temperature differs among plants. Three different pathways of photosynthesis exist of which two have practical importance.**
**-one group of plants produces $C_3H_6O_3$ as the first assimilate; plants in**

**this group are called** C3plants **after the length of the carbon chain of the first assimilate**
**-plants in the second group produce $C_4H_8O_4$ as the first assimilate; they are the** C4plants.
**An important difference between C3plants and C4plants is that respiration in the sunlit photosynthetic organs** (photorespiration) **is considerable in C3plants and negligible in C4plants.**

**Losses of assimilates incurred in photorespiration increase with temperature and intensity of light. This has practical consequences.**
**-C4plants make more efficient use of intercepted solar radiation than C3plants at high light intensity (there is little difference at low light intensity)**
**-C4plants reach their maximum rate of assimilation rate between 25 and 35 °C whereas C3plants perform best between 15 and 25 °C (Black, 1973). Not surprisingly, C4plants stem predominantly from the tropics. Most C3crops (not all) have their origin in more temperate regions. Representatives of both groups are included in Table 8.1.**

*Effects of light intensity and temperature on assimilation*

**The amount of solar energy at the outer extremity of the atmosphere varies with the latitude of the site and the time of year. Approximately half the** total global radiation **is** photosynthetically active radiation **(PAR). The transparancy of the atmosphere determines how much radiation reaches the canopy.** Light response curves **relate irradiance with** gross **assimilation. Light response curves are described by only two parameters.**
-light use efficiency at low light intensity **(EFF)**
-maximum rate of assimilation **(AMAX).**
**AMAX (kg $ha^{-1}$ $h^{-1}$) is the gross rate of assimilation at light saturation; AMAX is co-determined by photorespiration and is much greater for C4crops than for C3crops. AMAX is strongly temperaturedependent; EFF decreases by only 1% for every degree of temperature increase in C3plants, and even less in C4plants. For practical purposes EFF is a constant with a value of some 0.5 kg $ha^{-1}$ $h^{-1}$/J $m^{-2}$ $s^{-1}$ (de Wit et al., 1978).**

**Fig. 8.1. Light response curves of maize leaves at several temperatures (de Wit et al., 1978).**

**Figure 8.1 presents light response curves of maize leaves at several temperatures. Observe that ambient temperature has a much more pronounced effect on AMAX (the plateau) than on EFF (the initial angle of the curve).**

**It is unfortunate that curves like those in Figure 8.1 cannot be used to describe the assimilatory potential of fieldgrown crops. It appears that the photosynthetic activity of plant leaves is influenced by the radiation and temperature to which the leaves were exposed in the past. It is for this reason that the AEZ team defined** cropadaptability groups **with different AMAXtotemperature relations. The response curves in Figure 8.2 resemble those used by the AEZ team (FAO, 1978).**

Fig. 8.2. Generic AMAXtotemperature response curves (Versteeg & van Keulen, 1986).
*Legend*: I = C3crops in cool and temperate climates; II = C3crops in warm climates; III = C4crops in warm climates; IV = C4crops in cool climates.

Note that Figure 8.2 is a simplification; the optimum temperature for assimilation by a C3crop cannot be a steady 18 °C in cool climates and 27 °C in the tropics if it is codetermined by the temperatures to which the crop was actually exposed.
Therefore actual assimilation will be calculated as a fraction of assimilation at a reference temperature (Tref). Tref is the temperature to which the assimilating plant 'got used'; it is tentatively defined as the weighted average of the daytime temperatures ($T_{day}$) over the past 10 days, with a minimum of 15 °C and a maximum of 30 °C.

Curves I and II in Figure 8.2 suggest the following AMAXtotemperature relation for C3crops.

$$AMAX = 1.8 * Tref - 0.15 * (Tref - T_{day})^2 \qquad (8.2a)$$

Approximate AMAXtotemperature relations for C4crops are obtained by dividing response curves III and IV in Figure 8.2 in three linear trajecta.

if $T_{day}$ <= Tref then

$$AMAX = 110 - 10 * (Tref - T_{day}) \qquad (8.2b)$$

if $T_{day}$ > Tref then
AMAX = 110 - 2 * ($T_{day}$ - Tref) (8.2c)

if AMAX > 88 then AMAX = 88 (8.2d)

where
AMAXis maximum rate of assimilation at actual temperature (kg $ha^{-1}$ $h^{-1}$)
Tref is reference temperature (°C)
$T_{day}$ is daytime temperature (°C).

AMAXtotemperature response curves relate AMAX to the equivalent daytime temperature ($T_{day}$), not the average daily temperature ($T_{24h}$).

Average daily temperature ($T_{24h}$) is a function of equivalent daytime temperature ($T_{day}$), equivalent night temperature ($T_{night}$) and daylength (DL).

$$T_{24h} = [T_{day} * DL + T_{night} * (24 - DL)] / 24 \quad (8.3)$$

The equivalent daytime temperature ($T_{day}$) is found by integrating the temperature curve between sunrise and sunset (M. v.d. Berg, pers. comm.). It is assumed that the maximum temperature occurs at 14.00 hrs and the lowest temperature at sunrise.

$T_{day}$ = Tmid + (SUNSET - 14) * AMPL * sin(AUX) / (DL * AUX) (8.3.1)
with
Tmid = (Tmax + Tmin) / 2 (8.3.2)
AMPL = (Tmax - Tmin) / 2 (8.3.3)
SUNRISE = 12 - DL / 2 (8.3.4)
SUNSET = 12 + DL / 2 (8.3.5)
AUX = PI * (SUNSET - 14) / (SUNRISE + 10) (8.3.6)

where
Tmax is maximum daily temperature (°C)
Tmin is minimum daily temperature (°C)
DL is daylength (h $d^{-1}$)
PI is a constant (PI = 3.14159).

The equivalent night temperature ($T_{night}$) is found by integrating the temperature curve between sunset and sunrise.

$T_{night}$ = Tmid - AMPL * sin(AUX) / (PI - AUX) (8.3.7)

The daylength (DL) is a function of the day in the year and the latitude of the site (de Wit et al., 1978).

DL = 12 * (PI + 2 * asin(SSCC)) / PI (8.4)
with
SSCC = SSIN / CCOS (8.4.1)
SSIN = sin(LAT * RAD) * sin(DEC * RAD) (8.4.2)
CCOS = cos(LAT * RAD) * cos(DEC * RAD) (8.4.3)
DEC = -23.45 * cos(2 * PI * (DAY+10) / 365) (8.4.4)

where
RADis a conversion factor (degree to radian; RAD = PI / 180)
LATis latitude of the site (degree)
DECis declination of the sun (degree)
DAYis Julian day number on the northern hemisphere, or Julian day number plus or minus 182 on the southern hemisphere.

Note that Equations 8.2, 8.3 and 8.4 relate AMAX to a few readily available data, viz. latitude of the site (LAT, in degree), Julian day number (DAY), and daily maximum and minimum temperatures (Tmax and Tmin).

*Gross rate of $CO_2$reduction by plants*

The gross rate of $CO_2$reduction (Fgc, in kg $ha^{-1}$ $d^{-1}$) varies with the level of photosynthetically active radiation. Radiation at the top of the canopy is a function of
-daylength (DL; Equation 8.4)
-radiation at the outer extremity of the atmosphere
-losses of radiation in the atmosphere.

Photosynthetically active radiation at the outer extremity of the atmosphere (PAR) amounts to:

PAR = 0.5 * [SC * (1 + 0.033 * cos(2 * PI * DAY / 365))] * RDN
with (8.5)
RDN = SSIN + 24 * CCOS * $(1 - (SSCC)^2)^{0.5}$ / (DL * PI) (8.5.1)

where

PARis photosynthetically active radiation at the outer extremity of the atmosphere (J $m^{-2}$ $s^{-1}$)
SC is solar constant (SC = 1 353 J $m^{-2}$ $s^{-1}$)
RDNis fraction of SC at latitude 'LAT' and day 'DAY'.

(See Equations 8.4 for definitions of DL, SSCC, SSIN, CCOS, LAT and DAY.

The transparancy of the atmosphere determines how much photosynthetically active radiation arrives at the top of the canopy (PARCAN).

PARCAN = PAR * TRANS (8.6)

where
PARCANis photosynthetically active radiation at the top of the canopy (J $m^{-2}$ $s^{-1}$)
PARis photosynthetically active radiation at the outer extremity of the atmosphere (J $m^{-2}$ $s^{-1}$)
TRANSis atmospheric transmission.

TRANS is calculated from the Angström equation (Angström, 1924).

TRANS = *a* + *b* * SUNH / DL (8.6.1)

where
SUNH is number of sunhours (h $d^{-1}$)
DL is daylength (h $d^{-1}$)
*a*, *b*are coefficients.

Doorenbos et al. (1977) cite Glover & McCulloch (1958) who correlate coefficient '*a*' with the latitude.

*a* = 0.29 * cos(RAD * LAT) (8.6.2)

where
RAD is conversion factor (degree to radian; RAD = PI/180)
LAT is latitude of the site (degree).

Coefficient '*b*' correlates with the relative humidity of the atmosphere.

Equation 8.6.3 is based on data reported by Pelekanos & Papachristopoulos (1980).

$b$ = 1.25 - RHA (r² = 0.85) (8.6.3)

where
RHAis relative humidity of the atmosphere (from 0 to 1).

Spitters (1986) describes the gross rate of $CO_2$reduction (Fgc) assuming that
-response curves of leaf assimilation to absorbed PARCAN are hyperbolic
-absorption of photosynthetically active radiation decreases exponentially with leaf area depth (See also Goudriaan, 1986).

Fgc = DL * (AMAX / ke) * ln[(AMAX + CC) / (AMAX + CC * EXP(-LAI * ke))] (8.7)
with
CC = EFF * ke * PARCAN (8.7.1)

where
Fgc is gross rate of $CO_2$reduction by a closed reference crop (kg $ha^{-1}$ $d^{-1}$)
DL is daylength (h $d^{-1}$)
AMAX is maximum rate of assimilation at the actual temperature (kg $ha^{1}$ $h^{1}$)
ke is extinction coefficient for visible light (discussed hereafter)
LAI is leaf area index (discussed hereafter)
EFF is light use efficiency at low light intensity (= 0.5 kg $ha^{-1}$ $h^{-1}$ / J $m^{-2}$ $s^{-1}$)
PARCANis PAR at the top of the canopy (J $m^{-2}$ $s^{-1}$).

*Characteristics of the canopy*

The leaf area index (LAI) is the ratio of leaf area and ground. For example, a crop with a cumulative leaf area of 30 000 $m^2$ and standing on one hectare of land (10 000 $m^2$), has a leaf area index of 3.0. An approximate value for LAI is obtained by multiplying the dry mass of all living leaves by the specific leaf area (SLA).

$$LAI = livS(leaf) * SLA * 10^{-4} \quad (8.8)$$

where

livS(leaf) is dry mass of all living leaves (kg $ha^{-1}$)
(livS(leaf) will be discussed later in this section)

SLA is specific leaf area ($m^2$ $kg^{-1}$).

The specific leaf area (SLA) represents the total leaf area per unit dry leaf mass. It is codetermined by temperature, light intensity and relative development stage (RDS). Some authors suggest that SLA decreases linearly from a maximum value ($SLA_{max}$) at the time of germination, when the plant makes thin leaves, to a minimum value ($SLA_{min}$) at maturity. Experiments in Greece suggest that SLA changes with ln(RDS) rather than with RDS (Danalatos, in press). Equations 8.9 are empirical.

$$SLA = SLA_{min} - (SLA_{max} - SLA_{min}) * \ln(RDS) \quad (8.9a)$$

$$\text{if } SLA > SLA_{max} \text{ then } SLA = SLA_{max} \quad (8.9b)$$

where

$SLA_{max}$ is maximum specific leaf area ($m^2$ $kg^{-1}$)

$SLA_{min}$ is minimum specific leaf area ($m^2$ $kg^{-1}$)

RDS is relative development stage.

Table 8.1 includes indicative (ranges of) values for specific leaf area of common annual crops. Data from local experiment stations or, better still, from own measurement and experimentation are to be preferred.

The extinction coefficient for visible light (ke) is a function of the shape, surface properties and position of the leaves in the canopy. The fraction of all incoming radiation which falls through the canopy onto the soil surface decreases with increasing leaf mass (LAI) and is further dependent on ke. Recorded values for ke are between 0.2 and 0.8 (van Heemst, 1986); Table 8.1 suggests indicative values for common food and fibre crops.

**Table 8.1. Important crop characteristics: photosynthetic mechanism (C3/C4); specific leaf area (SLA, $m^2\ kg^{-1}$); extinction coefficient for visible light (ke); relative maintenance respiration rates (r(org), $kg\ kg^{-1}\ d^{-1}$). Sources: van Heemst (1988); N.G. Danalatos (pers. comm.); van Keulen (1986). nd = not determined; * = estimate.**

| Crop | C3/C4 | SLA range and generic value@ | ke | r(org) leaf | root | stem | st. org. |
|---|---|---|---|---|---|---|---|
| **barley** | **C3** | **18-27 (25)** | **0.44** | **0.015** | **0.010** | **0.015** | **0.007** |
| **cassava** | **C3** | **1823 (22)** | **0.8** | **0.012** | **0.010** | **0.004** | **0.003** |
| **chickpea** | **C3** | **1520 (13)** | **0.5*** | **0.030** | **0.010** | **0.015** | **0.009** |
| **cotton** | **C3** | **1624 (20)** | **0.6** | **0.010** | **0.010** | **0.015** | **0.010** |
| **cowpea** | **C3** | **32-40 (25)** | **0.5*** | **0.030** | **0.010** | **0.015** | **0.011** |
| **groundnut** | **C3** | **18 (28)** | **0.6** | **0.030** | **0.010** | **0.015** | **0.012** |
| **jute** | **C3** | **2833 (31)** | **0.5*** | **0.015** | **0.010** | **0.015** | |
| **lentil** | **C3** | **3237 (33)** | **0.5*** | **0.015** | **0.010** | **0.015** | **0.013** |
| **maize** | **C4** | **1435 (18)** | **0.6** | **0.013** | **0.010** | **0.010** | **0.010** |
| **millet** | **C4** | **18-23 (nd)** | **0.5** | **0.020** | **0.007** | **0.010** | **0.007** |
| **mung bean** | **C3** | **2030 (30)** | **0.5*** | **0.015** | **0.010** | **0.015** | **0.011** |
| **pigeon pea** | **C3** | **20-28 (nd)** | **0.5** | **0.030** | **0.010** | **0.015** | **0.010** |
| **potato** | **C3** | **2532 (nd)** | **0.5** | **0.010** | **0.010** | **0.015** | **0.007** |
| **rice** | **C3** | **18-27 (25)** | **0.4** | **0.015** | **0.010** | **0.015** | **0.0035** |
| **sesame** | **C3** | **2130 (23)** | **0.5*** | **0.015** | **0.010** | **0.015** | **0.012** |
| **sorghum** | **C4** | **1121 (20)** | **0.5** | **0.015** | **0.010** | **0.010** | **0.010** |
| **soya** | **C3** | **1523 (26)** | **0.4** | **0.015** | **0.010** | **0.015** | **0.017** |
| **sugarcane** | **C4** | **812 (10)** | **0.3** | **0.0134** | **0.010** | **0.0029** | |
| **sunflower** | **C3** | **2530 (nd)** | **0.8** | **0.015** | **0.010** | **0.0075** | **0.023** |
| **sweet potato** | **C3** | **1420 (22)** | **0.45** | **0.028** | **0.025** | **0.020** | **0.005** |
| **tobacco** | **C3** | **1031 (16)** | **0.5*** | **0.015** | **0.010** | **0.015** | |
| **wheat** | **C3** | **1624 (20)** | **0.5** | **0.017** | **0.010** | **0.015** | **0.010** |

*Gross production of sugars*

The potential gross production of assimilates by a field crop can be calculated from Equation 8.10.

Fgass = Fgc * 30/44 * cf(water) (8.10)

where
Fgass is gross rate of assimilate production by a field crop (kg $ha^{-1}$ $d^{-1}$)
Fgc is gross rate of $CO_2$ reduction by a closed reference crop (kg $ha^{-1}$ $d^{-1}$)
30/44 is ratio of molecule masses of $CH_2O$ and $CO_2$
cf(water) is correction factor for suboptimum availability of water (= 1.0 in PS1).

Note that production situation PS1 is, by definition, free from water stress. The correction factor for suboptimum availability of water (cf(water)) assumes a value 1.0. In calculations for other production situations, cf(water) can be less than 1.0 and expresses the effect of water stress on assimilation.

*Allocation of assimilates to plant organs*

Assimilates (sugars) are formed in photosynthetically active plant parts and subsequently allocated to the various plant organs. The rate at which plant organs (leaves, roots, stems and storage organ) receive assimilates for maintenance and growth (GAA(org)) is approximated by multiplying the gross rate of assimilate production (Fgass) by an assimilate allocation fraction (fr(org)).

GAA(org) = Fgass * fr(org) (8.11)

where
GAA(org) is gross rate of assimilate supply to plant part 'org' (kg $ha^{-1}$ $d^{-1}$)
Fgass is gross rate of assimilate production by a field crop (kg $ha^{-1}$ $d^{-1}$)
fr(org) is mass fraction of Fgass allocated to organ 'org'. (See Appendix A5 and Figure 8.3).

Allocation of Fgass to the various plant organs is correlated with phenological development. A considerable part of Fgass is earmarked

for leaf production early in the growing cycle. Few, if any, new leaves are formed near the end of the cycle when assimilates are predominantly used for filling storage organs.
Appendix A5 suggests RDStofr(org) relations for common annual crops. Linear interpolation between tabulated combinations of RDS and fr(org) is allowed.

Figure 8.3 presents the RDStofr(org) curves for maize cv. Pioneer 3183. (Danalatos, in press).

Fig 8.3. RDStofr(org) relations for maize cv. Pioneer 3183. (Danalatos, in press).

### *Maintenance respiration*

Maintenance respiration provides the energy which plants need to resynthesize degrading proteins and keep (transport) processes going against ionic gradients. Van Heemst (1988) suggests maintenance requirements at a reference temperature. These were calculated under the assumption that proteins need about 0.035 kg $(CH_2O)_n$ $kg^{-1}$ $d^{-1}$ for maintenance, and other components about 0.07 kg $kg^{-1}$ $d^{-1}$. (Stable proteins in storage organs have lower maintenance needs.)
Organspecific relative maintenance respiration rates (r(org), in kg $kg^{-1}$ $d^{-1}$; see Table 8.1) allow to calculate the maintenance respiration losses incurred by living plant organs under PS1 conditions and at the reference temperature.

MRRref(org) = r(org) * S(org) (8.12)

where
MRRref(org) is maintenance respiration rate of living plant part 'org' at the reference temperature (kg $ha^{-1}$ $d^{-1}$)
r(org) is organspecific relative maintenance respiration rate (kg $kg^{-1}$ $d^{-1}$)
S(org) is dry mass of living plant part 'org' (kg $ha^{-1}$).

Note that the reference temperature for maintenance respiration (Tmain) is not the same as the reference temperature for assimilation (Tref). Maintenance respiration takes place during the day and during the night. Tmain is tentatively defined as the weighted average of daily temperatures ($T_{24h}$) in the past 10 days, with a minimum of 15 °C and a maximum of 30 °C.

Maintenance respiration is strongly temperaturedependent. A temperature correction factor (cf(temp)) expresses maintenance respiration at ambient temperature as a fraction of maintenance respiration at reference temperature.

if $T_{24h}$ >= Tmain then cf(temp) = $Q_{10}^{((T24h-Tmain) / 10)}$ (8.13a)

else cf(temp) = $T_{24h}$ / Tmain (8.13b)

where
$Q_{10}$ is factor by which process speed increases if the temperature

rises 10 °C ($Q_{10}$ = 2 for enzymatic processes)
$T_{24h}$ is average daily temperature (°C)
Tmain is reference temperature for maintenance respiration (°C).

In production situations other than PS1 maintenance respiration needs are likely to decrease when water flow and energy demanding transport processes slow down in times of drought.

MRR(org) = MRRref(org) * cf(temp) * cf(water) (8.14)

where
MRR(org) is rate of maintenance respiration in plant part 'org' at actual (daily) temperature and actual availability of water (kg $ha^{-1}$ $d^{-1}$)
cf(temp) is correction factor for suboptimum daily temperature (from 0 to 1.0)
cf(water)is correction factor for suboptimum availability of water (= 1.0 in PS1).

*Growth respiration*

The net rates at which assimilates become available for growth of plant organs are found by diminishing the gross rates of assimilate supply (GAA(org); Equation 8.11) by the organspecific maintenance respiration (MRR(org); Equation 8.14).
Conversion of primary photosynthates to structural plant material (proteins, cellulose, lignin, suberin, waxes, fats, etc) requires energy. Plants 'liberate' this energy by burning assimilates. This growth respiration is one reason why the efficiency of conversion (Ec(org)) is less than 1.0. Conversion is not temperature dependent but is entirely a function of the composition of the newly formed plant matter.

Table 8.2 presents indicative values for Ec(org).

Table 8.2. Indicative values for 'heat sum for full development of leaf tissue' (Tleaf) and for efficiencies of conversion (Ec(org)). Sources: van Heemst (1988); Vertregt & Penning de Vries (1987); N.G. Danalatos (pers. comm.); Yu Zhenrong (pers. comm.).

| Crop | Tleaf | Ec(org) |
|---|---|---|

| | | | | | |
|---|---|---|---|---|---|
| | (°C d) | ------------------ | | | |
| | leaf | rootstem | s.o. | | |
| barley | 720 | 0.72 | 0.72 | 0.69 | 0.74 |
| cassava | 1250 | 0.72 | 0.72 | 0.69 | 0.81 |
| chick pea | 1120 | 0.72 | 0.72 | 0.69 | 0.77 |
| cotton | 1430 | 0.72 | 0.72 | 0.69 | 0.61 |
| cowpea | 575 | 0.72 | 0.72 | 0.69 | 0.81 |
| groundnut | 1000 | 0.72 | 0.72 | 0.69 | 0.50 |
| jute | 1155 | 0.72 | 0.72 | 0.69 | |
| lentil | 1380(?) | 0.72 | 0.72 | 0.69 | 0.71 |
| maize | 1000 | 0.72 | 0.72 | 0.69 | 0.72 |
| millet | 890 | 0.72 | 0.72 | 0.69 | 0.74 |
| mung bean | 1200 | 0.72 | 0.72 | 0.69 | 0.72 |
| potato | 1350 | 0.72 | 0.72 | 0.69 | 0.85 |
| pigeon pea | 1200 | 0.72 | 0.72 | 0.69 | 0.78 |
| rice (trad.) | 850 | 0.72 | 0.72 | 0.69 | 0.74 |
| rice (HYV) | 850 | 0.72 | 0.72 | 0.69 | 0.74 |
| sesame | 1380(?) | 0.72 | 0.72 | 0.69 | 0.62 |
| sorghum | 975 | 0.72 | 0.72 | 0.69 | 0.74 |
| soya | 520 | 0.72 | 0.72 | 0.69 | 0.68 |
| sugarcane | 900 | 0.72 | 0.72 | 0.72 | |
| sunflower | 1400 | 0.59 | 0.71 | 0.73 | 0.71 |
| sweet potato | 1600 | 0.72 | 0.72 | 0.69 | 0.80 |
| tobacco | 1050 | 0.72 | 0.72 | 0.69 | |
| wheat | 1000 | 0.72 | 0.72 | 0.69 | 0.79 |

Note that **most values for Ec(org) are close to 0.72, the generic value used by the AEZ team. Storage organs (s.o.) can have a different composition than leaves, roots and stems; Ec(s.o.) may therefore be less than 0.72 (e.g. oil crops) or greater (e.g. starch crops).**

### *Growth*

The increase in dry organ mass **in an interval of DT days amounts to:**

$$DWI(org) = [GAA(org) - MRRref(org)] * Ec(org) * DT \qquad (8.15)$$

where
DWI(org) is increase in dry organ mass (kg $ha^{-1}$)
GAA(org) is gross assimilate supply to plant part 'org' (kg $ha^{-1}$ $d^{-1}$)
MRR(org) is maintenance respiration rate in plant part 'org' at actual daily temperature and water availability (kg $ha^{-1}$ $d^{-1}$)
Ec(org) is efficiency of conversion (kg $kg^{-1}$)
DT is length of interval (d).

Cumulative dry organ masses (leaf mass, S(leaf); stems, S(stem); roots, S(root); storage organs, S(s.o.)) at the end of an interval are found by adding DWI(org) to the organ mass present at the beginning of the interval.

$$(new)S(org) = (old)S(org) + DWI(org) \qquad (8.16)$$

*Living and dead leaf mass*

Leaf tissue has a rather limited lifespan and leaves formed early in the growing cycle may die before the plant as a whole reaches maturity. Table 8.2 suggests values for the heat requirement for full leaf development (Tleaf, in °C d). Whenever a leaf reaches a heat sum which exceeds Tleaf, it dies. In other words, from the moment that the relative development stage of the crop (RDS) exceeds Tleaf / Tsum, there may be new formation of living leaves and dying of leaves at the same time. The living dry leaf mass is found by subtracting from the total leaf mass (S(leaf)) the dry mass of all living leaves at the time when the relative development stage of the crop reached (RDS - Tleaf / Tsum)).

if RDS > Tleaf / Tsum then $livS(leaf) = (new)S(leaf) - S(leaf)_{LRDS}$ (8.17a)

else $livS(leaf) = (new)S(leaf)$ (8.17b)

where
RDS is momentary relative development stage of the crop
Tleaf is heat requirement for full leaf development (°C d)
Tsum is heat requirement for full crop development (°C d)
livS(leaf) is living dry leaf mass at the end of the interval (kg $ha^{-1}$)
(new)S(leaf) is total dry leaf mass at the end of the interval (kg $ha^{-1}$)
$S(leaf)_{LRDS}$ is dry mass of living leaves at the moment when RDS

**amounted to ((present)RDS - Tleaf / Tsum) (kg $ha^{-1}$).**

Note that **more leaf mass might die in an interval than is formed; it is not uncommon that the living leaf mass (livS(leaf)) decreases even though the total leaf mass (S(leaf)) increases.**

Note further that **only living leaf mass requires maintenance. LivS(leaf) is substituted in Equations 8.12 and 8.14 and** not **S(leaf).**

***Total biomass production***

Total dry mass **(TDM) is calculated by summing all organ masses; substituting the** living **dry leaf mass (livS(leaf)) for S(leaf) yields the** total living dry mass **(TLDM).**

**TDM = S(leaf) + S(root) + S(stem) + S(s.o.) (8.18)**

**TLDM = livS(leaf) + S(root) + S(stem) + S(s.o.) (8.19)**

## 8.2 Pathway of calculation and data needs

***Flow diagram***

**Before the biophysical production potential can be calculated from the functional relations developed in section 8.1, a suitable algorithm must be constructed in which all Equations are placed in the proper context. Figure 8.4 presents the flow diagram for analysis of production situation PS1.**

**Complete analysis of production situation PS1 passes through three characteristic phases.**
-initialization, **i.e. input of system constants and initial (state) variables**
-recurrent interval calculations, **i.e. calculation of the gross supply of assimilates to the various plant parts (GAA(org)), maintenance respiration losses (MRR(org)), growth respiration and increases of dry (organ) mass (DWI(org)). Cumulative organ masses (S(org)) are added together to total dry mass (TDM) and total living dry mass (TLDM)**
-output of results. **When all intervals in a growing cycle are processed, i.e. when RDS = 1.0, the** biophysical production potential **(TDM) and the**

yield potential, **i.e. the economic produce, usually the storage organ mass (S(s.o.), are output.**

***Data needs***

**Table 8.3. lists the data needs for analyses of production situation PS1. The data items are arranged in four categories: General data, Management data, Crop data and Weather data.**

Fig. 8.4. Flow diagram for analysis of production situation PS1.

Table 8.3. Data needs for analysis of production situation PS1.

-------------------------------------------------------------------------------------------------------

<u>General data</u>:
DT(typically DT = 1 d)
LAT

<u>Management data</u>:
DAY(Julian number of day of germination or planting)
S(org)(initial dry leaf mass (S(leaf)), root mass (S(root)), stem mass (S(stem)), and storage organ mass (S(s.o.)).

<u>Crop data</u>:
C3/C4 (consult agronomic literature; Table 8.1)
$SLA_{max}$(consult agronomic literature; Table 8.1)
$SLA_{min}$(consult agronomic literature; Table 8.1)
ke(consult agronomic literature; Table 8.1)
Tleaf(consult agronomic literature; Table 8.2)
Tsum(consult agronomic literature; Table 6.1)
T0(consult agronomic literature; Table 6.1)
fr(org) (consult agronomic literature; Appendix A5)
r(org)(Table 8.1)
Ec(org)(Table 8.2).

**Weather data:**
**Forcing variables (called anew for each interval):**
**Tmax(meteorological reports)**
**Tmin(meteorological reports)**
**SUNH(meteorological reports)**
**RHA(meteorological reports).**
**------------------------------------------------------------------------------------------------------------------------**

8.3 Calculated examples

**Biophysical production and yield potentials will be calculated for the same situations as examined in Chapter 6 of this text (grossly simplified land-use systems with maize near Xuzhou, North China Plain). The computations will be done using option '1' of PS123, a hierarchical model of production situations which was developed to supplement this text. The model follows the calculation procedure(s) outlined in Figure 8.4.**
**The** land units **are defined by weather data (Tmax, Tmin, SUNH and RHA) recorded in Xuzhou in 1986, 1987 and 1988. (Soil data are irrelevant in production situation PS1.)**
The land utilization types **involve a local maize cultivar;** approximate **crop data were compiled by Mr Yu Zhenrong of Beijing Agricultural University. Germination takes place on the $150^{th}$ day in the year; sowing density is 10 kg $ha^{-1}$ with 10% mortality. Approximate initial organ masses, i.e. S(org) on Julian day # 150, were estimated by assuming that onethird of the fertile seed mass is respired in germination and the remaining twothirds are divided according to fr(org) at RDS = 0 (see Appendix A5).**

***How realistic are the system specifications ?***

**Sowing density**

**Sowing densities of maize range from 10 to 30 kg $ha^{-1}$. Information from Xuzhou suggests that most farmers sow 10 to 15 kg seed per hectare; the moisture content of the seed is between 12 and 15% and the mortality rate is 'low'.**
**Figure 8.5 presents** maximum **leaf area index (LAI) and biophysical yield potential calculated for scenarios with different sowing densities of maize. The weather data were recorded in Xuzhou in 1988; germination**

is on Julian day # 150 in all scenarios.

Fig. 8.5. Calculated maximum LAI and biophysical yield potential of maize near Xuzhou (1988) as a function of sowing density. (Dry seed; seed mortality is set to 10%).

Figure 8.5 shows that the calculated yield potential (S(s.o.)) is between 9 and 10 tons per hectare if the sowing density is between 4 and 30 kg ha$^{-1}$. The highest yields (more than 9.8 tons ha$^{-1}$) are calculated for sowing densities between 6 and 12 kg ha$^{-1}$. The overriding impression is that the system is 'not very sensitive to the sowing density'.

Note that using only 4 kg seed per hectare would NOT be a realistic option in practical farming. Analyses of production situation PS1 address a hypothetical system in which supplies of water and nutrients are optimum and weeds, pests and diseases do not occur. Production losses due to poorquality seed, weeds, pests and diseases in actual farming are mitigated by (chosing) a higher sowing density than needed in production situation PS1. In practice, a higher than minimum sowing density improves crop security.

## Germination date

The date of germination has consequences for the length of the growing cycle (GD), the constraintfree yield level (S(s.o.)) and the production potential (TDM). Table 8.4 lists some indicators of crop performance calculated for scenarios with different dates of germination. All scenarios used a sowing density of 12 kg $ha^{-1}$ with 10% seed mortality, and weather data as recorded in Xuzhou in 1988.

Table 8.4. Length of growing cycle (GD), yield potential (S(s.o.)), production potential (TDM) and maximum leaf area index (max. LAI) of maize in Xuzhou, North China Plain, calculated for PS1 scenarios with different dates of germination.

| Germination date (Julian day in 1988) | 110 | 120 | 130 | 140 | 150 | 160 | 170 | 180 |
|---|---|---|---|---|---|---|---|---|
| GD (d) | 119 | 114 | 111 | 100 | 108 | 100 | 127 | * |
| TDM (kg $ha^{-1}$) | 21 961 | 19 708 | 18 247 | 17 995 | 16 656 | 15 532 | 14 180 | * |
| S(s.o.) (kg $ha^{-1}$) | 8 596 | 8 329 | 8 347 | 9 099 | 9 814 | 9 873 | 10 488 | * |
| maximum LAI | 13.2 | 11.0 | 9.54 | 7.25 | 6.16 | 4.68 | 3.16 | * |

* crop succumbs to frost.

Table 8.4 shows that early sowing, associated with slow development early in the growing cycle and long vegetative growth, results in an unfavourably luxuriant canopy with high maintenance needs, and reduced net production of assimilates. (Farmers who grow maize for silage may have a different appreciation of luxuriant vegetative growth. The calculated examples pertain to maize grown for the grain.)
Late sowing is associated with rapid development early in the growing cycle and a shorter period of vegetative growth, a thinner canopy and reduced gross production of assimilates. However, this is more than compensated by lower losses (less maintenance respiration) and prolonged grain filling in the cooler autumn season. Only VERY late

**sowings fall prey to night frosts.**

**Similar analyses were done using weather data recorded in Xuzhou in 1986 and 1987. The results indicate that a sowing density of 10 to 15 kg ha$^{-1}$ and germination between 1 May and 15 July are associated with a biophysical yield potential of some 10 tons ha$^{-1}$ and a growing cycle of little over 100 d.**

***Crop growth over time***

**Figure 8.6 presents the (calculated) growth of maize sown to 12 kg ha$^{-1}$ and germinating on 1 June 1988 near Xuzhou, North China Plain. Note that production of leaves, stems and roots has priority early in the growing cycle. Vegetative growth declines after the midseason stage and becomes negative towards the end of the growing cycle when newly formed assimilates are entirely allocated to the storage organ and maintenance respiration eats away at the leaves, stems and roots. The simultaneous dying of senescent leaves contributes to what must be the farmer's notion of an ideal ripe corn field: yellow (dead) leaves on stems with grainfilled cobs and just enough root mass to keep the crop standing in anticipation of the harvester.**

**Fig. 8.6. Potential growth of maize near Xuzhou, North China Plain, calculated with the PS123 model. The maize is a local cultivar sown to 12 kg ha$^{-1}$ (10% seedling mortality); it germinated on 1 June 1988.**

## 8.4 Role of production situation PS1 in land-use systems analysis

Recall that **FAO's agroecological zoning is based on calculations of the 'potential net biomass production' of field crops ($B_{na}$; Equation 4.9). Potential production multiplied by a tabulated harvest index gives an estimated 'constraintfree yield' ($B_{ya}$; Equation 4.10) which serves as the** reference yield level **for highinput farming. The reference yield level for lowinput farming was arbitrarily set to 25% of the calculated constraintfree yield. An estimate of the 'anticipated crop yield' was obtained by applying correction factors for agroclimatic constraints to the calculated constraint-free yield.**
**Subsequently the land suitability class was found by matching anticipated crop yield against reference yield and accounting for unfavourable terrain conditions by applying phase, slope and texture rules.**

**The yield potential (S(s.o.)) calculated for a particular scenario under production situation PS1 has the same function as the constraintfree crop yield in the AEZ study. It is a reference by which the relative (biophysical) performance of other systems can be measured. However it does not have (all of) the shortcomings of the AEZ reference yield: it is a dependent variable whose value is calculated dynamically as a function of the compounded characteristics of the system.**

# CHAPTER 9

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## PS2: WATERLIMITED PRODUCTION POTENTIAL

## 9. PS2: WATERLIMITED PRODUCTION POTENTIAL

Production situation PS2 represents a land-use system in which production possibilities are determined by irradiance of photosynthetically active radiation (PAR), temperature, and availability of water. The land-use requirements 'optimum availability of PAR', 'optimum temperature' and 'optimum availability of water' are matched against the land qualities 'actual PAR', 'actual temperature' and 'actual availability of water' to determine the water-limited production potential. Production situation PS2 is already a much more complex situation than PS1 but still less complex than the production environment of many farmers in developing countries. Advanced farmers may examine alternative PS2 scenarios to evaluate water management options, identify optimum planting or sowing dates, select physically suitable areas for agricultural expansion in critically dry regions, and much more.

### 9.1 Availability of water in soil

Recall that synthesis of plant matter involves uptake of $CO_2$ from the atmosphere through stomatal openings in the leaves. Intake of $CO_2$ is almost always accompanied by transpiration. The water lost must be replenished by uptake from the soil. If the possibility of lateral water flow through the soil is ignored, availability of water for uptake is determined by:

-water (vapour) flow through the upper boundary of the rooting zone
-water flow through the lower boundary of the rooting zone
- uptake of water by the roots (equal to transpiration losses).

The rate at which the volume fraction of moisture in the rooting zone changes follows from a simple water budget equation.

$$RSM = [UPFLUX + (CR + D) \quad TR] / RD \qquad (9.1)$$

where
RSMis rate of change of volume fraction of moisture in the rooting zone ($d^{-1}$)
UPFLUXis net rate of water (vapour) flow through the upper boundary of the rooting zone (cm $d^{-1}$)
(CR + *D*)is net rate of water flow through the lower boundary of the

**rooting zone (cm $d^{-1}$)**
**TRis actual rate of transpiration (cm $d^{-1}$)**
**RDis equivalent depth of the rooting zone (cm).**

**Figure 9.1 shows the water fluxes that condition the volume fraction of moisture in the rooting zone and the availability of water for uptake by roots.**

**Fig 9.1. Water fluxes conditioning the volume fraction of moisture in the rooting zone.**

Recall that **the actual rate of transpiration (TR) is less than the theoretical maximum rate (TRM) when a crop senses moisture stress. Under conditions of steady state, assimilation decreases proportionally to**

**transpiration. The** water uptake correction factor **(cf(water)) is the relative rate of gross assimilation and represents the sufficiency of the land quality 'water availability' (see also INTSUFF; Equation 6.11).**

**cf(water) = TR / TRM (9.2)**

**where**
**cf(water)is relative rate of transpiration by plants exposed to water stress**
**TRis actual rate of transpiration (cm $d^{-1}$)**
**TRMis maximum rate of transpiration (cm $d^{-1}$).**

**The difference between analyses of production situation PS1 and production situation PS2 is that cf(water) in Equations 8.10 (Fgass) and 8.14 (MRR(org)) is 1.0 in production situation PS1, and between 0 and 1.0 in production situation PS2 (calculated as a function of, inter alia, all water fluxes to and from the rooting zone).**

***Water (vapour) flow through the upper boundary of the rooting zone***

**Gross rate of water supply (GROSSUP)**

**Water supply to the upper boundary of the rooting zone is composed of precipitation (PREC) and effective irrigation (IE); part of this water evaporates before it can enter the soil (EA).**

**GROSSUP = PREC + IE - EA (9.3)**

**where**
**GROSSUPis gross rate of water supply to the upper boundary of the rooting zone (cm $d^{-1}$)**
**PRECis gauged rate of precipitation (cm $d^{-1}$)**
**IEis effective rate of irrigation (cm $d^{-1}$)**
**EAis actual rate of evaporation (cm $d^{-1}$).**

Note that **influx of water through the upper boundary of the soil can never exceed the infiltration rate of the soil. If GROSSUP exceeds the infiltration capacity of the soil, excess supply is in first instance stored**

on top of the soil and sags into the soil in later intervals. If excess supply exceeds the momentary free surface storage capacity, the quantity that cannot be stored is discharged as surface runoff.
The infiltration rate and the actual surface storage capacity will be discussed in section 9.2 (Auxiliary relations).

Precipitation in Equation 9.3 (PREC) is the gauged rate without correction for interception, stem flow or drip.

Effective irrigation (IE) is found by multiplying the gross rate of water release at the project headworks by an irrigation efficiency factor. Doorenbos & Pruitt (1977) estimate the overall efficiency of irrigation from three partial efficiency factors. These express losses incurred in conveyance of water from headworks to field canals ($E_i$), in field canal flow ($E_f$), and in application ($E_d$).

$$IE = IG * E_i * E_f * E_d \qquad (9.4)$$

where
IEis effective rate of irrigation (cm $d^{-1}$)
IGis gross rate of water release at project headworks (cm $d^{-1}$)
$E_i$is efficiency of conveyance
$E_f$is field canal efficiency
$E_d$is efficiency of application.

Table 9.1 shows that the gross need for water may be several times the net need if conditions are unfavourable (small parcelling, unlined canals, poor management, etc.).

Table 9.1. Indicative values for conveyance ($E_i$), field canal ($E_f$), distribution ($E_i$*$E_f$) and field application ($E_d$) efficiencies of irrigation. Source: Doorenbos & Pruitt (1977).
-----------------------------------------

Conveyance efficiency, ($E_i$)
Continuous supply with no substantial change in flow: 0.9
Rotational supply in projects of 3000 7000 ha
and rotation areas of 70 300 ha, with

**effective management:**
**0.8**
**Rotational supply in large schemes (>10,000 ha)**
**and small schemes (<1000 ha) with less**
**effective communication/management: based on predetermined schedule 0.7**
**based on advance request 0.65**

Field canal efficiency ($E_f$)
**Blocks larger than 20 ha: unlined**
**0.8**
**lined or piped 0.9**
**Blocks up to 20 ha: unlined 0.7**
**lined or piped 0.8**

Distribution efficiency ($E_i$*$E_f$)
**Average for rotational supply,**
**with management and communication: adequate**
**0.65**
**sufficient 0.55**
**insufficient 0.4**
**poor 0.3**

Field application efficiency ($E_d$)
**Surface methods on: sandy soils**
**0.55**
**loamy soils 0.7**
**clayey soils 0.6**
**Subsurface methods:**
**0.8**
**Sprinklers in: hot dry climate**
**0.6**
**moderate climate 0.7**
**humid and cool climate 0.8**
----------------------------------------

Actual evaporation **(EA) can be calculated as in chapter 6 of this text where an estimated crop coefficient was used. This simplification is no longer needed because the actual transpiring leaf mass and the leaf area index are calculated for each interval in the growing cycle.**

Evaporation of water from a bare soil surface ($E_{bare}$) is equal to evaporation from an open water surface (E0) if the evaporated water can be replenished by the soil.
Campbell (1985) suggests that evaporation from an unsaturated bare soil is a function of the relative humidity of the air in the soil (RHS) and the relative humidity of the atmosphere (RHA).

$E_{bare}$ = E0 * (RHS - RHA) / (1 - RHA) (9.5)
with
RHS = exp(-2.1649 * $10^{-4}$ * PSI / (273 + $T_{24h}$)) (9.5.1)

where
$E_{bare}$ is rate of evaporation from bare soil (cm $d^{-1}$)
E0 is potential rate of evaporation (cm $d^{-1}$)
RHS is relative humidity of air in soil (between 0 and 1)
RHA is relative humidity of air above soil (between 0 and 1).

The maximum rate of evaporation (EM) is less than $E_{bare}$ if land is cropped and humidity and temperature are influenced by the canopy. The geometry of the canopy is expressed by a geometry coefficient (kef). In the absence of turbulence:

d(EM) / d(LAI) = -EM * kef

The canopy geometry coefficient represents the permeability of the canopy to energy fluxes in much the same way as the light extinction coefficient (ke) represents the throughfall of radiation through a canopy. Considering that evaporation from the soil surface is fueled by (throughfall of) radiation energy, one is tempted to substitute the light extinction coefficient (ke) for the geometry coefficient (kef).

EM = $E_{bare}$ * exp(-LAI * ke) (9.6)

where
ke is extinction coefficient for visible light. See Table 8.1.

Recall that a mulch layer forms when water transport to the surface is less than the evaporative demand. The mulch layer has an equivalent

**matric suction of PSIMUL cm and an equivalent depth of DMMUL cm. The mulch layer obstructs evaporation if the maximum possible vapour flux through the mulch (VAPFLUX) is less than the rate at which water is supplied to the the lower boundary of the mulch (WATSUPPLY). If it is assumed that supply stems wholly from the rooting zone, WATSUPPLY can be estimated from the generic flow equation (Equation 6.17).**

**WATSUPPLY = KPSI * ((PSIMUL - PSI) / (RD - DMMUL) - 1) (6.23)**

**where**
**WATSUPPLYis rate of upward flow to the lower boundary of the mulch layer, (cm $d^{-1}$)**
**KPSIis hydraulic conductivity (cm $d^{-1}$)**
**PSIMULis equivalent matric suction of the mulch layer (cm)**
**RDis equivalent rooting depth (cm)**
**DMMULis equivalent depth of the mulch layer (cm).**

Recall that **hydraulic conductivity (KPSI) is described by Equation 6.13.**

if **PSI =< $PSI_{max}$ then KPSI = K0 * exp(-ALFA * PSI) (6.13a)**

else **KPSI = AK * $PSI^{-n}$ (6.13b)**

**where**
**KPSIis hydraulic conductivity of soil with matric suction PSI (cm $d^{-1}$)**
**$PSI_{max}$is texturespecific suction boundary (cm; see Table 6.4)**
**K0is saturated hydraulic conductivity (cm $d^{-1}$; see Table 6.4)**
**ALFAis texturespecific geometry constant ($cm^{-1}$; see Table 6.4)**
**AKis texturespecific empirical constant ($cm^{-2.4}$ $d^{-1}$; see Table 6.4)**
***n*is empirical constant; in practice *n* = 1.4 for all soil materials.**

Recall that **RD is approximated by matching the momentary relative development stage (RDS) against the (cropspecific) relative development stage at which root growth ceases ($RDS_{root}$).**

if **RDS =< $RDS_{root}$ then**

$$RD = RDint + RDS * (0.5 * RDm - RDint) / RDS_{root} \quad (6.12a)$$

$$\text{else } RD = 0.5 * RDm \quad (6.12b)$$

where
RDis momentary equivalent rooting depth (cm)
RDintis equivalent rooting depth at germination or planting (cm; see Table 5.3)
RDmis maximum rooting depth (cm; see Table 5.3)
RDSis momentary relative development stage
$RDS_{root}$is relative development stage at which root growth ceases (see Table 6.3).

Recall that **the equivalent matric suction of the mulch layer (PSIMUL) is greater than that of the underlying rooting zone (PSI) and less than the suction of airdry soil (PSIATM).**

$$PSIMUL = (PSI + PSIATM) / 2 \quad (6.16)$$

with

$$PSIATM = (273 + T_{24h}) * 10^4 * \ln(RHA) / -2.1649 \quad (6.16.1)$$

where
PSIMUL is equivalent matric suction of the mulch layer (cm)
PSIis matric suction of the root zone (cm)
PSIATMis matric suction of airdry soil (cm)
RHAis relative humidity of air (0 to 1)
$T_{24h}$ is average daily temperature (°C).

**The** equivalent depth of the mulch layer **(DMMUL) can be calculated from the generic flow equation (Equation 6.17) by substituting EM for the flux term (*F*) and isolating the distance term.**

$$DMMUL = KMUL * (PSIATM - PSI) / (EM + KMUL) \quad (6.18)$$

where
DMMULis equivalent depth of the mulch layer (cm)
KMULis hydraulic conductivity of the mulch layer (cm $d^{-1}$).

**KMUL is calculated from Equation 6.19.**

if PSIMUL < $PSI_{max}$ then KMUL = K0 * exp(-ALFA * PSIMUL)(6.19a)

else KMUL = AK * $(PSIMUL)^{-n}$ (6.19b)

where
$PSI_{max}$is texturespecific suction boundary (cm; see Table 6.4)
K0 is saturated hydraulic conductivity (cm $d^{-1}$; see Table 6.4)
ALFAis texturespecific geometry constant ($cm^{-1}$; see Table 6.4)
AKis texturespecific empirical constant ($cm^{-2.4}$ $d^{-1}$; see Table 6.4)
*n*is an empirical constant; for practical applications $n$ = 1.4.

Rijtema (1971) describes the maximum water vapour flux through a mulch layer (VAPFLUX) as a function of the vapour pression gradient and diffusion coefficients.

VAPFLUX = AIRDIFF * DMDA * SVAP * (RHMUL - RHA) / DMMUL (6.22)
where
VAPFLUXis maximum vapour flux through the mulch layer (cm $d^{-1}$)
AIRDIFFis vapour diffusion coefficient in air ($cm^2$ $d^{-1}$ $mbar^{-1}$)
DMDAis ratio of diffusion coefficients of mulch layer and air
SVAP is saturated vapour pressure of air (mbar)
RHMUL is relative humidity of air in the mulch layer (0 - 1)
RHAis relative humidity of atmospheric air (0 - 1).

with
AIRDIFF = 2.38 + 0.0192 * $T_{24h}$ (6.22.1)
DMDA = 0.9 * (SM0 - SMMUL) - 0.1 (6.22.2)
SMMUL = SM0 * $PSIMUL^{(-GAM * \ln(PSIMUL))}$ (6.14a)
SVAP = 6.11 * exp(17.4 * $T_{24h}$ / (239 + $T_{24h}$)) (6.22.3)
RHMUL = exp(-2.1649 * $10^{-4}$ * PSIMUL / (273 + $T_{24h}$)) (6.22.4)

where
$T_{24h}$ is average daily temperature (°C)
SM0is total pore fraction of soil material ($cm^3$ $cm^{-3}$)
SMMULis volume fraction of moisture in the mulch layer ($cm^3$ $cm^{-3}$)
GAMis texturespecific constant ($cm^{-2}$; see Table 6.4)
PSIMULis equivalent matric suction of the mulch layer (cm).

The actual rate of evaporation (EA) can now be found by matching supply (i.e. WATSUPPLY or VAPFLUX, whichever has the smaller value) against demand (EM).

if WATSUPPLY > VAPFLUX then VAPSUPPLY = VAPFLUX (6.24a)

else VAPSUPPLY = WATSUPPLY (6.24b)
and
if VAPSUPPLY > EM then EA = EM (6.25a)

else EA = VAPSUPPLY (6.25b)

where
VAPSUPPLYis maximum rate at which water vapour is supplied to the upper boundary of the mulch layer (cm $d^{-1}$).

Note that evaporation is maximum when land is flooded.

if SS > 0 then EA = EM (9.7)

where
SSis equivalent depth of water on flooded or ponded land (cm).

The gross rate of surface water supply (GROSSUP; Equation 9.3) can now be calculated.

Net rate of surface water supply (NETSUP)

It will be assumed that a mulch layer absorbs all incoming surface water until its moisture content has become equal to the moisture content of the underlying soil and the mulch has ceased to exist. The net supply of water to the upper boundary of the rooting zone (NETSUP) is found by correcting gross supply for water absorption by a mulch.

MULWAT = DMMUL * SMMUL + GROSSUP * DT (9.8.1)

if MULWAT > DMMUL * SMPSI then
NETSUP = (MULWAT - DMMUL * SMPSI) / DT (9.8a)
SMMUL = SMPSI

else NETSUP = 0 (9.8b)
SMMUL = SMMUL + GROSSUP / DMMUL

where
MULWATis calculated (maximum) amount of water in the mulch layer (cm)
NETSUPis net rate of water supply to the upper boundary of the rooting zone (cm $d^{-1}$).

## Net water flux through the upper boundary of the rooting zone (UPFLUX)

Influx of water from surface storage (DS) and rate of surface runoff (SR) are calculated by matching net water supply (NETSUP) against momentary infiltration rate (IM) and momentary surface storage capacity (ASSC). There are three possibilities.

-If supply of water to the soil surface is just equal to IM, there is no change in the amount of water stored on top of the soil and there is no runoff.

if NETSUP = IM then
DS = 0 and SR = 0 (9.9a)

-If supply of water to the soil surface is less than the infiltration rate of the soil, all water can infiltrate and there is still some infiltration capacity left. (Some of) the water stored on top of the soil can infiltrate and there is no runoff. The decrease of surface storage cannot exceed the amount of water stored on top of the soil (SS), so that two possibilities must be considered.

if IM  NETSUP >= SS / DT then
DS = SS / DT and SR = 0 (9.9b)

if IM  NETSUP < SS / DT then
DS = IM  NETSUP and SR = 0 (9.9c)

-If supply of water to the soil surface exceeds the momentary infiltration rate, **excess water is in first instance stored in available surface storage capacity (ASSC  SS). If not all excess supply can be accommodated, the storage space is filled and the rest of the water is lost as runoff. Consequently, there are again two possibilities.**

if **(NETSUP  IM)** > **(ASSC  SS) / DT then**
**DS = (ASSC  SS) / DT and SR = NETSUP  IM + DS** **(9.9d)**

if **(NETSUP  IM)** =< **(ASSC  SS) / DT then**
**DS = IM  NETSUP and SR = 0** **(9.9e)**

**where**
**NETSUPis net rate of water supply to the upper boundary of the rooting zone (cm $d^{-1}$)**
**IMis actual infiltration rate (cm $d^{-1}$)**
**ASSCis actual surface storage capacity (cm)**
**SSis actual surface storage (cm)**
**DSis rate at which water on top of the soil sags into the rooting zone (cm $d^{-1}$)**
**SRis rate of surface runoff (cm $d^{-1}$)**
**DTis length of interval (d).**

**Infiltration (IM) and actual surface storage capacity (ASSC) will be discussed in section 9.2 ('Auxiliary relations').**

**The total net rate of water flow through the upper boundary of the rooting zone (UPFLUX, cm $d^{-1}$) is calculated from Equation 9.10.**

**UPFLUX = NETSUP + DS - SR** **(9.10)**

***Water flow through the lower boundary of the rooting zone***

**The generic flow equation (Equation 6.17) shows that flow of water in soil is driven by a** hydraulic head **composed of a matrix component (PSI) and a gravity component (*G*).**

Recall that **the gravity component is equal to the** negative **vertical distance between the points of flow. The total hydraulic head at a point above the phreatic level assumes a positive value if the absolute suction** at that point (|PSI|) is greater than the absolute vertical distance between that point and the phreatic level (|*G*|). A positive hydraulic head drives upward flow of water (from the water table) and a negative hydraulic head drives downward flow.

Upward flow is capillary rise (CR, cm $d^{-1}$); downward flow is deep percolation (*D*, cm $d^{-1}$). There is no capillary rise if there is percolation, and vice versa. (If there is equilibrium, there is neither capillary rise nor percolation.)

The net rate of water flow through the lower boundary of the rooting zone is included in the water balance equation (Equation 9.1) as (CR + *D*). This term is positive in the case of capillary rise and negative in the case of percolation.

<u>Percolation (*D*)</u>

Percolation of water from the rooting zone to the subsoil takes place when the distance between the phreatic level (at ZT cm below the surface) and the lower boundary of the rooting zone (at RD cm below the surface) is equal to or greater than PSI cm.

if PSI =< (ZT  RD) then *D* = KPSI * (PSI / (ZT  RD)  1) (9.11a)

else *D* = 0 (9.11b)

where
*D*is rate of percolation from the rooting zone to the groundwater (cm $d^{-1}$)
KPSIis hydraulic conductivity (cm $d^{-1}$; see Equation 6.13)
PSIis soil suction in the rooting zone (cm)
ZTis depth of phreatic level (cm)
RDis equivalent depth of the rooting zone (cm).

<u>Capillary rise (CR)</u>

Capillary rise is upward vertical flow of water from the phreatic level to the lower boundary of the rooting zone. Subsituting Equation 6.13 in the generic flow equation (6.17) will NOT produce a useful description of capillary rise. The rate of capillary rise must be computed with

numerical or gaussian integration.
Table 9.2 presents CRPSI combinations for loess loam. Tables for all 'standard' soil texture classes are included in Appendix A6.

To estimate the approximate rate of capillary rise,
-select the tabulated suction nearest to the matric suction of the rooting zone
-select, on the same line, the tabulated distance nearest to the actual flow distance (ZT - RD)
-read CR at the top of the selected column.

For example, consider a loess loam with PSI = 500 cm, RD = 60 cm, and ZT = 170 cm. The matric component of the hydraulic head is +500 cm; the gravity component amounts to -(170 - 60) cm. The hydraulic gradient has a positive value and drives upward flow.
Table 9.2 suggests that the rate of capillary rise to the lower root zone boundary is close to 0.15 cm $d^{-1}$.

Table 9.2. Capillary rise (CR) in loess loam soil as a function of matric suction in the rooting zone (PSI) and distance of flow (ZT  RD). For other texture classes see Appendix A6. Source: Rijtema, 1969 (modified).

| Loess loam | CR (cm $d^{-1}$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 0.50 | 0.40 | 0.30 | 0.20 | 0.15 | 0.10 | 0.06 | 0.02 |
| PSI: 20 cm | 18.9 | 19.1 | 19.3 | 19.5 | 19.7 | 19.8 | 19.9 | 20.0 |
| 50 cm | 43.8 | 44.9 | 46.0 | 47.3 | 47.9 | 48.6 | 49.1 | 49.7 |
| 100 cm | 65.4 | 69.0 | 73.3 | 78.9 | 82.4 | 86.8 | 91.1 | 96.6 |
| 250 cm | 72.0 | 77.1 | 83.8 | 93.9 | 101.5 | 113.1 | 129.3 | 169.4 |
| 500 cm | 75.0 | 80.8 | 88.7 | 101.2 | 111.1 | 127.2 | 151.9 | 226.4 |
| 1 000 cm | 77.2 | 83.6 | 92.5 | 106.8 | 118.6 | 138.4 | 170.2 | 277.1 |
| 2 500 cm | 79.4 | 86.3 | 96.1 | 112.2 | 125.9 | 149.2 | 188.2 | 329.7 |
| 5 000 cm | 80.6 | 87.8 | 98.1 | 115.2 | 129.8 | 155.2 | 198.1 | 359.2 |
| 10 000 cm | 81.5 | 88.9 | 99.6 | 117.5 | 132.9 | 159.7 | 205.6 | 381.8 |
| 16 000 cm | 82.0 | 89.5 | 100.4 | 118.7 | 134.5 | 162.1 | 209.7 | 393.9 |

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*Loss of water from the inner root zone*

Recall that **uptake of water by crops is (almost) equal to the rate of transpiration (TR). Plants can produce to their biophysical potential only if the availability of water is optimum (and transpiration is maximum). Plants curb their consumption of water if supply is constrained; actual transpiration becomes less than maximum and production less than the biophysical potential. To calculate the effect of water stress on assimilation, one must**
-calculate the maximum rate of transpiration **(TRM)**
-identify the optimum soil moisture range**, or the critical soil moisture potential(s) that mark the beginning of water stress**
-calculate the actual rate of transpiration **(TR) by matching demand (the theoretical maximum rate, TRM) against supply (MUR, the maximum rate of uptake of stored soil moisture the roots).**

<u>Maximum rate of transpiration rate (TRM)</u>

**In chapter 6, TRM was calculated by simply multiplying the potential rate of evapotranspiration (ET0) by the crop coefficient of a hypothetical reference crop ($kc_{ref}$) and a turbulence coefficient (TC).**

Note that **assimilation is a function of** transpiration **(TR0) and NOT of** ***evapo*****transpiration. Potential transpiration by a Penmantype reference crop is found by subtracting evaporation from evapotranspiration.**

**The reference crop has a constant leaf area index (LAI = 5 to 6) and is adequately supplied with water. With evaporation proceeding at the maximum rate (EM, Equation 9.6), the potential transpiration rate amounts to:**

**TR0 = ET0 $E_{bare}$ * exp((5 to 6) * ke)**
**or**
**TR0 = ET0 0.05 * E0** **(9.12.1)**

**where**
**TR0is potential rate of transpiration (cm $d^{-1}$)**
**ET0is potential rate of evapotranspiration (cm $d^{-1}$)**

E0is potential rate of evaporation (cm $d^{-1}$).

The properties of the canopy and the turbulence of the atmosphere determine the actual exposure of a crop to the evaporative demand of the atmosphere.

Recall that a turbulence coefficient (TC) was used in Chapter 6 to express the effect of turbulence on transpiration. TC ranges between 1.0 (flow entirely laminar) to TCM. The latter is the same as the crop coefficient suggested in Table 5.1A for the midseason development stage of adequately watered crops.

TC = 1 + (TCM - 1) * (1 - exp(-LAI * ke)) (9.12.2)

where
TCis turbulence coefficient
TCMis (tabulated) maximum value for the turbulent coefficient
LAIis leaf area index
keis extinction coefficient.

The term (1 - exp(-LAI * ke)) expresses the relative exposure of the canopy to the atmosphere. Equation 9.12.2 is based on the assumption that relative exposure of a canopy to the atmosphere and relative exposure to radiation follow the same pattern over the growing cycle.

Maximum transpiration by a real crop (TRM) is calculated by correcting the potential rate of transpiration (TR0) for incomplete soil coverage and for nonlaminar flow.

TRM = TR0 * (1 - exp(-LAI * ke)) * TC (9.12)

<u>Optimum availability of soil moisture</u>

Normally one associates water stress in crops with water shortage. However shortage of air (oxygen) in the soil also interferes with uptake of water. Plants not equipped with air ducts (aerenchym) in their roots have difficulty to take up water in wet environments; they show symptoms of drought and close their stomata.
Consequently there are two critical boundary values in the range of moisture in soils: one value associated with wetness and low matric suction, and another with drought and high suction.

There is no concensus about the minimum content of air at which root activity is still uninhibited; a critical volume fraction of air of 0.08 $cm^3$ $cm^{-3}$ seems not unrealistic for land utilization types with dryland crops. It is tentatively assumed that the root activity of dryland crops stops altogether if the soil contains less air than 0.04 $cm^3$ $cm^{-3}$ and that crops perish if exposed to this condition for 20 consecutive days.

Note that such generic values cannot be (always) correct because root activity and the need for oxygen vary over time, e.g. as a function of the temperature. However any attempt to describe the actual oxygen requirement of roots as a dependent variable would complicate the water balance more than is justified in the present setup.

A critically low moisture content occurs when the maximum rate of water uptake (MUR) is just equal to the theoretical transpiration needs (TRM).

$MUR = (PSI_{leaf} - PSI) / (R_{plant} + R_{root})$ (6.9a)

if MUR < 0 then MUR = 0 (6.9b)
with
$R_{plant} = 680 + 0.53 * PSI_{leaf}$ (6.9.1)
$R_{root} = 13 / (RD * KPSI)$ (6.9.2)

where
$PSI_{cr}$is critically high soil matric suction (cm)
$PSI_{leaf}$is critical leaf water head (cm; Table 6.2)
$R_{plant}$represents resistance to flow in the plant (d)
$R_{root}$represents resistance to flow to the roots (d)
KPSIis hydraulic conductivity (cm $d^{-1}$)
RDis equivalent rooting depth (cm).

The actual rate of transpiration (TR) can now be calculated for soil moisture fractions between SM0 and $SMPSI_{leaf}$.

if SMPSI >= (SM0  0.04) then TR = 0 (9.13a)

if (SM0  0.04) > SMPSI > (SM0  0.08) then
TR = TRM * (SM0  0.04  SMPSI) / 0.04 (9.13b)

else if MUR >= TRM then TR = TRM (9.13c) else **TR** = **MUR** **(9.13d)**

9.2 Auxiliary relations

***Surface storage of water (SS)***

**Many agricultural lands are flooded for longer or shorter periods. The obvious example is a rice field where flooding is a cultivation measure but flooding occurs also where dryland crops are grown, e.g. during and directly after a heavy shower or irrigation. The** surface storage capacity **(SSC) represents the equivalent water layer that can be stored on top of the land; it is a function of the slope and surface properties of the land. See Figure 9.2.**

**Fig. 9.2. Storage capacity on top of the soil (SSC).**

**$\sin^2$(SIG  PHI) cotan(SIG + PHI) + cotan(SIG  PHI)**

**SSC = 0.5 * dr * ------- * ---------------------**

sin(SIG) 2 * cos(SIG) * cos(PHI)
(9.14)
where
SSCis equivalent surface storage capacity (cm)
dris surface roughness or furrow depth (cm)
SIGis clod angle or furrow angle (degree)
PHIis average slope of the land (degree).

The clod or furrow angle (SIG) is between 30 and 45 degrees in most cases. The surface roughness (dr) is some 10 cm for contourploughed land, 4 to 6 cm for land tilled with light equipment, and 1 to 2 cm for untilled land.

Note that Equation 9.14 does not apply to bunded rice land where surface storage is determined by effective bund height.

Equation 9.14 describes the theoretical surface storage capacity. Actual surface storage capacity (ASSC) is normally less than SSC because depressions are interconnected and surface roughness decreases in the course of a cropping season. ASSC is between 0 and SSC and is a land (unit) characteristic.
The equivalent water layer that is actually stored on top of the land (SS) is a dependent variable with a value between 0 and ASSC cm.

*Maximum rate of infiltration (IM)*

Infiltration is determined by matric forces and gravity forces. Sorptivity expresses the rate of water absorption which would take place if matric forces were the only driving forces. Table 9.3 gives the reference sorptivity (S0) of completely dry soil materials. Stroosnijder (1976) demonstrates that the actual sorptivity of moist soil (SPSI) changes with the volume fraction of moisture.

SPSI = S0 * (1 SMPSI / SM0) (9.15.1)

where
SPSIis actual sorptivity (cm $d^{-0.5}$)
S0is reference sorptivity (cm $d^{-0.5}$)
SMPSIis volume fraction of moisture in the rooting zone ($cm^3$ $cm^{-3}$)
SM0is total pore fraction of the soil material ($cm^3$ $cm^{-3}$).

Note that SMMUL must be substituted for SMPSI in Equation 9.15.1 if a mulch layer is present.

The influence of matric suction on infiltration decreases as infiltration goes on. Ultimately, sorption becomes negligible and the rate of infiltration approaches the hydraulic permeability of the transmission zone ($K_{tr}$). Indicative values for $K_{tr}$ for each of the standard texture classes are listed in Table 9.3.

Infiltration is determined by matric forces and gravity forces.

$$IM = SPSI * DT^{-0.5} + K_{tr} \qquad (9.15)$$

where
IMis equivalent rate of infiltration (cm $d^{-1}$)
SPSIis actual sorptivity (cm $d^{-0.5}$)
$K_{tr}$is hydraulic permeability of transmission zone (cm $d^{-1}$)
DTis length of interval (d).

Table 9.3. Indicative values for standard sorptivity (S0) and permeability of the transmission zone ($K_{tr}$) of reference soil materials.

| Texture class | S0 (cm $d^{-0.5}$) | $K_{tr}$ (cm $d^{-1}$) |
|---|---|---|
| coarse sand | 50.16 | 119.23 |
| loamy sand | 19.20 | 30.33 |
| fine sand | 21.44 | 17.80 |
| fine sandy loam | 17.57 | 9.36 |
| silt loam | 14.46 | 5.32 |
| loam | 11.73 | 3.97 |
| loess loam | 13.05 | 8.88 |
| sandy clay loam | 19.05 | 16.51 |
| silty clay loam | 6.15 | 1.18 |
| clay loam | 4.70 | 0.76 |
| light clay | 10.74 | 2.66 |
| silty clay | 3.98 | 0.80 |
| heavy clay | 1.93 | 0.15 |

| | | |
|---|---|---|
| **peat** | **7.44** | **1.86** |

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## 9.3 Adjustment of state variables

***Adjusting the volume fraction of moisture in the rooting zone (SMPSI)***

**The water balance equation (Equation 9.1) describes the change of the volume fraction of moisture in soil (RSM, $d^{-1}$) in an interval. Moisture content (SMPSI) and matric suction (PSI) of the rooting zone can now be adjusted.**

**(new)SMPSI = (old)SMPSI + RSM * DT (9.16)**

**(new)PSI = $\exp((1 / GAM * \ln(SM0 / (new)SMPSI))^{0.5})$ (6.14b)**

***Adjusting the depth of the phreatic level (ZT)***

**If the possibility of lateral water flow through the soil is ignored, percolation and capillary rise determine (changes in) the depth of the phreatic level (ZT). The phreatic level rises in the case of percolation and falls with capillary rise.**
**Assume that the volume fraction of moisture below the rooting zone increases linearly from SMPSI $cm^3 cm^{-3}$ at a depth of RD cm to SM0 $cm^3 cm^{-3}$ at the phreatic level. This situation is represented by line 'A' in Figure 9.3.**
**If water flows in or out of the rooting zone, the phreatic level changes by DELTZT cm and a new moisture profile establishes itself between RD and (ZT+DELTZT). See line 'B' in Figure 9.3 for a situation with capillary rise.**

Fig. 9.3. Simplified soil moisture profiles before (line 'A') and after (line 'B') capillary rise.

A total of (CR + *D*) * DT cm water passes the lower boundary of the rooting zone in one interval. This amount is equal to the difference between the areas under lines 'A' and 'B' in Figure 9.3.

DELTZT = 2 * (CR + *D*) * DT / (SM0  SMPSI) (9.17.1)

where
DELTZTis change of the phreatic level (cm).

Note that Equation 9.17.1 assumes a symmetrical moisture profile over the distance from RD to ZT. This may not always be the case.

The depth of the water table at the end of the interval is calculated from Equation 9.17.

(new)ZT = (old)ZT + DELTZT (9.17)

Note that the water table may be controlled externally, e.g. by a nearby river or by artificial drainage. If so, ZT is not a dependent variable but has a fixed value.

*Adjusting the actual surface storage (SS)*

(new)SS = (old)SS  DS * DT (9.18)

where
SSis actual surface storage (cm)
DSis rate at which surface storage decreases (cm $d^{-1}$).

## 9.4 Pathway of calculation and data needs

*Flow diagram*

Figure 9.4 presents a routine to extend the analysis of production situation PS1 to an analysis of situation PS2. The routine bypasses the operation 'cf(water) = 1' in the calculations at PS1 level (see Figure 8.4). Instead, it matches the momentary water needs of the crop against the momentary availability of soil moisture. The calculated sufficiency of moisture supply, i.e. cf(water) with a value between 0 and 1, is used in the calculations.
After adjustment of the state variables SMPSI, PSI, ZT and SS, the calculations continue as in analyses of production situation PS1.

*Data needs*

Table 9.4 lists the additional data needs for analyses of production situation PS2. The data items are grouped in five categories: General data, Management data, Crop data, Weather data and Soil/terrain data.

Note that the data in Table 9.4 have to be collected in addition to the data listed in Table 8.3.

Note further that **tabulated (default) values for crop and soil parameters are mentioned in Table 9.4 to help you fill data gaps. Default values are to be used with caution; they are no substitute for measured values.**

**Fig. 9.4. Flow diagram of a routine to calculate cf(water). Substitution in Figure 8.4 extends the analysis of production situation PS1 to an analysis of situation PS2.**

**Table 9.4. Additional data needs for analyses of production situation PS2.**

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**General data:**
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**Management data:**
IE(consult Irrigation Authority)
SSC(consult local Extension Service)
PSIint(consult local Extension Service)
SSint(consult local Extension Service)
ZTint(consult Irrigation Authority on depth and variability of water table over the growing season)
RDint(consult local Extension Service; Table 5.3).

**Crop data:**
$RDS_{root}$(consult agronomic literature; Table 6.3)
RDm(consult agronomic literature; Table 5.3)
$PSI_{leaf}$(consult agronomic literature; Table 6.2)
TCM(typically between 1.0 and 1.2; Table 5.1A and text).

**Weather data:**
Forcing variables:
PREC(meteorological reports)
E0(meteorological reports)
ET0(meteorological reports).

**<u>Soil and terrain data</u>:**
**SM0(soil reports; Table 6.4)**
**GAM(own measurements; Table 6.4)**
**$PSI_{max}$(Table 6.4)**
**K0(own measurements; Table 6.4)**
**ALFA(Table 6.4)**
**AK(Table 6.4)**
**S0(own measurements; Table 9.3)**
**$K_{tr}$(own measurements; Table 9.3).**
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## 9.5 Calculated examples

**Water-limited production and yield potentials are calculated for the same land-use systems as examined before, i.e. maize on loess loam soil near Xuzhou, in the North China Plain. The sowing density is 12 kg $ha^{-1}$, with 10% seedling mortality, and the crop germinates on 1 June in all scenarios. The initial water depth is set to 500 cm.**
**The analyses are done with PS123, a demonstration model developed to supplement the present text. Option '2' of PS123 follows the flow diagram of Figure 9.4.**
**The relative performance of rainfed maize in different years is presented in Table 9.5 which is basically the same as Table 6.7. However sufficiency of water availibility is not expressed by the ratio of actual and maximum transpiration but by the ratio of the water-limited and biophysical yield and production potentials.**

**Table 9.5. Relative yield and production of land-use systems with rainfed cotton, maize and green peppers near Xuzhou, North China**

Plain. All crops germinate on day # 150 on loess loam soil with a matric suction of 1000 cm and groundwater at 500 cm below the surface of the soil. Sufficiency values from Table 6.7 are included for comparison.

| | cotton | | | maize | | | gr.peppers | | |
|---|---|---|---|---|---|---|---|---|---|
| | rel. yield | rel. prod. | Table 6.7 | rel. yield | rel. prod. | Table 6.7 | | | Table 6.7 |
| 1986 | 0.75 | 0.94 | 0.54 | 0.11 | 0.32 | 0.40 | + | + | 0.11 |
| 1987 | 0.69 | 0.91 | 0.62 | 0.996 | 0.999 | 0.76 | + | + | 0.24 |
| 1988 | 0.51 | 0.89 | 0.49 | 0.83 | 0.88 | 0.54 | + | + | 0.15 |

\+ crop dies of drought stress

Table 9.5 confirms that matching water availability against water needs of a permanently constraintfree crop (Table 6.7) can perhaps indicate the comparative adequacy of water supply but not the absolute sufficiency of water availability.

Note that water stress affects production and yield differently. Drought late in the season often depresses yield more than production. This has practical implications.
For example, cotton producers are not interested in production; they measure the success of farming by the yield of cotton seed and lint. Maize growers may be interested in the production of storage organs (containing the grain) or in the total biomass (silage), or both. Calculating both yield and production potentials helps to make a more meaningful assessment of the suitability of land.

Relative yield and production potentials allow to define potential land suitability classes at the PS2 level. Using class boundaries as suggested by FAO (1978), one would classify the land unit of Table 9.5 as 'very suitable' for rainfed cotton, 'not suitable' for rainfed peppers, and 'suitable' for rainfed maize in normal years (1987 and 1988) but 'not suitable' for rainfed maize in dry years (1986).

Running scenarios with different specifications reveals the merits of defined management packages. The low yield of rainfed maize in 1986 will be examined as an example.
Table 9.6A shows some telling indicators of system performance, calculated for each day in the growing cycle but presented as 10days averages to keep the output concise.

Table 9.6A. Indicators of crop performance in production situation PS2. The values were generated for rainfed maize on loess loam soil near Xuzhou, North China Plain. The crop was sown to 12 kg $ha^{-1}$ (10% mortality) and germinated on 1 June 1986 (Julian day # 150); PSIint was set to 1000 cm, ZTint to 500 cm (variable), surface storage capacity (SSC) is 1 cm and SSint is nil.
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Table 9.6A shows that moisture stress develops between the 30th and 40th day in the growing cycle when cf(water) decreases from 1.00 (no stress) to 0.16. Growth is strongly affected; leaf production stagnates and almost all living leaves die. This reduces consumptive water needs during the remainder of the growing cycle (which explains cf(water) values of 1.00 after day # 210). These values suggest that irrigation is needed on the 30th day in the growing cycle.

Table 9.6B shows what happens if 3 cm water (net !) are applied on 1 July. Growth is prolonged and the leaf area index reaches a high value (8.13) but the transpiration losses associated with such luxuriant growth can not be met without further irrigation. The leaf mass wilts quickly. Grain filling ceases after 80 days and although the production of cobs increases from 1510 kg $ha^{-1}$ to 2604 kg $ha^{-1}$, it is unlikely that the production of grain will improve much.

A scenario with repeated irrigations, viz. 3 cm water on day # 180 and 6 cm on day # 190, promises a total biomass production of 18671 kg $ha^{-1}$ with a yield component of 7904 kg $ha^{-1}$. Running more scenarios, with different timing and application rates, allows to identify promising irrigation strategies.

Table 9.6B. Same scenario as in Table 9.6A but with 3 cm of irrigation water applied on Julian day # 180.

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Fig. 9.5. Water-limited yield and production potentials of rainfed maize as a function of phreatic depth. Other system specifications are as in previous calculations.

Figure 9.5 shows the production and yield potentials of similar systems but with fixed groundwater depth. The figure suggests that water control by pumping would increase agricultural output. However (salinity) problems associated with shallow groundwater have not been considered in the analyses!

Note that the calculated examples are neither based on reliable primary information nor are the results verified in field experimentation. The exercises in this section merely demonstrate the procedure (and are great entertainment).

## 9.6 Role of production situation PS2 in land suitability assessment

Worldwide, shortage of water is one of the greatest limitations to agriculture. Potential land suitability at the level of production situation PS2 indicates the relative potential of land-use systems at a level of investments that is of interest to all but the poorest farmers. Farmers who cannot remedy limitations caused by shortage or imbalance of nutrients or occurrence of weeds, pests and diseases, do not work in production situation PS2. Their production environment is far too complex to be modelled. See Figure 9.6.

Fig. 9.6. Inputoutput relations for production situations PS-1 (X1Y1) and PS2 (X2Y2), and for a poor farmer (XnYn) who has no unused resources and whose actual yield and production represent the potential. PSn is too complex to be handled with simulation techniques.

This chapter must not be concluded without a word of caution. Quantified land-use systems analysis is a better tool for assessing the suitability of land and for signalling misuse of resources. However... .

-The approach is a new one and not free from growing pains. It needs to be further improved and tested. YOU are invited to contribute.

-The potential of land-use systems was discussed without paying attention to longterm sustainability and impact on the environment.

-Quantified methods generate numbers. Planners and decision makers love numbers. They look so much more trustworthy than qualitative assessments that can never quite conceal the land evaluator's doubts and reservations. We calculate and we doubt.

# CHAPTER 10

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## PS3: ASSESSING FERTILIZER REQUIREMENTS

## 10. PS3: ASSESSING FERTILIZER REQUIREMENTS

**Production situation PS3 examines 'availability of nutrients to a crop'. This land quality is determined by**
-supply of nutrient elements **to the rooting zone (by mineralization of organic matter, dissociation of minerals, atmospheric deposition, autotrophic and symbiotic binding of atmospheric nitrogen, application of manure or fertilizer, etc)**
-loss of nutrient elements **from the rooting zone (by leaching, volatilization, uptake, erosion, etc)**
-inactivation of nutrient elements **(in compounds of low solubility such as stable organomineral compounds, or by the biomass)**
-numerous interactions **(synergisms, antagonisms).**
**The complexity and dynamics of nutrient supply to crops precludes to calculate yield and production potentials as dependent variables in a production situation that is conditioned by temperature, photosynthetically active radiation, availability of water** and **availability of plant nutrients. It is possible however to calculate the approximate input of fertilizer(s) needed to meet a set production target. This target cannot exceed the water-limited production potential.**

**The** fertilizer requirement **for meeting a production target can be calculated if one knows**
**-how much of each nutrient (element) the crop must minimally take up for target production. This is the** nutrient uptake requirement **for nutrient 'el' (NUR(el))**
**-how much of NUR(el) is furnished by the system itself. This is the** base uptake **of nutrient 'el' (BU(el))**
**-which fraction of each (fertilizer) element is actually taken up by the crop. This is the** recovery fraction **of nutrient 'el' (RF(el)).**

### 10.1 Uptake of nutrients by crops

***Nutrient uptake requirement (NUR(el))***

**The nutrient status of crops is judged by the levels of nutrient elements in the economic produce or** 'yield' **(normally the storage organ), and the crop residue or** 'straw' **(calculated as the difference between target production and target yield). Pot trials and field experiments have**

shown that plants cannot grow normally if they cannot maintain specific minimum concentrations of nutrient elements in yield and straw.

Table 10.1 lists indicative values for the minimum concentrations of nitrogen, phosphorus and potassium in the yield and straw of four types of crop.

Table 10.1. Indicative minimum concentrations of nitrogen (N), phosphorus (P) and potassium (K) in yield (MCY(el)) and straw (MCSTR(el)) of four types of crop. Source: van Keulen (1986).

| | MCY(el) (kg $kg^{-1}$) | | | MCSTR(el) (kg $kg^{-1}$) | | |
|---|---|---|---|---|---|---|
| | N | P | K | N | P | K |
| Grain crops | 0.01 | 0.0011 | 0.003 | 0.004 | 0.0005 | 0.008 |
| Oil seeds | 0.0155 | 0.0045 | 0.0055 | 0.0034 | 0.0007 | 0.008 |
| Root crops | 0.008 | 0.0013 | 0.012 | 0.012 | 0.0011 | 0.0033 |
| Tuber crops | 0.0045 | 0.0005 | 0.005 | 0.015 | 0.0019 | 0.005 |

The nutrient uptake requirement is calculated by multiplying the dry masses of yield and straw by their respective minimum element concentrations.

$$NUR(el) = Ytarget * MCY(el) + (TDMtarget - Ytarget) * MCSTR(el) \quad (10.1)$$

where
NUR(el)is nutrient uptake requirement, i.e. net quantity of nutrient 'el' that must be taken up for target production (kg $ha^{-1}$)
MCY(el)is minimum concentration of nutrient 'el' in economic produce (kg $kg^{-1}$)
MCSTR(el)is minimum concentration of nutrient 'el' in crop residue (kg $kg^{1}$)
Ytargetis (target) yield (kg $ha^{-1}$).

For example, for a scenario with a water-limited yield potential of 7 900 kg $ha^{-1}$ and a potential biomass production of 18 670 kg $ha^{-1}$, the uptake

**requirements for nitrogen (N), phosphorus (P) and potassium (K) would be**
**-NUR(N) = 7 900 * 0.01 + (18 670 - 7 900) * 0.004 = 122 kg ha$^{-1}$**
**-NUR(P) = 7 900 * 0.0011 + (18 670 - 7 900) * 0.0005 = 14.1 kg ha$^{-1}$**
**-NUR(K) = 7 900 * 0.003 + (18 670 - 7 900) * 0.008 = 110 kg ha$^{-1}$**

Note that **calculated nutrient uptake requirements are** minimum **requirements; a crop could take up more than NUR(el) kg ha$^{-1}$ but this would not result in more production or yield. It could possibly improve the quality of the product. For example, the baking quality of wheat flour improves noticeably if the crop enjoyed 'luxury consumption' of nitrogen, i.e. if the nitrogen concentration of the grain is higher than 1% of the dry mass of the grain.**

**Yielduptake response curves are normally as represented by the dotted line in Figure 10.1. If it is ignored that production of harvested plant parts starts only after some vegetative growth has taken place, yielduptake curves can be broken down into two linear trajecta.**

**Figure 10.1 shows the theoretical maizeyieldtonitrogenuptake response curve for a scenario with a target yield of 7 900 kg ha$^{-1}$ (dry storage organ) and a target production of 18 670 kg ha$^{-1}$ (total dry biomass). The figure suggests that 1 kg nitrogen taken up gives a return of 7 900 / 122 = 64.8 kg storage organ,** until NUR(N) is met.

**Fig. 10.1. Theoretical maizeyieldtonitrogenuptake response curve.**

***Base uptake (BU(el))***

**Fertilizer trials are conducted under PS3 conditions; all plants in an experiment grow under the same temperature, solar radiation and water supply, and weeding, plant protection and harvesting are optimum.**
**Assume that Figure 10.2 stems from a field experiment. The water-limited yield and production potentials are 7 900 kg ha$^{-1}$ and 18 670 kg ha$^{-1}$, respectively. The unfertilized plot (the 'control plot' of the experiment) produced a** control yield **of 1 000 kg ha$^{-1}$. The yieldtonitrogenuptake ratio of 64.8 kg kg$^{-1}$ implies that the** base uptake **of nitrogen (BU(N)) amounted to 1 000 / 64.8 = 15.4 kg ha$^{-1}$.**

**BU(el) = CY / (Ytarget / NUR(el))** **(10.2)**

**where**
**BU(el)is base uptake of nutrient 'el' (kg ha$^{-1}$)**
**CYis control yield (kg ha$^{-1}$).**

Fig. 10.2. Observed yieldtonitrogenfertilizer response curve.

Note that farmers' fields are not cropped to PS3 specifications; they are not entirely free from weeds, pests or diseases. Farmers normally achieve lower yields from an unfertilized field than the control yield in a properly conducted fertilizer experiment.

On the other hand, even fertilizer experiments may be misleading. They normally include many fields, each planted to the same variety but with different fertilizer applications. The trials are laid out over several years and the location of the control plot(s) changes each year. Nutrients applied but not taken up by the crop in one year may, partly, remain in the surface soil and increase the base uptake from that field in a later experiment.

The paucity of reliable experimental data forces land-use analysts to rely heavily on information from farmers. If one takes care to consult only the best farmers in the region, one will underestimate base uptake only slightly.

*Element recovery from fertilizer (RF(el))*

In the experiment of Figure 10.2, the nitrogen uptake requirement (NUR(N)) is met by applying 400 kg urea $ha^{-1}$. Urea has a nitrogen content of 46% (Table 10.2). In other words, 0.46 * 400 kg $ha^{-1}$ must be applied to bridge the gap between nitrogen uptake requirement (122 kg $ha^{-1}$) and base uptake of nitrogen (15.4 kg $ha^{1}$). The recovery fraction of fertilizernitrogen, i.e. the ratio of applied nitrogen and nitrogen taken up, amounts to (122 kg $ha^{-1}$ 15.4 kg $ha^{-1}$) / (0.46 kg $kg^{-1}$ * 400 kg $kg^{-1}$), or 0.58.

In theory the recovery fraction can assume any value between 0 and 1.

In practice it varies from less than 0.1 to, say, 0.8. Recovery of nitrogen, for example, is reduced by volatilization of ammoniacal nitrogen, leaching of nitrate ions, escaping gaseous Ncompounds and immobilization of nitrogen by the biomass and by the soil.
Improving uptake of nutrients by adapting management attributes is a basic characteristic of agriculture. RF(el) is improved by optimizing the selection of types or combinations of fertilizers, and by optimizing the timing and mode of fertilizer application. Banded application or deep placement of fertilizers is common practice where immobilization of broadcast nutrients is high. Losses of fertilizer elements can generally be reduced (and recovery improved) if only small doses of fertilizer are given at a time, so that most of the nutrient(s) applied can be absorbed by the roots in a short time.

Table 10.2. Nutrient concentrations of commercial N, P, and Kfertilizers (EC(el), kg kg[-1]).

| | N | | | P | K |
|---|---|---|---|---|---|
| | as $NO_3$ | as $NH_4$ | other | | |
| ammonium sulphate | | 0.21 | | | |
| calcium nitrate | 0.145 | 0.01 | | | |
| Chile salpeter | 0.16 | | | | |
| muriate of ammonium | | 0.24 | | | |
| potassium nitrate | 0.13 | | | | 0.37 |
| urea | | | 0.46 | | |
| monoammonium phosphate | 0.11 | | | 0.21 | |
| single superphosphate | | | | 0.08 | |
| double superphosphate | | | | 0.17 | |
| triple superphosphate | | | | 0.19 | |
| basic slag/rock phos. | | | | 0.07 | |
| muriate of potash | | | | | 0.46 |
| KMg sulphate | | | | | 0.22 |
| potassium sulphate | | | | | 0.40 |

Broadcasting urea at the time of transplanting is a common cultivation

measure in regions with flooded rice fields. Normally, only a small fraction of the ureanitrogen is recovered by the crop. The favourable temperature and high oxygen content of the shallow water layer on top of a rice field ensure rapid microbial transformation of ureaN to ammonium ions ($NH_4^+$) and subsequently to nitrate ions ($NO_3^-$). The nitrate ions move downward with percolating water or by diffusion. Deeper soil layers have become depleted of oxygen by microbes that decompose soil organic matter. These microbes welcome the incoming nitrate as an oxygen source and reduce it to gaseous $N_2$ and $N_2O$. These escape to the atmosphere.
The problem can be solved by adapting the cultivation practice. 'Placing' urea directly in the oxygenpoor layer raises RF(N) from less than 0.2 to 0.5 or more because ureaN is converted only to $NH_4^+$ions. These are not reduced to gaseous Nforms and are to a considerable extent retained (adsorbed) by negatively charged clay and organic matter.

The efficiency of fertilizer use is largely determined by the skill and motivation of the individual farmer. RF(N) and RF(K) values of 0.5 kg $kg^{-1}$ are quite normal; slightly higher values can be expected where management/technology is 'advanced' and lower values in regions where management is only 'elementary'. Where RF(N) or RF(K) are clearly less than 0.5 kg $kg^{-1}$, it makes sense to critically examine the current cultivation practice.
The chemistry of phosphorus in soils is more complex than that of nitrogen or potassium; RF(P) is largely determined by soil conditions. Table 10.3 lists broad groups of soil materials arranged according to increasing phosphorus retention (and decreasing phosphorus recovery) from superphosphate.

Table 10.3. Recovery of phosphorus from broadcast superphosphate as determined by soil material.

| RF(P)range (kg $kg^{-1}$) | Soil material |
|---|---|
| 0.30 | Quartzitic sand |
| . | Organic soil material |
| . | Young, neutral, coarse and medium textured alluvial material |
| 0.15 | Young, nearneutral alluvial clay |
| . | Nearneutral, (strongly) humic soil material |
| . | Weakly to medium acid, wellstructured clay |

| | |
|---|---|
| . | Vertic 2:1 clays |
| 0.10 | Neutral to weakly alkaline, calcareous soil material |
| . | Old, acid, red or yellow soil material, rich in iron and aluminium |
| . | Very acid 'podsolized' soil material |
| . | Strongly acid oxydized pyritic material |
| 0.02 | Volcanic soil material, rich in allophane |

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## 10.2 Fertilizer requirement

**The relation between nutrient uptake, yield, and fertilizer application is depicted in a 4quadrant diagram in Figure 10.3.**
**-the upper right quadrant is identical with Figure 10.1**
**-the upper left quadrant is a mirror image of Figure 10.2**
**-the lower left quadrant presents the nutrient content of the fertilizer (Table 10.2)**
**-the lower right quadrant shows which fraction of the nutrient added is recovered by the crop (RF(el)).**

**Fig. 10.3. Maize yield, application of urea, application of nitrogen, and uptake of nitrogen in the sample PS3 scenario.**

Note that **any quadrant of Figure 10.3 can be constructed if the contents of the other three quadrants are known.**

**Figure 10.3 demonstrates that application of FR(f) kg ha$^{-1}$ of fertilizer 'f' (with a nutrient content of EC(el) kg kg$^{-1}$) is required to increase uptake of nutrient 'el' from BU(el) to NUR(el) kg ha$^{-1}$.**

**FR(f) = (NUR(el) - BU(el)) / (EC(el) * RF(el))** **(10.3)**

**where**
**FR(f)is fertilizer requirement (kg ha$^{-1}$)**
**NUR(el)is nutrient uptake requirement for nutrient 'el' (kg ha$^{-1}$)**
**BU(el)is base uptake of nutrient 'el' (kg ha$^{-1}$)**
**EC(el)is mass fraction of nutrient 'el' in fertilizer 'f' (kg kg$^{-1}$)**
**RF(el)is recovery fraction of fertilizernutrient 'el' (kg kg$^{-1}$).**

**Linear relations in all quadrants of Figure 10.3 suggest that uptake of nutrient elements increases proportionally with fertilizer application as long as the nutrient uptake requirement is not met. This is not always so in practical farming.**

**Consider, for example, a land-use system with a phosphorusfixing soil. Application of a low dose of Pfertilizer may not result in a measurable yield increase at all because the phosphorus added is quickly immobilized. Application of a higher dose is needed to saturate the immediate phosphorus fixing capacity of the soil and bring about the desired increase in production.**

Note that **variable RF(el) will not be considered in this text.**

## 10.3 Identifying elements in short supply

**Nutrient availability is clearly insufficient when the water-limited production potential is much greater than the control yield of a properly**

conducted fertilizer experiment. The control field must be free from limitations to plant growth that are not considered in production situation PS3 (no micronutrient deficiencies or toxicities, no mechanical obstruction to root growth, etc). Limiting nutrient concentrations can be identified by

-chemical analysis of plant tissue

-interpretation of deficiency symptoms like discolouration or necrosis of plant organs.

(Both methods have the disadvantage that conclusions can only be drawn when the damage is already done. Facilities for tissue analyses are not always available and deficiency symptoms are not always unambiguous.)

Analyses of plant tissue from fertilizer experiments suggest that the maximum and minimum concentrations of nitrogen and phosphorus in crops differ by a factor four at the most (van Keulen, 1986). In theory the ratio of P and Nconcentrations in living tissue could vary sixteenfold; in practice P/Nratios vary only fourfold, between P/N = 0.04 and P/N = 0.15.

When the P/Nratio is close to 0.04, absolute phosphorus shortage inhibits further uptake of nitrogen (even if it is present in the soil). When the P/Nratio is close to 0.15, relative phosphorus shortage (induced by absolute nitrogen shortage) inhibits further uptake of phosphorus. The P/Nratio is normally close to 0.1 when both elements are available in sufficient amounts.

Nitrogen shortage is the commonest nutrient disorder. Crops need comparatively large quantities of nitrogen and the soil is an open system for nitrogen. If the nitrogen concentrations of yield and straw are well above the minimum concentrations suggested in Table 10.1, shortage of nitrogen is unlikely and other elements must be checked. Phosphorus shortage is then a likely possibility. Potassium deficiency is much less common, particularly in the tropics.

If nitrogen concentrations are close to the tabulated minimum values, a nitrogen fertilizer might be applied. Eliminating the nitrogen deficiency improves growth; the demand for other nutrients increases as well. The effect of nitrogen application remains below expectation if the increased NUR(P) and NUR(K) cannot be met by the soil. Phosphorus and/or potassium fertilizer must then be applied in addition to nitrogen fertilizer.

Soil analyses **have little predictive value and are no alternative to tissue analysis or interpretation of deficiency symptoms. 'Total element' analyses of soil material can perhaps expose structural shortage of nutrient elements, e.g. in mineralogically poor soils or in overexploited and chemically exhausted soils, but give no information on the exact amounts of nutrient elements that a crop could take up from the rooting zone.**

**Analyses of** 'available' **elements in soil materials promise more than they deliver. The amounts of 'available' elements are estimated by treating a soil sample with a mild extraction agent that simulates the action of plant roots in taking up nutrients from the soil. It might not be unrealistic to hope for a correlation between the concentration of an element in the soil extract and the concentration in plants grown on that same soil material *if the plants are grown under constant (controlled) conditions*, e.g. in a climate chamber. Since no one can guarantee that conditions in actual farming will be the same as those for which the correlation was established, 'available element' data are misleading.**

## 10.4 Data needs

**If data from well documented fertilizer experiments are available, FR(f) can be calculated from the following information.**
**control production and yield (kg ha$^{-1}$)**
**yield and production from one or more fertilized plot(s) (kg ha$^{-1}$)**
**fertilizer selection and timing and mode of fertilizer applications (kg ha$^{-1}$)**
**target production and yield (kg ha$^{-1}$).**

**If data from fertilizer experiments are not available, a value for FR(f) can be approximated by estimating control yield and production with "best farmers' information" and using generic element recovery values (RF(el)), postulated in accordance with the level of farm management, the available technology and the soil conditions of the land unit.**

## 10.5 Calculated examples

***One element in short supply***

**The theory of nutrient uptake and fertilizer needs was discussed for a situation in which nitrogen deficiency constrained a maize crop. The**

**same reasoning applies to other crops and to (application of) other nutrients.**

**For example, if shortage of phosphorus were responsible for the (low) control yield of 1000 kg dry maize ha$^{-1}$, one could calculate the approximate Pfertilizer requirement as follows (target yield and production are as in previous examples).**

**- NUR(P) = 7 900 * 0.0011 + (18 670  7 900) * 0.0005 = 14.1 kg ha$^{-1}$**

**-Ytarget / NUR(P) = 7 900 / 14.1 = 560 kg kg$^{-1}$**

**-BU(P) = 1 000 / 560 = 1.79 kg ha$^{-1}$**

**Farmers on phosphorusfixing soils normally use rock phosphate or basic slag as a phosphorus fertilizer. Table 10.2 shows that rock phosphate has a Pcontent of some 7% by weight. The low solubility of rock phosphate explains the low recovery of phosphorus from rock phosphate (3 to 5%). If RF(P) is arbitrarily set to 0.04 kg kg$^{1}$, the approximate requirement for rock phosphate can be calculated from Equation 10.3.**

**FR(rock phosphate) = (14.1 kg ha$^{-1}$ - 1.79 kg ha$^{-1}$) / (0.07 kg kg$^{-1}$ * 0.04 kg kg$^{-1}$) = 4400 kg ha$^{-1}$.**

**This figure must be interpreted as follows: 'to eliminate the phosphorus limitation for a number of years, rock phosphate must be applied at a rate of some 4.5 tons per hectare'. (Most phosphorus not taken up in one growing season remains in the soil for later use.)**

**If triple superphosphate (TSP) is used instead of rock phosphate, EC(P) = 0.19 kg kg$^{-1}$ (Table 10.2) and RF(P) = 0.08 kg kg$^{-1}$ (Table 10.3). The calculated FR(TSP) amounts to (14.1 kg ha$^{-1}$  1.79 kg ha$^{-1}$) / (0.19 kg kg$^{-1}$ * 0.08 kg kg$^{-1}$) = 810 kg ha$^{-1}$. The high cost of TSP and its greater solubility (less is carried over to later crops) make broadcasting a less attractive proposition. To increase recovery (and reduce costs) on phosphorusfixing soils, TSP is** placed **in the direct vicinity of the roots.**

***More than one element in short supply***

**If more than just one element is in short supply, e.g. nitrogen** and **phosphorus, it is possible to remedy the phosphorus deficiency with a generous Pfertilizer application at the beginning of the growing season. The nitrogen fertilizer requirement can then be calculated as explained. A blanking dressing of slowly soluble phosphorus fertilizer does not**

harm the environment but a (too) high nitrogen dressing is not advisable. Excessive loss of nitrogen and undesirable physiological reactions, e.g. lodging, could be the result.

If the control crop shows symptoms of phosphorus and nitrogen deficiency, it may be assumed that the concentrations of both elements approach minimum levels. In the sample scenario (yieldto(N)uptake ratio of 64.8 kg $kg^{-1}$ and a control yield of 1000 kg $ha^{-1}$), the base uptake of nitrogen amounts to BU(N) = 1 000 / 64.8 = 15.4 kg $ha^{-1}$. The input of urea needed for a yield of 7 900 kg $ha^{-1}$ at an 'average' nitrogen recovery of 0.5 kg $kg^{-1}$ amounts to (122 kg $ha^{1}$ 15.4 kg $ha^{-1}$) / (0.46 kg $kg^{-1}$ * 0.5 kg $kg^{-1}$) = 463 kg $ha^{-1}$.
This urea requirement (say, 9 bags of 50 kg each) must be applied in addition to the calculated rock phosphate requirement of 4.5 tons $ha^{-1}$.

If the control crop shows symptoms of Pdeficiency but no signs of nitrogen deficiency, there is sufficient nitrogen available in the soil to allow a base uptake of nitrogen of 15.4 kg $ha^{-1}$. However it is not certain that the soil can meet the nitrogen uptake requirement for (much higher) target production. Nitrogen fertilizer must still be used but the dose could be less than the 463 kg (urea) $ha^{-1}$ calculated in the foregoing section. Consider the following reasoning.

With phosphorus in short supply, the overall Pconcentration of the plant tissue is close to NUR(P) / TDMtarget = 14.1 kg $ha^{-1}$ / 18 670 kg $ha^{-1}$ = 0.00075 kg $kg^{-1}$. Uptake of nitrogen is impaired by shortage of phosphorus (relative Nshortage); the overall P/Nratio in the control crop is likely to be close to 0.04. This puts the overall concentration of nitrogen in the control crop at some 0.00075 / 0.04, or 0.0189 kg $kg^{-1}$.

The yield/strawratio of the control crop is between the yield/strawratio of the target (i.e. 7 900 kg $ha^{-1}$ / (18 670 kg $ha^{-1}$ - 7 900 kg $ha^{-1}$) = 0.73 kg $kg^{-1}$), and 1.0 (the normal value for constraintfree shortstraw cereal crops). The total dry mass on the control field must have been between (1 000 + 1 000 / 1.0) = 2000 kg $ha^{-1}$ and (1 000 + 1 000 / 0.73) = 2 370 kg $ha^{-1}$.
The base uptake of nitrogen is found by multiplying the total mass of the control crop by the overall concentration of nitrogen: BU(N) = (2000 to 2370) kg $ha^{-1}$ * 0.0189 kg $kg^{-1}$ = 37.8 to 44.8 kg $ha^{-1}$.
The approximate urea requirement can now be calculated from Equation 10.3. FR(urea) = (122 kg $ha^{-1}$ - (37.8 to 44.8) kg $ha^{-1}$) / (0.46 kg kg⁻

**$^{1}$ * 0.5 kg kg$^{-1}$) = 336 to 366 kg ha$^{-1}$. This corresponds with 7 bags (urea) ha$^{-1}$.**

**The final assessment under this scenario would thus be: 'Apply, in addition to a blanking dressing of 4.5 tons of rock phosphate, not more than 9 bags and not less than 7 bags of urea per hectare to achieve the water-limited production potential'.**

== NOTES ==

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# APPENDIXES

A1. RATING CRITERIA FOR THE BURA WEST IRRIGATION SCHEME
**(Source: Muchena, 1987)**

**The rating specifications presented closely follow the guidelines issued by the Kenya Soil Survey (KSS, 1977) except for a few modifications made by Muchena to meet the particular conditions of the Bura West Irrigation Scheme.**

Available water capacity (Awc)

**The available water capacity (Awc) is determined by subtracting moisture content at permanent wilting point (pF 4.2) from moisture content at field capacity (set at pF 2.0) and multiplying the result by the 'effective rooting depth'. The latter is one metre or the depth to an impermeable or limiting layer if shallower.**

| Rating | Awc (cm water) |
|---|---|
| 1 | >16.0 |
| 2 | 12.1-16.0 |
| 3 | 8.1-12.0 |
| 4 | 4.0-8.0 |
| 5 | <4.0 |

**The final rating of available water capacity is adjusted for hindrances to root growth. For example, if a natric horizon occurs close to the surface, the rating is downgraded two classes.**

Absence of salinity (ASal)

**Two depths are considered: 030 cm (where most of the roots are present), and 30100 cm.**

| Rating | ASal; the highest ECe reading within: | |
|---|---|---|
| | 030 cm | 30100 cm |
| 1 | <2.0 | <4.0 |
| 2 | 2.0-4.0 | 4.0-8.0 |
| 3 | 4.1-8.0 | 8.1-15.0 |
| 4 | 8.1-15.0 | 15.1-30.0 |

| | | |
|---|---|---|
| 5 | >15.0 | >30.0 |

**The most limiting factor determines the final rating. For example, if the rating of ASal is '1' within 030 cm and '2' within 30100 cm, then the final rating is '2'.**

Absence of sodicity (ASod)

**Separate ratings are given for two depths: 030 cm and 30100 cm. For each depth the highest exchangeable sodium percentage (ESP) measured is rated; the most limiting figure determines the final rating.**

| Rating | ASod; the highest ESP reading within: 030 cm | 30100 cm |
|---|---|---|
| 1 | <6.0 | <6.0 |
| 2 | 6.0-10.0 | 6.0-15.0 |
| 3 | 10.1-15.0 | 15.1-40.0 |
| 4 | 15.1-40.0 | >40.0 |
| 5 | >40.0 | |

Availability of oxygen for root growth (Oxy)

**The soil drainage classes specified in the Soil Survey Manual (Soil Survey Staff, 1951) are used for rating oxygen availability.**

| Rating | Oxy (soil drainage class) |
|---|---|
| 1 (very high) | well drained to excessively drained |
| 2 (high) | moderately well drained |
| 3 (moderate) | imperfectly drained |
| 4 (low) | poorly drained |
| 5 (very low) | very poorly drained |

Conditions for germination (Ger)

**The structure of the topsoil and the susceptibility to crusting are determine the conditions for germination. Susceptibility to crusting is**

judged (on a scale from 0 to 10) from laboratory tests and field observations.

| Rating | Topsoil structure | Relative susceptibility to crusting |
|---|---|---|
| 1 (very high) | single grain, crumb, granular | 3-4 |
| 2 (high) | medium subangular blocky | 5 |
| 3 (moderate) | coarse subangular blocky | 6 |
| 4 (low) | massive | 7-8 |
| 5 (very low) | platy | 9-10 |

Availability of nutrients (Nut)

The ratings are based on the soil's exchange properties, 'available' nutrients (Mehlich et al, 1962), organic carbon percentage, pH$H_2O$ and POlsen value. The negative effects of salinity and sodicity on soil fertility are taken into account in separate ratings for ASal and ASod.

| Rating | CEC | orgC | av.P | K | Ca | Mg | pH |
|---|---|---|---|---|---|---|---|
| | (cmol/kg) | (%) | (ppm) | (------cmol/kg-------) | | | (1:2.5) |
| 1 (high) | >16 | >2 | >20 | >0.5 | >6 | >3 | 5.66.8 |
| 2 (moderate) | 61612 | | 1120 | 0.20.5 | 36 | 13 | 6.97.5 |
| 3 (low) | 36 | 0.51 | 510 | 0.10.2 | 13 | 0.51 | 7.68.7 |
| 4 (very low) | <3 | <0.5 | <5 | <0.1 | <1 | <0.5 | >8.7 |

Available foothold for roots (Rts)

| Rating | Rootable depth | Descriptive class |
|---|---|---|
| 1 (very high) | >120 | very deep |
| 2 (high) | 80 - 120 | deep |
| 3 (moderate) | 50 - 80 | moderately deep |
| 4 (low) | 25 - 50 | shallow |
| 5 (very low) | <25 | very shallow |

Workability and ease of tillage (Wrk)

**The rating is based on dry and moist topsoil consistence (030 cm).**

| **Subrating** | **Dry consistence** | **Subrating** | **Moist consistence** |
|---|---|---|---|
| **1** | **loose** | **1** | **loose** |
| **2** | **soft** | **2** | **very friable** |
| **3** | **slightly hard** | **3** | **friable** |
| **4** | **hard** | **4** | **firm** |
| **5** | **very/extremely hard** | **5** | **very/extremely firm** |

| **FINAL RATING** | **Sum of subratings** |
|---|---|
| **1** | **2-3** |
| **2** | **4-5** |
| **3** | **6-7** |
| **4** | **8-9** |
| **5** | **10** |

Possibilities for drainage (Drain)

**This land quality is rated on the assumption that the compounded effects of natural drainage conditions, texture, presence of impermeable layers, type of clay minerals and calcium carbonate status are mirrored by the infiltration rate.**

| **Rating** | **Infiltration rate (cm/hour)** |
|---|---|
| **1** | **0.8-3.5** |
| **2** | **0.5-0.8 or 3.57.0** |
| **3** | **0.2-0.5 or 7.111.0** |
| **4** | **0.1-0.2 or 11.112.5** |
| **5** | **<0.1 or >12.5** |

**If impermeable substrata hinder drainage, the ratings are downgraded in accordance with the severity of the limitation. For example, if an impermeable substratum occurs at 50 cm from the surface, the final**

**rating is 5 irrespective of the infiltration rate of the upper layer(s).**

A2. AEZ SOIL RATINGS

**(FAO World Soil Resources Report 48; 8285)**

**GLEYSOLS**

| | Wheat | | Sorghum | | Millet | | Beans | |
|---|---|---|---|---|---|---|---|---|
| | **low** | **high** | **low** | **high** | **low** | **high** | **low** | **high** |
| **Eutric Gleysol** | **N2** | **N1N2** | **N2** | **N1N2** | **N2** | **N1N2** | **N2** | **N1N2** |
| **Calcaric Gleysol** | **N2** | **N1N2** | **N2** | **N1N2** | **N2** | **N1N2** | **N2** | **N1N2** |
| **Dystric Gleysol** | **N2** | **N1N2** | **N2** | **N1N2** | **N2** | **N1N2** | **N2** | **N1N2** |
| **Mollic Gleysol** | **N2** | **N1N2** | **N2** | **N1N2** | **N2** | **N1N2** | **N2** | **N1N2** |
| **Humic Gleysol** | **N2** | **N1N2** | **N2** | **N1N2** | **N2** | **N1N2** | **N2** | **N1N2** |
| **Plinthic Gleysol** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** |
| **Gelic Gleysol** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** |

| | Maize | | Soya | | Cotton | | Wh. Potato | |
|---|---|---|---|---|---|---|---|---|
| | **low** | **high** | **low** | **high** | **low** | **high** | **low** | **high** |
| **Eutric Gleysol** | **N2** | **N1N2** | **N2** | **N1N2** | **N2** | **N1N2** | **N2** | **N1N2** |
| **Calcaric Gleysol** | **N2** | **N1N2** | **N2** | **N1N2** | **N2** | **N1N2** | **N2** | **N2** |
| **Dystric Gleysol** | **N2** | **N1N2** | **N2** | **N1N2** | **N2** | **N1N2** | **N2** | **N1N2** |
| **Mollic Gleysol** | **N2** | **N1N2** | **N2** | **N1N2** | **N2** | **N1N2** | **N2** | **N1N2** |
| **Humic Gleysol** | **N2** | **N1N2** | **N2** | **N1N2** | **N2** | **N1N2** | **N2** | **N1N2** |
| **Plinthic Gleysol** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** |
| **Gelic Gleysol** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** |

| | Sw. Potato | | Sugarcane | | Cassava | | Rice | |
|---|---|---|---|---|---|---|---|---|
| | **low** | **high** | **low** | **high** | **low** | **high** | **low** | **high** |
| **Eutric Gleysol** | **N2** | **N1N2** | **S2N2** | **S2N1** | **N2** | **N2** | **S1** | **S1** |
| **Calcaric Gleysol** | **N2** | **N1N2** | **S2N2** | **S2N1** | **N2** | **N2** | **S1** | **S1** |
| **Dystric Gleysol** | **N2** | **N1N2** | **S2N2** | **S2N1** | **N2** | **N2** | **S1** | **S1** |
| **Mollic Gleysol** | **N2** | **N1N2** | **S2N2** | **S2N1** | **N2** | **N2** | **S1** | **S1** |
| **Humic Gleysol** | **N2** | **N1N2** | **S2N2** | **S2N1** | **N2** | **N2** | **S1** | **S1** |
| **Plinthic Gleysol** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** | **S2N2** |
| **Gelic Gleysol** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** |

**REGOSOLS**

| | Wheat | | Sorghum | | Millet | | Beans | |
|---|---|---|---|---|---|---|---|---|
| | **low** | **high** | **low** | **high** | **low** | **high** | **low** | **high** |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Eutric Regosol** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** |
| **Calcaric Regosol** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S2** | **S2** |
| **Dystric Regosol** | **S2** | **S1** | **S2** | **S1** | **S2** | **S1** | **S2** | **S1** |
| **Gelic Regosol** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** |

| | Maize | | Soya | | Cotton | | Wh. Potato | |
|---|---|---|---|---|---|---|---|---|
| | **low** | **high** | **low** | **high** | **low** | **high** | **low** | **high** |
| **Eutric Regosol** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** |
| **Calcaric Regosol** | **S2** | **S2** | **S2** | **S2** | **S1** | **S1** | **S2N2** | **S1S2** |
| **Dystric Regosol** | **S2** | **S1** | **S2** | **S1** | **S2** | **S1** | **S2** | **S1** |
| **Gelic Regosol** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** |

| | Sw. Potato | | Sugarcane | | Cassava | | Rice | |
|---|---|---|---|---|---|---|---|---|
| | **low** | **high** | **low** | **high** | **low** | **high** | **low** | **high** |
| **Eutric Regosol** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S2** | **S2** |
| **Calcaric Regosol** | **S1** | **S1** | **S1** | **S1** | **S2** | **S2** | **S2** | **S2** |
| **Dystric Regosol** | **S2** | **S1** | **S2** | **S1** | **S2** | **S1** | **S2** | **S2** |
| **Gelic Regosol** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** |

LITHOSOLS **N2 for all crops (at both input levels)**

ARENOSOLS

| | Wheat | | Sorghum | | Millet | | Beans | |
|---|---|---|---|---|---|---|---|---|
| | **low** | **high** | **low** | **high** | **low** | **high** | **low** | **high** |
| **Cambic Arenosol** | **N2** | **S2N2** | **S2** | **S2** | **S2** | **S1** | **S2** | **S2** |
| **Luvic Arenosol** | **N2** | **S2N2** | **S2** | **S2** | **S2** | **S1** | **S2** | **S2** |
| **Ferralic Arenosol** | **N2** | **N2** | **S2N2** | **S2N2** | **S2** | **S1N2** | **S2N2** | **S2N2** |
| **Albic Arenosol** | **N2** | **N2** | **N2** | **N2** | **S2N2** | **S2N2** | **N2** | **N2** |

| | Maize | | Soya | | Cotton | | Wh. Potato | |
|---|---|---|---|---|---|---|---|---|
| | **low** | **high** | **low** | **high** | **low** | **high** | **low** | **high** |
| **Cambic Arenosol** | **N2** | **S2** | **S2** | **S2** | **S2N2** | **S2N2** | **S2** | **S1S2** |
| **Luvic Arenosol** | **N2** | **S2** | **S2** | **S2** | **S2N2** | **S2N2** | **S2** | **S1S2** |
| **Ferralic Arenosol** | **N2** | **S2N2** | **S2N2** | **S2N2** | **N2** | **N2** | **S2N2** | **S2N2** |
| **Albic Arenosol** | **N2** | **N2** | **N2** | **N2** | **S2N2** | **S2N2** | **N2** | **N2** |

| | Sw. Potato | | Sugarcane | | Cassava | | Rice | |
|---|---|---|---|---|---|---|---|---|
| | **low** | **high** | **low** | **high** | **low** | **high** | **low** | **high** |
| **Cambic Arenosol** | **S2N2** | **S2N2** | **S2N2** | **S2N2** | **S2** | **S2** | **N2** | **N2** |
| **Luvic Arenosol** | **S2N2** | **S2N2** | **S2N2** | **S2N2** | **S2** | **S2** | **N2** | **N2** |
| **Ferralic Arenosol** | **S2N2** | **S2N2** | **S2N2** | **S2N2** | **S2** | **S2N2** | **N2** | **N2** |
| **Albic Arenosol** | **N2** | **N2** | **N2** | **N2** | **S2N2** | **S2N2** | **N2** | **N2** |

**RENDZINAS**

| | Wheat | | Sorghum | | Millet | | Beans | |
|---|---|---|---|---|---|---|---|---|
| | **low** | **high** | **low** | **high** | **low** | **high** | **low** | **high** |
| **All Rendzinas:** | **S2N2** | **S2N2** | **S2** | **S2** | **S2** | **S2** | **S2N2** | **S2N2** |

| | Maize | | Soya | | Cotton | | Wh. Potato | |
|---|---|---|---|---|---|---|---|---|
| | **low** | **high** | **low** | **high** | **low** | **high** | **low** | **high** |
| **All Rendzinas:** | **S2N2** | **S2N2** | **S2N2** | **S2N2** | **S2N2** | **S2N2** | **S2N2** | **S2N2** |

| | Sw. Potato | | Sugarcane | | Cassava | | Rice | |
|---|---|---|---|---|---|---|---|---|
| | **low** | **high** | **low** | **high** | **low** | **high** | **low** | **high** |
| **All Rendzinas:** | **S2N2** | **S2N2** | **S2N2** | **S2N2** | **S2N2** | **S2N2** | **N2** | **N2** |

**RANKERS** **N2' for all crops except for Wh. Potato (S2N2 for both input levels).**

**ANDOSOLS**

| | Wheat | | Sorghum | | Millet | | Beans | |
|---|---|---|---|---|---|---|---|---|
| | **low** | **high** | **low** | **high** | **low** | **high** | **low** | **high** |
| **Ochric Andosol** | **S2** | **S1** | **S1** | **S1** | **S1** | **S1** | **S2** | **S1** |
| **Mollic Andosol** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** |
| **Humic Andosol** | **S1S2** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1S2** | **S1** |

**Vitric Andosol N2 N2 S2N2 S2N2 S2N2 S2N2 N2 N2**

Maize Soya Cotton Wh. Potato
**low high low high low high low high**

**Ochric Andosol S2 S1 S2 S1 S2 S1 S2 S1**
**Mollic Andosol S1 S1 S1 S1 S1 S1 S1 S1**
**Humic Andosol S1S2 S1 S1S2 S1 S1S2 S1 S1S2 S1**
**Vitric Andosol N2 N2 N2 N2 S2N2 S2N2 S2N2**
**S2N2**

Sw. Potato Sugarcane Cassava Rice
**low high low high low high low high**

**Ochric Andosol S2 S1 S2 S1 S1 S1 S1 S1**
**Mollic Andosol S1 S1 S1 S1 S1 S1 S1 S1**
**Humic Andosol S1S2 S1 S1S2 S1 S1 S1 S1 S1**
**Vitric Andosol S2N2 S2N2 N2 N2 S2 S2 N2 N2**

VERTISOLS

Wheat Sorghum Millet Beans
**low high low high low high low high**

**Pellic Vertisol S2N2 S1 S2N2 S1 S2N2 S2**
**S2N2 S1S2**
**Chromic Vertisol S2N2 S1 S2N2 S1 S2N2 S2 S2N2 S1S2**

Maize Soya Cotton Wh. Potato
**low high low high low high low high**

**Pellic Vertisol S2N2 S1 S2N2 S1S2 S2 S1 N2**
**S2**
**Chromic Vertisol S2N2 S1 S2N2 S1S2 S2 S1 N2 S2**

Sw. Potato Sugarcane Cassava Rice
**low high low high low high low high**

**Pellic Vertisol N2 S2 S2 S1 N2 S2 S2 S1**
**Chromic Vertisol N2 S2 S2 S1 N2 S2 S2 S1**

**SOLONCHAKS**

| | Wheat low | Wheat high | Sorghum low | Sorghum high | Millet low | Millet high | Beans low | Beans high |
|---|---|---|---|---|---|---|---|---|
| **Orthic Solonchak** | **N2** | **N1N2** | **N2** | **N1N2** | **N2** | **N1N2** | **N2** | **N2** |
| **Mollic Solonchak** | **N2** | **N1N2** | **N2** | **N1N2** | **N2** | **N1N2** | **N2** | **N2** |
| **Takyric Solonchak** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** |
| **Gleyic Solonchak** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** |

| | Maize low | Maize high | Soya low | Soya high | Cotton low | Cotton high | Wh. Potato low | Wh. Potato high |
|---|---|---|---|---|---|---|---|---|
| **Orthic Solonchak** | **N2** | **N2** | **N2** | **N2** | **N2** | **N1** | **N2** | **N2** |
| **Mollic Solonchak** | **N2** | **N2** | **N2** | **N2** | **N2** | **N1** | **N2** | **N2** |
| **Takyric Solonchak** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** |
| **Gleyic Solonchak** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** |

| | Sw. Potato low | Sw. Potato high | Sugarcane low | Sugarcane high | Cassava low | Cassava high | Rice low | Rice high |
|---|---|---|---|---|---|---|---|---|
| **Orthic Solonchak** | **N2** | **N2** | **N2** | **N1N2** | **N2** | **N1** | **N2** | **N2** |
| **Mollic Solonchak** | **N2** | **N2** | **N2** | **N1N2** | **N2** | **N1** | **S2N2** | **S2N1** |
| **Takyric Solonchak** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** |
| **Gleyic Solonchak** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** | **S2N2** | **S2N1** |

**SOLONETZ**

| | Wheat low | Wheat high | Sorghum low | Sorghum high | Millet low | Millet high | Beans low | Beans high |
|---|---|---|---|---|---|---|---|---|
| **Orthic Solonetz** | **N2** | **S2N2** | **N2** | **S2N2** | **N2** | **S2N2** | **N2** | **N2** |
| **Mollic Solonetz** | **S2** | **S2** | **S2** | **S2** | **S2** | **S2** | **N2** | **N2** |
| **Gleyic Solonetz** | **N2** | **N1N2** | **N2** | **N1N2** | **N2** | **N1N2** | **N2** | **N2** |

| | Maize low | Maize high | Soya low | Soya high | Cotton low | Cotton high | Wh. Potato low | Wh. Potato high |
|---|---|---|---|---|---|---|---|---|
| **Orthic Solonetz** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Mollic Solonetz | N2 | N2 | N2 | N2 | N2 | N2 | N2 | N2 |
| Gleyic Solonetz | N2 | N2 | N2 | N2 | N2 | N2 | N2 | N2 |

| | Sw. Potato | | Sugarcane | | Cassava | | Rice | |
|---|---|---|---|---|---|---|---|---|
| | **low** | **high** | **low** | **high** | **low** | **high** | **low** | **high** |
| **Orthic Solonetz** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** | **N1N2** |
| **Mollic Solonetz** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** | **N1N2** |
| **Gleyic Solonetz** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** | **N1N2** |

**XEROSOLS**

| | Wheat | | Sorghum | | Millet | | Beans | |
|---|---|---|---|---|---|---|---|---|
| | **low** | **high** | **low** | **high** | **low** | **high** | **low** | **high** |
| **Haplic Xerosol** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** |
| **Calcic Xerosol** | **S2** | **S2** | **S2** | **S2** | **S1** | **S1** | **S2** | **S2** |
| **Gypsic Xerosol** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** |
| **Luvic Xerosol** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** |

| | Maize | | Soya | | Cotton | | Wh. Potato | |
|---|---|---|---|---|---|---|---|---|
| | **low** | **high** | **low** | **high** | **low** | **high** | **low** | **high** |
| **Haplic Xerosol** | **S1** | **S1** | **S2** | **S2** | **na** | **na** | **na** | **na** |
| **Calcic Xerosol** | **N2** | **N2** | **N2** | **N2** | **na** | **na** | **na** | **na** |
| **Gypsic Xerosol** | **N2** | **N2** | **N2** | **N2** | **na** | **na** | **na** | **na** |
| **Luvic Xerosol** | **S1** | **S1** | **S1** | **S1** | **na** | **na** | **na** | **na** |

| | Sw. Potato | | Sugarcane | | Cassava | | Rice | |
|---|---|---|---|---|---|---|---|---|
| | **low** | **high** | **low** | **high** | **low** | **high** | **low** | **high** |
| **Haplic Xerosol** | **na** | **na** | **na** | **na** | **na** | **na** | **na** | **na** |
| **Calcic Xerosol** | **na** | **na** | **na** | **na** | **na** | **na** | **na** | **na** |
| **Gypsic Xerosol** | **na** | **na** | **na** | **na** | **na** | **na** | **na** | **na** |
| **Luvic Xerosol** | **na** | **na** | **na** | **na** | **na** | **na** | **na** | **na** |

**YERMOSOLS** **not applicable (n.a.)**

**KASTANOZEMS**

| | Wheat | Sorghum | Millet | Beans |
|---|---|---|---|---|

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **low** | **high** | **low** | **high** | **low** | **high** | **low** | **high** |
| **Haplic Kastanozem** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** |
| **Calcic Kastanozem** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1S2** | **S1S2** |
| **Luvic Kastanozem** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** |

| | Maize | | Soya | | Cotton | | Wh. Potato | |
|---|---|---|---|---|---|---|---|---|
| | **low** | **high** | **low** | **high** | **low** | **high** | **low** | **high** |
| **Haplic Kastanozem** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** |
| **Calcic Kastanozem** | **S1S2** | **S1S2** | **S1S2** | **S1S2** | **S1** | **S1** | **S1N2** | **S2N2** |
| **Luvic Kastanozem** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** |

| | Sw. Potato | | Sugarcane | | Cassava | | Rice | |
|---|---|---|---|---|---|---|---|---|
| | **low** | **high** | **low** | **high** | **low** | **high** | **low** | **high** |
| **Haplic Kastanozem** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S2** | **S2** |
| **Calcic Kastanozem** | **S1** | **S1** | **S1** | **S1** | **S2** | **S2** | **S2** | **S2** |
| **Luvic Kastanozem** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** |

CHERNOZEMS

| | Wheat | | Sorghum | | Millet | | Beans | |
|---|---|---|---|---|---|---|---|---|
| | **low** | **high** | **low** | **high** | **low** | **high** | **low** | **high** |
| **Haplic Chernozem** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** |
| **Calcic Chernozem** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1S2** | **S1S2** |
| **Luvic Chernozem** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** |
| **Glossic Chernozem** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** |

| | Maize | | Soya | | Cotton | | Wh. Potato | |
|---|---|---|---|---|---|---|---|---|
| | **low** | **high** | **low** | **high** | **low** | **high** | **low** | **high** |
| **Haplic Chernozem** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** |
| **Calcic Chernozem** | **S1S2** | **S1S2** | **S1S2** | **S1S2** | **S1** | **S1** | **S2N2** | **S2N2** |
| **Luvic Chernozem** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** |
| **Glossic Chernozem** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** |

| | Sw. Potato | | Sugarcane | | Cassava | | Rice | |
|---|---|---|---|---|---|---|---|---|
| | **low** | **high** | **low** | **high** | **low** | **high** | **low** | **high** |
| **Haplic Chernozem** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S2** | **S2** |
| **Calcic Chernozem** | **S1** | **S1** | **S1** | **S1** | **S2** | **S2** | **S2** | **S2** |
| **Luvic Chernozem** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** |
| **Glossic Chernozem** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S2** | **S2** |

**PHAEOZEMS**

| | Wheat | | Sorghum | | Millet | | Beans | |
|---|---|---|---|---|---|---|---|---|
| | **low** | **high** | **low** | **high** | **low** | **high** | **low** | **high** |
| **Haplic Phaeozem** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** |
| **Calcaric Phaeozem** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1S2** | **S1S2** |
| **Luvic Phaeozem** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** |
| **Gleyic Phaeozem** | **S2** | **S2** | **S2** | **S2** | **S2** | **S2** | **S2** | **S2** |

| | Maize | | Soya | | Cotton | | Wh. Potato | |
|---|---|---|---|---|---|---|---|---|
| | **low** | **high** | **low** | **high** | **low** | **high** | **low** | **high** |
| **Haplic Phaeozem** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** |
| **Calcaric Phaeozem** | **S1S2** | **S1S2** | **S1S2** | **S1S2** | **S1** | **S1** | **S2N2** | **S2N2** |
| **Luvic Phaeozem** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** |
| **Gleyic Phaeozem** | **S2** | **S2** | **S2** | **S2** | **N2** | **N1N2** | **N2** | **N1N2** |

| | Sw. Potato | | Sugarcane | | Cassava | | Rice | |
|---|---|---|---|---|---|---|---|---|
| | **low** | **high** | **low** | **high** | **low** | **high** | **low** | **high** |
| **Haplic Phaeozem** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** |
| **Calcaric Phaeozem** | **S1** | **S1** | **S1** | **S1** | **S2** | **S2** | **S1** | **S1** |
| **Luvic Phaeozem** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** |
| **Gleyic Phaeozem** | **N2** | **N1N2** | **S2** | **S2** | **N2** | **N2** | **S1** | **S1** |

**GREYZEMS**

| | Wheat | | Sorghum | | Millet | | Beans | |
|---|---|---|---|---|---|---|---|---|
| | **low** | **high** | **low** | **high** | **low** | **high** | **low** | **high** |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Orthic Greyzem** | **S1** | **S1** | **na** | **na** | **na** | **na** | **S1** | **S1** |
| **Gleyic Greyzem** | **S2** | **S2** | **na** | **na** | **na** | **na** | **S2** | **S2** |

| | Maize | | Soya | | Cotton | | Wh. Potato | |
|---|---|---|---|---|---|---|---|---|
| | **low** | **high** | **low** | **high** | **low** | **high** | **low** | **high** |
| **Orthic Greyzem** | **S1** | **S1** | **S1** | **S1** | **na** | **na** | **S1** | **S1** |
| **Gleyic Greyzem** | **S2** | **S2** | **S2** | **S2** | **na** | **na** | **N2** | **N1N2** |

| | Sw. Potato | | Sugarcane | | Cassava | | Rice | |
|---|---|---|---|---|---|---|---|---|
| | **low** | **high** | **low** | **high** | **low** | **high** | **low** | **high** |
| **Orthic Greyzem** | **S1** | **S1** | **na** | **na** | **na** | **na** | **na** | **na** |
| **Gleyic Greyzem** | **N2** | **N1N2** | **na** | **na** | **na** | **na** | **na** | **na** |

**CAMBISOLS**

| | Wheat | | Sorghum | | Millet | | Beans | |
|---|---|---|---|---|---|---|---|---|
| | **low** | **high** | **low** | **high** | **low** | **high** | **low** | **high** |
| **Eutric Cambisol** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** |
| **Dystric Cambisol** | **S2** | **S1** | **S2** | **S1** | **S2** | **S1** | **S2** | **S1** |
| **Humic Cambisol** | **S2** | **S1** | **S2** | **S1** | **S2** | **S1** | **S2** | **S1** |
| **Gleyic Cambisol** | **S2** | **S2** | **S2** | **S2** | **N2** | **N2** | **S2** | **S2** |
| **Gelic Cambisol** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** |
| **Calcic Cambisol** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1S2** | **S1S2** |
| **Chromic Cambisol** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** |
| **Vertic Cambisol** | **S2** | **S1** | **S2** | **S1** | **S2N2** | **S2** | **S1S2** | **S1** |
| **Ferralic Cambisol** | **S2** | **S1S2** | **S2** | **S1S2** | **S2** | **S1S2** | **S2** | **S1S2** |

| | Maize | | Soya | | Cotton | | Wh. Potato | |
|---|---|---|---|---|---|---|---|---|
| | **low** | **high** | **low** | **high** | **low** | **high** | **low** | **high** |
| **Eutric Cambisol** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** |
| **Dystric Cambisol** | **S2** | **S1** | **S2** | **S1** | **S2** | **S1** | **S2** | **S1** |
| **Humic Cambisol** | **S2** | **S1** | **S2** | **S1** | **S2** | **S1** | **S2** | **S1** |
| **Gleyic Cambisol** | **S2** | **S2** | **S2** | **S2** | **N2** | **N1N2** | **N2** | **N1N2** |
| **Gelic Cambisol** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** |
| **Calcic Cambisol** | **S1S2** | **S1S2** | **S1S2** | **S1S2** | **S1** | **S1** | **S2N2** | **S2N2** |
| **Chromic Cambisol** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** |
| **Vertic Cambisol** | **S1S2** | **S1** | **S2** | **S1S2** | **S1S2** | **S1** | **S2N2** | **S2** |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Ferralic Cambisol** | **S2** | **S1S2** | **S2** | **S1S2** | **S2** | **S1S2** | **S2N2** | **S2N2** |

| | Sw. Potato | | Sugarcane | | Cassava | | Rice | |
|---|---|---|---|---|---|---|---|---|
| | **low** | **high** | **low** | **high** | **low** | **high** | **low** | **high** |
| **Eutric Cambisol** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** |
| **Dystric Cambisol** | **S2** | **S1** | **S2** | **S1** | **S2** | **S1** | **S2** | **S1** |
| **Humic Cambisol** | **S2** | **S1** | **S2** | **S1** | **S2** | **S1** | **S2** | **S1** |
| **Gleyic Cambisol** | **N2** | **N1N2** | **S2** | **S2** | **N2** | **N2** | **S1** | **S1** |
| **Gelic Cambisol** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** |
| **Calcic Cambisol** | **S1** | **S1** | **S1** | **S1** | **S2** | **S2** | **S1S2** | **S1S2** |
| **Chromic Cambisol** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** |
| **Vertic Cambisol** | **S2N2** | **S2** | **S1S2** | **S1** | **S2N2** | **S2** | **S1** | **S1** |
| **Ferralic Cambisol** | **S2N2** | **S2N2** | **S2** | **S1S2** | **S2N2** | **S2N2** | **S2N2** | **S2N2** |

LUVISOLS

| | Wheat | | Sorghum | | Millet | | Beans | |
|---|---|---|---|---|---|---|---|---|
| | **low** | **high** | **low** | **high** | **low** | **high** | **low** | **high** |
| **Orthic Luvisol** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** |
| **Chromic Luvisol** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** |
| **Calcic Luvisol** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1S2** | **S1S2** |
| **Vertic Luvisol** | **S2** | **S1** | **S2** | **S1** | **S2N2** | **S2** | **S1S2** | **S1** |
| **Ferric Luvisol** | **S2** | **S1S2** | **S2** | **S1S2** | **S2** | **S1S2** | **S2** | **S1S2** |
| **Albic Luvisol** | **S2** | **S1** | **S2** | **S1** | **S2** | **S1** | **S2** | **S1** |
| **Plinthic Luvisol** | **S2N2** | **S2N2** | **S2N2** | **S2N2** | **S2N2** | **S2N2** | **S2N2** | **S2N2** |
| **Gleyic Luvisol** | **N2** | **N1N2** | **N2** | **N1N2** | **N2** | **N1N2** | **N2** | **N1N2** |

| | Maize | | Soya | | Cotton | | Wh. Potato | |
|---|---|---|---|---|---|---|---|---|
| | **low** | **high** | **low** | **high** | **low** | **high** | **low** | **high** |
| **Orthic Luvisol** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** |
| **Chromic Luvisol** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** |
| **Calcic Luvisol** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1N2** | **S1N2** |
| **Vertic Luvisol** | **S1S2** | **S1** | **S2** | **S1S2** | **S1S2** | **S1** | **S2N2** | **S2** |
| **Ferric Luvisol** | **S2** | **S1S2** | **S2** | **S1S2** | **S2** | **S1S2** | **S2N2** | **S2N2** |

**Albic Luvisol S2 S1 S2 S1 S2 S1 S2 S1**
**Plinthic Luvisol S2N2 S2N2 S2N2 S2N2 S2N2 S2N2 S2N2**
**S2N2**
**Gleyic Luvisol N2 N1N2 N2 N1N2 N2 N1N2 N2**
**N1N2**

Sw. Potato Sugarcane Cassava Rice
**low high low high low high low high**

**Orthic Luvisol S1 S1 S1 S1 S1 S1 S1 S1**
**Chromic Luvisol S1 S1 S1 S1 S1 S1 S1 S1**
**Calcic Luvisol S1 S1 S1 S1 S2 S2 S1 S1**
**Vertic Luvisol S2 S2 S1S2 S1 S1N2 S2 S1 S1**
**Ferric Luvisol S2N2 S2N2 S2 S1S2 S2N2 S2N2 S2N2**
**S2N2**
**Albic Luvisol S2 S2 S2 S2 S2 S1 S2 S2**
**Plinthic Luvisol S2N2 S2N2 S2N2 S2N2 S2N2 S2N2 S2 S2**
**Gleyic Luvisol N2 N1N2 S2N2 S2N1 N2 N2 S1 S1**

PODZOLUVISOLS
Wheat Sorghum Millet Beans
**low high low high low high low high**

**Eutric Pluvisol S2 S1 na na na na S1 S1**
**Dystric Pluvisol N1 S2 na na na na S2 S1**
**Gleyic Pluvisol N1 N1N2 na na na na N2 N1N2**

Maize Soya Cotton Wh. Potato
**low high low high low high low high**

**Eutric Pluvisol S2S1 S1 S2S1 S1 na na S1 S1**
**Dystric Pluvisol S2 S1 S2 S1 na na S2 S1**
**Gleyic Pluvisol N2 N1N2 S2N2 S2N1 na na N2 N1N2**

Sw. Potato Sugarcane Cassava Rice
**low high low high low high low high**

**Eutric Pluvisol S1 S1 S1 S1 na na na na**
**Dystric Pluvisol S2 S1 S2 S1 na na na na**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Gleyic Pluvisol** | **N2** | **N1N2** | **S2N2** | **S2N1** | **na** | **na** | **na** | **na** |

PODZOLS

| | Wheat | | Sorghum | | Millet | | Beans | |
|---|---|---|---|---|---|---|---|---|
| | **low** | **high** | **low** | **high** | **low** | **high** | **low** | **high** |
| **Orthic Podzol** | **N1** | **S2** | **na** | **na** | **na** | **na** | **S2** | **S2** |
| **Leptic Podzol** | **N1** | **S2** | **na** | **na** | **na** | **na** | **S2** | **S2** |
| **Ferric Podzol** | **S2N2** | **S2N2** | **na** | **na** | **na** | **na** | **S2N2** | **S2N2** |
| **Humic Podzol** | **N1** | **S2** | **N1** | **S2** | **S2** | **S1** | **S2** | **S2** |
| **Placic Podzol** | **2** | **N2** | **na** | **na** | **na** | **na** | **N2** | **N2** |
| **Gleyic Podzol** | **N2** | **N1N2** | **na** | **na** | **na** | **na** | **N2** | **N1N2** |

| | Maize | | Soya | | Cotton | | Wh. Potato | |
|---|---|---|---|---|---|---|---|---|
| | **low** | **high** | **low** | **high** | **low** | **high** | **low** | **high** |
| **Orthic Podzol** | **S2** | **S2** | **S2** | **S2** | **S2N2** | **S2N2** | **S2** | **S1S2** |
| **Leptic Podzol** | **S2** | **S2** | **S2** | **S2** | **S2** | **S2** | **S2** | **S2S1** |
| **Ferric Podzol** | **S2N2** | **S2N2** | **S2N2** | **S2N2** | **S2N2** | **S2N2** | **S2N2** | **S2N2** |
| **Humic Podzol** | **S2** | **S1S2** | **S2** | **S2** | **S2** | **S1** | **S2** | **S1S2** |
| **Placic Podzol** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** |
| **Gleyic Podzol** | **N2** | **N1N2** | **N2** | **N1N2** | **N2** | **N1N2** | **N2** | **N1N2** |

| | Sw. Potato | | Sugarcane | | Cassava | | Rice | |
|---|---|---|---|---|---|---|---|---|
| | **low** | **high** | **low** | **high** | **low** | **high** | **low** | **high** |
| **Orthic Podzol** | **N2** | **S2N2** | **S2N2** | **S2N2** | **S2** | **S2** | **na** | **na** |
| **Leptic Podzol** | **S2N2** | **S2N2** | **S2N2** | **S2N2** | **S2** | **S1S2** | **na** | **na** |
| **Ferric Podzol** | **S2N2** | **S2N2** | **S2N2** | **S2N2** | **S2** | **S2** | **na** | **na** |
| **Humic Podzol** | **S2** | **S1S2** | **S2** | **S1S2** | **S2** | **S1S2** | **na** | **na** |
| **Placic Podzol** | **N2** | **N2** | **N2** | **N2** | **N2** | **N2** | **na** | **na** |
| **Gleyic Podzol** | **N2** | **N1N2** | **N2** | **N1N2** | **N2** | **N2** | **S2** | **S2** |

PLANOSOLS

Wheat Sorghum Millet Beans

| | low | high | low | high | low | high | low | high |
|---|---|---|---|---|---|---|---|---|
| Eutric Planosol | N1 | S2 | N1 | S2 | S2 | S2 | S2 | S2 |
| Dystric Planosol | N1 | S2 | N1 | S2 | S2 | S2 | S2N2 | S2 |
| Mollic Planosol | N1 | S2 | N1 | S2 | S2 | S2 | S2 | S2 |
| Humic Planosol | N1 | S2 | N1 | S2 | S2 | S2 | S2N1 | S2 |
| Solodic Planosol | N2 | N1N2 | N2 | N1N2 | N2 | N2 | N2 | N2 |
| Gelic Planosol | N2 | N2 | N2 | N2 | N2 | N2 | N2 | N2 |

| | Maize | | Soya | | Cotton | | Wh. Potato | |
|---|---|---|---|---|---|---|---|---|
| | low | high | low | high | low | high | low | high |
| Eutric Planosol | S2 | S1S2 | S2 | S1S2 | S2 | S1S2 | S2 | S1S2 |
| Dystric Planosol | S2N2 | S2 | S2N2 | S2 | S2N2 | S2 | S2N2 | S2N1 |
| Mollic Planosol | S2 | S1S2 | S2 | S1S2 | S2 | S1S2 | S2 | S2 |
| Humic Planosol | S2N2 | S2 | S2N2 | S2 | S2N2 | S2 | S2N2 | S2N1 |
| Solodic Planosol | N2 | N1N2 | N2 | N1N2 | S2N2 | S2N2 | N2 | N1N2 |
| Gelic Planosol | N2 | N2 | N2 | N2 | N2 | N2 | N2 | N2 |

| | Sw. Potato | | Sugarcane | | Cassava | | Rice | |
|---|---|---|---|---|---|---|---|---|
| | low | high | low | high | low | high | low | high |
| Eutric Planosol | S1S2 | S1S2 | S1S2 | S1 | S2 | S2 | S1 | S1 |
| Dystric Planosol | S2N2 | S2N1 | S2 | S1S2 | S2N2 | S2 | S2 | S1 |
| Mollic Planosol | S2 | S2 | S1 | S1 | S2 | S2 | S1 | S1 |
| Humic Planosol | S2N2 | S2N1 | S2 | S1 | S2 | S2 | S2 | S1 |
| Solodic Planosol | N2 | N1N2 | S2N2 | S2N1 | N2 | N2 | S2N2 | S2N1 |
| Gelic Planosol | N2 | N2 | N2 | N2 | N2 | N2 | N2 | N2 |

ACRISOLS

| | Wheat | | Sorghum | | Millet | | Beans | |
|---|---|---|---|---|---|---|---|---|
| | low | high | low | high | low | high | low | high |
| Orthic Acrisol | S2 | S1 | S2 | S1 | S2 | S1 | S2 | S1S2 |
| Ferric Acrisol | S2 | S2 | S2 | S1S2 | S2 | S1S2 | S2N2 | S2 |
| Humic Acrisol | S2 | S1 | S2 | S1 | S2 | S1 | S2 | S1 |
| Plinthic Acrisol | S2N2 | S2N2 | S2N2 | S2N2 | S2N2 | S2N2 | S2N2 | S2N2 |
| Gleyic Acrisol | N2 | N1N2 | N2 | N1N2 | N2 | N1N2 | N2 | |

**N1N2**

Maize Soya Cotton Wh. Potato
**low high low high low high low high**

**Orthic Acrisol S2 S1S2 S2 S1 S2 S1 S2 S1S2**
**Ferric Acrisol S2N2 S2 S2N2 S2 S2N2**
**S2 S2N2 S2N2**
**Humic Acrisol S2 S1 S2 S1 S2 S1 S2 S1**
**Plinthic Acrisol S2N2 S2N2 S2N2 S2N2 S2N2 S2N2 N2 N2**
**Gleyic Acrisol N2 N1N2 N2 N1N2 N2 N1N2 N2**
**N1N2**

Sw. Potato Sugarcane Cassava Rice
**low high low high low high low high**

**Orthic Acrisol S2 S1 S2 S1 S1 S1 S1 S1**
**Ferric Acrisol S2N2 S2N2 S2N2 S2 S2N2 S2N2 S2N2**
**S2N2**
**Humic Acrisol S2 S1 S2 S1 S1 S1 S2 S1**
**Plinthic Acrisol S2N2 S2N2 N2 N2 S2N2 S2N2 S2 S2**
**Gleyic Acrisol N2 N1N2 S2N2 S2N1 N2 N2 S1 S1**

**NITOSOLS**
Wheat Sorghum Millet Beans
**low high low high low high low high**

**Eutric Nitosol S1 S1 S1 S1 S1 S1 S1 S1**
**Dystric Nitosol S2 S1 S2 S1 S2 S1 S2 S1**
**Humic Nitosol S2 S1 S2 S1 S2 S1 S2 S1**

Maize Soya Cotton Wh. Potato
**low high low high low high low high**

**Eutric Nitosol S1 S1 S1 S1 S1 S1 S1 S1**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Dystric Nitosol** | **S2** | **S1** | **S2** | **S1** | **S2** | **S1** | **S2** | **S1** |
| **Humic Nitosol** | **S2** | **S1** | **S2** | **S1** | **S2** | **S1** | **S2** | **S1** |

| | Sw. Potato | | Sugarcane | | Cassava | | Rice | |
|---|---|---|---|---|---|---|---|---|
| | **low** | **high** | **low** | **high** | **low** | **high** | **low** | **high** |
| **Eutric Nitosol** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** | **S1** |
| **Dystric Nitosol** | **S2** | **S1** | **S2** | **S1** | **S2** | **S1** | **S2** | **S1** |
| **Humic Nitosol** | **S2** | **S1** | **S2** | **S1** | **S2** | **S1** | **S2** | **S1** |

**FERRALSOLS**

| | Wheat | | Sorghum | | Millet | | Beans | |
|---|---|---|---|---|---|---|---|---|
| | **low** | **high** | **low** | **high** | **low** | **high** | **low** | **high** |
| **Orthic Ferralsol** | **na** | **na** | **S2** | **S1** | **S2** | **S1** | **S2** | **S2** |
| **Xanthic Ferralsol** | **na** | **na** | **S2** | **S1** | **S2** | **S1** | **S2N2** | **S2N2** |
| **Rhodic Ferralsol** | **na** | **na** | **S2** | **S1** | **S2** | **S1** | **S2** | **S1** |
| **Humic Ferralsol** | **na** | **na** | **S2** | **S1** | **S2** | **S1** | **S2** | **S1** |
| **Acric Ferralsol** | **na** | **na** | **N2** | **S2** | **N2** | **S2** | **N2** | **S2N1** |
| **Plinthic Ferralsol** | **na** | **na** | **S2N2** | **S2N2** | **S2N2** | **S2N2** | **S2N2** | **S2N2** |

| | Maize | | Soya | | Cotton | | Wh. Potato | |
|---|---|---|---|---|---|---|---|---|
| | **low** | **high** | **low** | **high** | **low** | **high** | **low** | **high** |
| **Orthic Ferralsol** | **S2** | **S2** | **S2** | **S2** | **S2** | **S2** | **S2** | **S2** |
| **Xanthic Ferralsol** | **S2N2** | **S2N2** | **S2N2** | **S2N2** | **S2N2** | **S2N2** | **S2N2** | **S2N2** |
| **Rhodic Ferralsol** | **S2** | **S1** | **S2** | **S1** | **S2** | **S1** | **S2** | **S1S2** |
| **Humic Ferralsol** | **S2** | **S1** | **S2** | **S1** | **S2** | **S1** | **S2** | **S1S2** |
| **Acric Ferralsol** | **N2** | **S2N1** | **N2** | **S2N1** | **S2N1** | **N2** | **N2** | **N2** |
| **Plinthic Ferralsol** | **S2N2** | **S2N2** | **S2N2** | **S2N2** | **S2N2** | **S2N2** | **N2** | **N2** |

| | Sw. Potato | | Sugarcane | | Cassava | | Rice | |
|---|---|---|---|---|---|---|---|---|
| | **low** | **high** | **low** | **high** | **low** | **high** | **low** | **high** |

**Orthic Ferralsol S2 S1S2 S2 S2 S2 S1 S2 S2**
**Xanthic Ferralsol S2N2 S2N2 S2N2 S2N2 S2 S2 N2 N2**
**Rhodic Ferralsol S2 S1 S2 S1 S2 S1 S1S2 S1S2**
**Humic Ferralsol S2 S1S2 S2 S1 S2 S1 S1S2 S1S2**
**Acric Ferralsol N2 S2N1 N2 N1S2 S2N2 S2N1 N2 N2**
**Plinthic Ferralsol S2N2 S2N2 S2N2 S2N2 S2N2 S2N2 S2 S2N2**

HISTOSOLS

Wheat Sorghum Millet Beans
**low high low high low high low high**

**Eutric Histosol N2 N1N2 N2 N1N2 N2 N1N2 N2**
**N1N2**
**Dystric Histosol N2 N1N2 N2 N1N2 N2 N1N2 N2 N1N2**
**Gelic Histosol N2 N2 N2 N2 N2 N2 N2 N2**

Maize Soya Cotton Wh. Potato
**low high low high low high low high**

**Eutric Histosol N2 N1N2 N2 N1N2 N2 N2 N2**
**N1N2**
**Dystric Histosol N2 N1N2 N2 N1N2 N2 N2 N2 N1N2**
**Gelic Histosol N2 N2 N2 N2 N2 N2 N2 N2**

Sw. Potato Sugarcane Cassava Rice
**low high low high low high low high**

**Eutric Histosol N2 N1N2 N2 N1N2 N2 N1N2 S2N2**
**S2N2**
**Dystric Histosol N2 N1N2 N2 N1N2 N2 N1N2 N2 N2**
**Gelic Histosol N2 N2 N2 N2 N2 N2 N2 N2**

A3. PHASESLOPETEXTURE RULES FOR MODIFYING SOIL RATINGS **(Source: FAO World Soil Resources Report 48; 8689)**

***Phase modifications***

**The soil unit ratings are modified if soil/terrain limitations occur that are indicated as** 'phases' **on the Soil Map of the World (FAOUnesco, 1974).**

-Stony phase: **for all crops except rice, the low level input ratings are decreased by one class and the high level input ratings are downgraded to N2. It is considered that mechanized cultivation is not possible (by definition) in stony phase areas and that yields from such lands under low input levels are decreased by stoniness. For rice, the ratings are downgraded to N2 for both input levels.**

-Lithic phase: **for all crops except potato, sweet potato, cassava and rice, the low level input ratings and the high level input ratings are half decreased by one class and half downgraded to N2. For potato, cassava and sweet potato, the low level input ratings are half decreased by one class and half downgraded to N2, whereas for high level input conditions the ratings are completely downgraded to N2, to cater for the hazard in attempting mechanized harvesting of these crops in shallow soils. For rice, the ratings are downgraded to N2 for both input levels.**

-Petric phase: **for all crops except rice, ratings for both levels of inputs are decreased by one class (the other half remains unchanged). For rice, all high input level ratings are decreased by one class and all high input level ratings are downgraded to N2.**

-Petrocalcic phase: **for wheat, sorghum, millet and beans, the low input level ratings are decreased by one class. The high input level ratings for these crops are half decreased by one class and the other half is downgraded to N2. For maize, soya, cotton, potato, sweet potato and rice, ratings for both input levels are half decreased by one class and half downgraded to N2. For cassava which is highly sensitive to an excess of $CaCO_3$, both input level ratings are entirely downgraded to N2. For sugarcane which is more tolerant, both input level ratings are half decreased by one class (the other half remains unchanged).**

-Petrogypsic phase: **for wheat, sorghum and millet, half the low input level ratings are decreased by one class and the other half is downgraded to N2. The high input level ratings for these crops are entirely** downgraded to N2. For beans, maize, soya, potato, sweet potato, cassava and rice, both input level ratings are entirely downgraded to N2. For sugarcane and cotton, both input level ratings are half decreased by one class and half downgraded to N2.

-Petroferric phase: for all crops, low input level ratings are half decreased by one class and the other half is downgraded to N2. The high input level ratings are entirely downgraded to N2.

-Phreatic phase: all ratings remain unchanged for all crops at both levels of inputs.

-Fragipan phase: for all crops except rice, the low input level ratings remain unchanged. The high input level ratings are half decreased by one class (the other half remains unchanged). For rice, both input level ratings remain unchanged.

-Duripan phase: for all crops except cotton and rice, both input level ratings are half decreased by one class (the other half remains unchanged). For the deep rooted cotton crop, both input level ratings are half decreased by one class and half downgraded to N2. For rice, both input level ratings remain unchanged.

-Saline phase: for rice, cassava, sweet potato, potato, soya and maize, the low input level ratings are entirely downgraded to N2; the high input level ratings are half downgraded to N2 and half to N1. For sugarcane, sorghum and wheat, the low input level ratings are half decreased by one class and half downgraded to N2; the high input level ratings are half decreased by one class and the other half is downgraded to N1. For the tolerant cotton crop, both input level ratings are half decreased by one class and the other half remains unchanged. For millet, the low input level rating is downgraded to N2 and the high input level rating is downgraded to N1. For the very susceptible bean crop, both input level ratings are downgraded to N2.

-Sodic phase: for rice, cassava, sweet potato, potato and millet, the low input level ratings are entirely downgraded to N2; the high input level ratings are half downgraded to N2 and half to N1. For sugarcane and sorghum, both input level ratings are half decreased by one class and half downgraded to N2. For wheat, both input level ratings are half downgraded to N2 and half to N1. For cotton, the ratings for both levels of inputs are half decreased by one class and half downgraded to N2 in the case of a low level of inputs, or downgraded to N1 in the case of a high input level. For the very susceptible bean, maize and soya crops, both input level ratings are entirely downgraded to N2.

-Cerrado phase: as this phase is limited to areas of Acric Ferralsols and Plinthic Acrisols, it is implicitly dealt with in the ratings of these soil units in all regions.

Phases which indicate an indurated or cemented layer within 100 cm from the surface received combination ratings (e.g. S2N2) assuming that in 50 percent of the area the layer is moderately deep (say 60100 cm) and in the other half the layer is shallow (less than 60 cm deep). In general, such depth limitations are less severe for small grain crops and more severe for coarse grain and root crops. Shallow soil depths pose severe limitations to highinput (mechanized) cultivation especially the 'Petro'phases which indicate a cemented layer.

*Slope modifications*

-Slopes of less than 8 percent require no modification of soil unit ratings.

-Slopes of 8 to 30 percent are treated as follows.

Of all low level input ratings, i.e. hand cultivation, onethird remain unchanged, onethird is decreased by one class and the remaining onethird is downgraded to N2. This modification is applied to all crops except rice where the ratings for both levels of inputs are downgraded to N2.

Of all high level input ratings, onethird remain unchanged and the remaining twothirds are downgraded to N2 because mechanized cultivation is not considered possible on some twothirds of these slopes.

-Slopes greater than 30 percent are 85 percent downgraded to N2. The remaining 15 percent are treated as if the slope were between 8 and 30 percent. This implies that 5 percent of the land with slopes greater than

**30 percent keeps the original rating(s) at both levels of inputs.**

***Texture modifications***

**All ratings of soils having less than 18 percent clay and more than 65 percent sand are decreased by one class. This rule does not apply to (1) all Arenosols, (2) all Podzols, (3) Ferric Acrisols, (4) Vitric Andosols, and (5) Xanthic Ferralsols because light texture limitations have already been accounted for in the soil unit ratings. All ratings of medium or finely textured soils remain unchanged.**

A4. AEZ AGROCLIMATIC CONSTRAINTS
**(Condensed from: FAO World Soil Resources Report 48, 9597)**

| ***Constraints:*** | ***Severity:*** |
|---|---|
| **'a' water stress,** | **'0' no or slight; no yield loss,** |
| **'b' weeds, pests and/or diseases,** | **'1' moderate; 25 % yield loss,** |
| **'c' defective yield formation/quality,** | **'2' severe; 50 % yield loss.** |
| **'d' impeded workability/harvesting.** | |

I.Crops in cropadaptability groups II and III in tropical and subtropical (summer rainfall) areas

millet sorghum maize soya
------------- ------------- ------------- -------------

**inputs: low high low high low high low high**
**constraint: abcd abcd abcd abcd abcd**
**abcd abcd abcd**

**LGP: 75 89 2010 2010 2110 2010 2120**
**2020 2020 2020**

**90119 1000 1000 2100 2000 2110 2010**
**2010 2010**
**120149 0000 0000 11001000 11001000**
**1000 1000**
**150179 0000 0000 0000 0000 0000**
**0000 0000 0000**
**180209 0100 0100 0000 0000 0000**
**0000 0100 0000**
**210239 01100111 01100011 0100 0001 0110**
**0001**
**240269 0221 0222 0121 0022 01010002**
**0110 0002**
**270299 0221 0222 0221 0122 01010102**
**0111 0102**
**300329 0221 0222 0221 0222 01010102**
**0211 0112**

**330364 0222 0222 0222 0222 0112 0112**
**0222 0122**
**365 0222 0222 0222 0222 0222 0222**
**0222 0222**

bean cotton sw. potato cassava
------------- ------------- ------------- -----------
--
**inputs: low high low high low high low high**
**constraint: abcd abcd abcd abcd abcd**
**abcd abcd abcd**

**LGP: 75 89 2020 2020 2000 2000 2010**
**2010 2010 2010**

**90119 2010 2010 2110 2000 2010 2010**
**2010 2010**
**120149 1000 1000 1110 1000 10011001**
**1011 1011**
**150179 0000 0000 01100000 0000 0000**
**1101 1001**
**180209 0100 0000 01100000 0000**
**0000 0100 0000**
**210239 01100001 01100110 0000 0000**
**0100 0000**
**240269 0210 0002 01100111 0010 0000**
**0100 0000**
**270299 0211 0102 0121 0121 0010 0001**
**0100 0000**
**300329 0211 0112 0221 0122 0020 0012**
**0100 0000**
**330364 0222 0122 0222 0222 0020**
**0012 01100011**
**365 0222 0222 0222 0222 0021 0022**
**0111 0012**

II.Crops in cropadaptability groups I and IV in tropical and subtropical areas

spring wheat winter wheat
------------------------------------------------------ --------------

altitude
(m): 15002000 20002500 25003000 01500
temperature (ºC): 17.520.0 15.017.5 12.515.0
inputs: low high low high low high low high
constraint: abcd abcd abcd abcd abcd
abcd abcd abcd

LGP: 75 89 2010 2010 2010 2010 2010
2010 2010 2010

90119 2000 2000 2010 2010 2010 2010
2010 2010
120149 1000 1000 1000 1000 2010
2010 2000 2000
150179 0000 0000 0000 0000 1000 1000
1000 1000
180209 0000 0000 0000 0000 0000
0000 0000 0000
210239 01100011 0100 0101 0000 0000
0100 0100
240269 0111 0111 01100111 01100111 0100 0100
270299 0221 0222 0221 0222 02110212
-- --
300329 0221 0222 0221 0222 0221
0222 -- --
330364 0222 0222 0222 0222 0222
0222 -- --
365 0222 0222 0222 0222 0222 0222
-- --

beans potato
------------------------------------------------------ ------------
--
altitude
(m): 15002000 20002500 25003000
15003000
temperature (ºC): 17.520.0 15.017.5 12.515.0 12.520.0
inputs: low high low high low high low high
constraint: abcd abcd abcd abcd abcd
abcd abcd abcd

LGP: 75 89 2020 2020 2020 2020 2020

2020 2010 2010
90119 2010 2010 2020 2020 2020
2020 2010 2010
120149 1000 1000 2010 2010 2020
2020 10011001
150179 0000 0000 0000 0000 10101010
0000 0000
180209 0100 0000 0100 0000 0100
0000 0000 0000
210239 01100001 01100001 01100000
0100 0101
240269 02110001 0210 0001 0210 0001
0111 0111
270299 02110102 02110102 02110102
02110212
300329 02110112 02110112 02110112 0221 0222
330364 0222 0122 0222 0122 0222
0122 0222 0222
365 0222 0222 0222 0222 0222 0222
0222 0222

maize
-----------------------------------------------------
altitude (m): 15001600 19002000
24002500
temperature (°C): 19.520.0 17.017.5 15.015.5
inputs: low high low high low high
constraint: abcd abcd abcd abcd abcd
abcd

LGP: 75
89 2120 2020 2120 2020 2120
2020
90119 2110 2010 2120 2020 2120

2020
120149 11001000 2120 2020 2120
2020
150179 0000 0000 10101010 2020 2020
180209 0000 0000 1000 1000
2020 2020
210239 0100 0001 0000 0000 2010
2010
240269 01010002 0000 0000 2010
2010
270299 01010102 0100 0001 11001001
300329 01010102 01010102 01010101
330364 0112 0112 0112 0112 0112 0112
365 0222 0222 0222 0222 0222 0222

sorghum
------------------------------------------------------
altitude (m): 15001600 19002000
24002500
temperature (°C): 19.520.0 17.017.5 15.015.5
inputs: low high low high low high
constraint: abcd abcd abcd abcd abcd
abcd

LGP: 75
89 2120 2020 2120 2020 2120
2020
90119 2110 2010 2120 2020 2120
2020
120149 11001000 2120 2020 2120
2020
150179 0000 0000 10101010 2020 2020
180209 0000 0000 1000 1000
2020 2020
210239 01100011 0000 0000 2020
2020
240269 0121 0022 0100 0001 2010
2010
270299 0221 0122 0111 0012 10101011
300329 0221 0222 0221 0122 0111
0112
330364 0222 0222 0222 0222 0222

0222
365 0222 0222 0222 0222 0222 0222

## A5. TENTATIVE RDSfr(org) RELATIONS

**The mass fractions of gross assimilate production that are apportioned to leaves, roots, stems and storage organs (fr(org)) are a function of the relative development stage (RDS) of the crop.**
**To determine RDSfr(org) relations, PS1 experiments must be repeatedly harvested. Monitoring temperature and radiation during the experiments allows to calculate relative development stages at successive harvests. The increments in organ mass between harvests (WIH(org)) are measured. Efficiencies of assimilate conversion (Ec(org)) are known (Table 8.2); gross production of assimilates (FgassH) and maintenance respiration losses between harvests (MRLH(org)) can be calculated.**

**fr(org) = (WIH(org) / Ec(org) + MRLH(org)) / FgassH**

**Linear interpolation between combinations of RDS and fr(org) is allowed.**

***Tentative combinations of RDS and fr(org)***

| | | | | | |
|---|---|---|---|---|---|
| barley | **RDS** | **0** | **0.20** | **0.59** | **>0.60** |
| **generic** | | | | | |
| **fr(leaf)** | **0.30** | **0.50** | **0.00** | **0.00** | |
| **fr(root)** | **0.70** | **0.50** | **0.00** | **0.00** | |
| **fr(stem)** | **0.00** | **0.00** | **1.00** | **0.00** | |
| **fr(s.o.)** | **0.00** | **0.00** | **0.00** | **1.00** | |

| | | | | | | |
|---|---|---|---|---|---|---|
| cassava | **RDS** | **0** | **0.03** | **0.08** | **0.16** | **>0.36** |
| **cv 'Faroka'** | | | | | | |
| **fr(leaf)** | **0.50** | **0.45** | **0.33** | **0.16** | **0.16** | |
| **fr(root)** | **0.40** | **0.30** | **0.24** | **0.03** | **0.03** | |
| **fr(stem)** | **0.10** | **0.25** | **0.43** | **0.66** | **0.29** | |
| **fr(s.o.)** | **0.00** | **0.00** | **0.00** | **0.15** | **0.52** | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| chick pea | **RDS** | **0** | **0.24** | **0.29** | **0.48** | **0.79** | **>0.87** |
| **generic** | | | | | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| fr(leaf) | 0.34 | 0.42 | 0.64 | 0.52 | 0.10 | 0.00 | |
| fr(root) | 0.33 | 0.17 | 0.20 | 0.00 | 0.00 | 0.00 | |
| fr(stem) | 0.33 | 0.41 | 0.16 | 0.48 | 0.40 | 0.00 | |
| fr(s.o.) | 0.00 | 0.00 | 0.00 | 0.00 | 0.50 | 1.00 | |
| cotton | RDS | 0 | 0.39 | 0.46 | 0.83 | >0.87 | |
| **chinese cv** | | | | | | | |
| fr(leaf) | 0.40 | 0.51 | 0.44 | 0.00 | 0.00 | | |
| fr(root) | 0.33 | 0.15 | 0.12 | 0.00 | 0.00 | | |
| fr(stem) | 0.27 | 0.34 | 0.44 | 0.10 | 0.00 | | |
| fr(s.o.) | 0.00 | 0.00 | 0.00 | 0.90 | 1.00 | | |
| cowpea | RDS | 0 | 0.32 | 0.51 | 0.63 | 0.77 | >0.86 |
| **generic** | | | | | | | |
| fr(leaf) | 0.60 | 0.76 | 0.54 | 0.33 | 0.00 | 0.00 | |
| fr(root) | 0.40 | 0.24 | 0.35 | 0.00 | 0.00 | 0.00 | |
| fr(stem) | 0.00 | 0.00 | 0.11 | 0.34 | 0.28 | 0.00 | |
| fr(s.o.) | 0.00 | 0.00 | 0.00 | 0.33 | 0.72 | 1.00 | |
| groundnut | RDS | 0 | 0.03 | 0.08 | 0.27 | 0.86 | 1 |
| **generic** | | | | | | | |
| fr(leaf) | 0.20 | 0.20 | 0.66 | 0.52 | 0.05 | 0.00 | |
| fr(root) | 0.20 | 0.20 | 0.20 | 0.10 | 0.00 | 0.00 | |
| fr(stem) | 0.60 | 0.60 | 0.14 | 0.38 | 0.24 | 0.00 | |
| fr(s.o.) | 0.00 | 0.00 | 0.00 | 0.00 | 0.71 | 1.00 | |
| jute | RDS | 0 | 0.20 | 0.30 | 0.50 | 1 | |
| **generic** | | | | | | | |
| fr(leaf) | 0.54 | 0.60 | 0.53 | 0.04 | 0.00 | | |
| fr(root) | 0.35 | 0.28 | 0.25 | 0.17 | 0.00 | | |
| fr(stem) | 0.11 | 0.12 | 0.22 | 0.79 | 1.00 | | |
| lentil | RDS | 0 | 0.30 | 0.60 | 1 | | |
| **generic** | | | | | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| fr(leaf) | 0.38 | 0.48 | 0.32 | 0.00 | | | |
| fr(root) | 0.37 | 0.20 | 0.02 | 0.02 | | | |
| fr(stem) | 0.25 | 0.32 | 0.66 | 0.00 | | | |
| fr(s.o.) | 0.00 | 0.00 | 0.00 | 0.98 | | | |
| | | | | | | | |
| maize **generic** | **RDS** | **0** | **0.20** | **0.30** | **0.60** | **>0.70** | |
| fr(leaf) | 0.60 | 0.70 | 0.65 | 0.16 | 0.00 | | |
| fr(root) | 0.40 | 0.30 | 0.23 | 0.06 | 0.00 | | |
| fr(stem) | 0.00 | 0.00 | 0.12 | 0.78 | 0.00 | | |
| fr(s.o.) | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | | |
| | | | | | | | |
| maize **cv 'Aris'** | **RDS** | **0** | **0.08** | **0.38** | **0.45** | **0.50** | **0.60** |
| fr(leaf) | 0.35 | 0.35 | 0.32 | 0.28 | 0.25 | 0.05 | |
| fr(root) | 0.35 | 0.30 | 0.08 | 0.04 | 0.00 | 0.00 | |
| fr(stem) | 0.30 | 0.35 | 0.60 | 0.68 | 0.70 | 0.40 | |
| fr(s.o.) | 0.00 | 0.00 | 0.00 | 0.00 | 0.05 | 0.55 | |
| RDS | 0.63 | >0.75 | | | | | |
| fr(leaf) | 0.00 | 0.00 | | | | | |
| fr(root) | 0.00 | 0.00 | | | | | |
| fr(stem) | 0.35 | 0.00 | | | | | |
| fr(s.o.) | 0.65 | 1.00 | | | | | |
| | | | | | | | |
| maize **cv 'Pioneer'** | **RDS** | **0** | **0.08** | **0.38** | **0.45** | **0.50** | |
| fr(leaf) | 0.35 | 0.35 | 0.32 | 0.28 | 0.25 | | |
| fr(root) | 0.35 | 0.30 | 0.08 | 0.04 | 0.00 | | |
| fr(stem) | 0.30 | 0.35 | 0.60 | 0.68 | 0.51 | | |
| fr(s.o.) | 0.00 | 0.00 | 0.00 | 0.00 | 0.24 | | |
| RDS | 0.60 | >0.63 | | | | | |
| fr(leaf) | 0.05 | 0.00 | | | | | |
| fr(root) | 0.00 | 0.00 | | | | | |
| fr(stem) | 0.08 | 0.35 | | | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| fr(s.o.) | 0.87 | 1.00 | | | | | |
| | | | | | | | |
| maize | RDS | 0 | 0.21 | 0.37 | 0.53 | 0.69 | |
| **cv 'Arjuna'** | | | | | | | |
| **fr(leaf)** | **0.32** | **0.48** | **0.35** | **0.13** | **0.07** | | |
| **fr(root)** | **0.38** | **0.13** | **0.13** | **0.06** | **0.06** | | |
| **fr(stem)** | **0.30** | **0.39** | **0.52** | **0.42** | **0.22** | | |
| **fr(s.o.)** | **0.00** | **0.00** | **0.00** | **0.39** | **0.65** | | |
| | | | | | | | |
| RDS | 0.80 | 1 | | | | | |
| | | | | | | | |
| **fr(leaf)** | **0.00** | **0.00** | | | | | |
| **fr(root)** | **0.00** | **0.00** | | | | | |
| **fr(stem)** | **0.18** | **0.00** | | | | | |
| **fr(s.o.)** | **0.82** | **1** | | | | | |
| | | | | | | | |
| millet | RDS | 0 | 0.16 | 0.50 | 0.78 | >0.91 | |
| **generic** | | | | | | | |
| **fr(leaf)** | **0.50** | **0.53** | **0.14** | **0.00** | **0.00** | | |
| **fr(root)** | **0.38** | **0.34** | **0.12** | **0.00** | **0.00** | | |
| **fr(stem)** | **0.12** | **0.13** | **0.74** | **0.64** | **0.00** | | |
| **fr(s.o.)** | **0.00** | **0.00** | **0.00** | **0.36** | **1.00** | | |
| | | | | | | | |
| mungbean | RDS | 0 | 0.33 | 0.39 | 0.60 | 0.67 | 1 |
| **generic** | | | | | | | |
| **fr(leaf)** | **0.42** | **0.56** | **0.48** | **0.00** | **0.00** | **0.00** | |
| **fr(root)** | **0.35** | **0.14** | **0.10** | **0.07** | **0.03** | **0.00** | |
| **fr(stem)** | **0.23** | **0.30** | **0.42** | **0.19** | **0.00** | **0.00** | |
| **fr(s.o.)** | **0.00** | **0.00** | **0.00** | **0.74** | **0.97** | **1.00** | |
| | | | | | | | |
| pigeon pea | RDS | 0 | 0.37 | 0.57 | 0.72 | 0.76 | |
| **generic** | | | | | | | |
| **fr(leaf)** | **0.38** | **0.38** | **0.33** | **0.28** | **0.28** | | |
| **fr(root)** | **0.24** | **0.24** | **0.24** | **0.23** | **0.19** | | |
| **fr(stem)** | **0.38** | **0.38** | **0.43** | **0.40** | **0.40** | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| fr(s.o.) | **0.00** | **0.00** | **0.00** | **0.09** | **0.13** | | |
| **RDS** | **0.89** | >**0.93** | | | | | |
| fr(leaf) | **0.08** | **0.00** | | | | | |
| fr(root) | **0.00** | **0.00** | | | | | |
| fr(stem) | **0.12** | **0.00** | | | | | |
| fr(s.o.) | **0.80** | **1.00** | | | | | |
| potato | **RDS** | **0** | **0.10** | **0.50** | >**0.80** | | |
| **generic** | | | | | | | |
| fr(leaf) | **0.70** | **0.60** | **0.00** | **0.00** | | | |
| fr(root) | **0.30** | **0.40** | **0.30** | **0.00** | | | |
| fr(stem) | **0.00** | **0.00** | **0.40** | **0.10** | | | |
| fr(s.o.) | **0.00** | **0.00** | **0.30** | **0.40** | | | |
| rice | **RDS** | **0** | **0.08** | **0.30** | **0.38** | **0.45** | |
| **generic** | | | | | | | |
| fr(leaf) | **0.38** | **0.40** | **0.48** | **0.47** | **0.42** | | |
| fr(root) | **0.60** | **0.32** | **0.08** | **0.08** | **0.07** | | |
| fr(stem) | **0.02** | **0.28** | **0.44** | **0.45** | **0.51** | | |
| fr(s.o.) | **0.00** | **0.00** | **0.00** | **0.00** | **0.00** | | |
| **RDS** | **0.60** | >**0.75** | | | | | |
| fr(leaf) | **0.21** | **0.00** | | | | | |
| fr(root) | **0.06** | **0.00** | | | | | |
| fr(stem) | **0.73** | **0.00** | | | | | |
| fr(s.o.) | **0.00** | **1.00** | | | | | |
| sesame | | **RDS** | **0** | **0.12** | **0.24** | **0.40** | **0.70** |
| **generic** | | | | | | | |
| fr(leaf) | **0.72** | **0.70** | **0.65** | **0.39** | **0.22** | | |
| fr(root) | **0.10** | **0.10** | **0.10** | **0.10** | **0.03** | | |
| fr(stem) | **0.18** | **0.20** | **0.25** | **0.51** | **0.31** | | |
| fr(s.o.) | **0.00** | **0.00** | **0.00** | **0.00** | **0.44** | | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **RDS** | **0.76** | **0.88** | **1** | | | | |
| | **fr(leaf)** | **0.21** | **0.21** | **0.00** | | | | |
| | **fr(root)** | **0.01** | **0.00** | **0.00** | | | | |
| | **fr(stem)** | **0.25** | **0.07** | **0.00** | | | | |
| | **fr(s.o.)** | **0.53** | **0.72** | **1.00** | | | | |
| sorghum | **RDS** | **0** | **0.22** | **0.34** | **0.56** | **0.61** | | |
| **generic** | | | | | | | | |
| | **fr(leaf)** | **0.45** | **0.55** | **0.65** | **0.25** | **0.13** | | |
| | **fr(root)** | **0.55** | **0.35** | **0.25** | **0.05** | **0.00** | | |
| | **fr(stem)** | **0.00** | **0.10** | **0.10** | **0.70** | **0.80** | | |
| | **fr(s.o.)** | **0.00** | **0.00** | **0.00** | **0.00** | **0.07** | | |
| | **RDS** | **0.65** | **>0.70** | | | | | |
| | **fr(leaf)** | **0.00** | **0.00** | | | | | |
| | **fr(root)** | **0.00** | **0.00** | | | | | |
| | **fr(stem)** | **0.85** | **0.00** | | | | | |
| | **fr(s.o.)** | **0.15** | **1.00** | | | | | |
| soya | **RDS** | **0** | **0.24** | **0.40** | **0.48** | **0.61** | **>0.74** | |
| **generic** | | | | | | | | |
| | **fr(leaf)** | **0.30** | **0.70** | **0.70** | **0.60** | **0.50** | **0.00** | |
| | **fr(root)** | **0.70** | **0.10** | **0.10** | **0.05** | **0.00** | **0.00** | |
| | **fr(stem)** | **0.00** | **0.20** | **0.20** | **0.25** | **0.20** | **0.00** | |
| | **fr(s.o.)** | **0.00** | **0.00** | **0.00** | **0.10** | **0.30** | **1.00** | |
| sugarcane | **RDS** | **0** | **0.14** | **0.45** | **0.90** | **>0.91** | | |
| **generic** | | | | | | | | |
| | **fr(leaf)** | **0.70** | **0.75** | **0.18** | **0.20** | **0.00** | | |
| | **fr(root)** | **0.30** | **0.25** | **0.15** | **0.03** | **0.03** | | |
| | **fr(stem)** | **0.00** | **0.00** | **0.67** | **0.77** | **0.00** | | |
| | **fr(s.o.)** | **0.00** | **0.00** | **0.00** | **0.00** | **0.97** | | |
| sunflower | **RDS** | **0** | **0.40** | **0.53** | **0.56** | **0.68** | **>0.75** | |
| **generic** | | | | | | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| fr(leaf) | 0.33 | 0.33 | 0.38 | 0.34 | 0.00 | 0.00 | |
| fr(root) | 0.34 | 0.34 | 0.24 | 0.16 | 0.00 | 0.00 | |
| fr(stem) | 0.33 | 0.33 | 0.38 | 0.50 | 0.28 | 0.00 | |
| fr(s.o.) | 0.00 | 0.00 | 0.00 | 0.00 | 0.72 | 1.00 | |
| | | | | | | | |
| sweet pepper | **RDS** | **0** | **0.48** | **1** | | | |
| **generic** | | | | | | | |
| fr(leaf) | 0.30 | 0.51 | 0.16 | | | | |
| fr(root) | 0.40 | 0.12 | 0.04 | | | | |
| fr(stem) | 0.30 | 0.37 | 0.14 | | | | |
| fr(s.o.) | 0.00 | 0.00 | 0.66 | | | | |
| | | | | | | | |
| tobacco | **RDS** | **0** | **0.10** | **0.50** | **1** | | |
| **generic** | | | | | | | |
| fr(leaf) | 0.40 | 0.50 | 0.66 | 0.66 | | | |
| fr(root) | 0.55 | 0.45 | 0.00 | 0.00 | | | |
| fr(stem) | 0.05 | 0.05 | 0.34 | 0.34 | | | |
| fr(s.o.) | 0.00 | 0.00 | 0.00 | 0.00 | | | |
| | | | | | | | |
| wheat | **RDS** | **0** | **0.11** | **0.20** | **0.35** | **0.47** | **>0.56** |
| **generic** | | | | | | | |
| fr(leaf) | 0.50 | 0.66 | 0.56 | 0.34 | 0.10 | 0.00 | |
| fr(root) | 0.50 | 0.34 | 0.23 | 0.09 | 0.04 | 0.00 | |
| fr(stem) | 0.00 | 0.00 | 0.21 | 0.57 | 0.86 | 0.00 | |
| fr(s.o.) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | |
| | | | | | | | |
| wheat | **RDS** | **0** | **0.08** | **0.30** | **0.31** | **0.46** | **>0.55** |
| **chinese cv** | | | | | | | |
| fr(leaf) | 0.50 | 0.65 | 0.26 | 0.24 | 0.09 | 0.00 | |
| fr(root) | 0.50 | 0.30 | 0.13 | 0.00 | 0.00 | 0.00 | |
| fr(stem) | 0.00 | 0.05 | 0.61 | 0.76 | 0.67 | 0.00 | |
| fr(s.o.) | 0.00 | 0.00 | 0.00 | 0.00 | 0.24 | 1.00 | |

A6. CAPILLARY RISE TABLES

**(After Rijtema, 1969)**

**Capillary rise (CR, in cm $d^{-1}$) is determined by matrix properties (assumedly correlated with the texture class) and hydraulic gradient. The latter is determined by the matric suction of the rooting zone (PSI) and the distance of capillary rise (ZT - RD).**

**An example: Consider a** rooting zone with an equivalent depth (RD) of 60 cm, in loamy fine sand with **a matric suction (PSI) of 500 cm. The phreatic level is at 170 cm below the soil surface.**
**The matrix component of the hydraulic head is +500 cm; the gravity component amounts to -(170-60) cm. The hydraulic gradient is (500 + -(170 - 60)) / (170 - 60), or 3.55 cm $cm^{-1}$. This** positive **gradient drives upward flow. The table for loamy fine sand suggests that the rate of capillary rise from the phreatic level (at 170 cm depth) to the rooting zone (with a matric suction of 500 cm and a lower boundary at 60 cm depth) is close to 0.40 cm $d^{-1}$.**

coarse sand

| CR:0.50 | 0.40 | 0.30 | 0.20 | 0.15 | 0.10 | 0.06 | 0.02 | |
|---|---|---|---|---|---|---|---|---|
| PSI: 20 | 19.8 | 19.9 | 19.9 | 19.9 | 19.9 | 20.0 | 20.0 | 20.0 |
| 5034.3 | 35.3 | 36.5 | 38.2 | 39.4 | 41.0 | 42.9 | 46.3 | |
| 10034.4 | 35.4 | 36.7 | 38.6 | 39.8 | 41.7 | 44.0 | 49.0 | |
| 25034.5 | 35.5 | 36.8 | 38.6 | 39.9 | 41.8 | 44.1 | 49.5 | |
| 50034.5 | 35.5 | 36.8 | 38.6 | 39.9 | 41.8 | 44.2 | 49.8 | |
| 1000 | 34.5 | 35.5 | 36.8 | 38.6 | 40.0 | 41.9 | 44.3 | 50.0 |
| 2500 | 34.5 | 35.5 | 36.8 | 38.7 | 40.0 | 41.9 | 44.4 | 50.2 |
| 5000 | 34.5 | 35.5 | 36.8 | 38.7 | 40.0 | 41.9 | 44.4 | 50.3 |
| 10000 | 34.5 | 35.5 | 36.8 | 38.7 | 40.0 | 41.9 | 44.4 | 50.3 |
| 16000 | 34.5 | 35.5 | 36.8 | 38.7 | 40.0 | 41.9 | 44.4 | 50.4 |

loamy fine sand

| CR:0.50 | 0.40 | 0.30 | 0.20 | 0.15 | 0.10 | 0.06 | 0.02 | |
|---|---|---|---|---|---|---|---|---|
| PSI: 20 | 19.4 | 19.5 | 19.7 | 19.8 | 19.8 | 19.9 | 19.9 | 20.0 |
| 5047.2 | 47.7 | 48.3 | 48.8 | 49.1 | 49.4 | 49.6 | 49.9 | |
| 10082.9 | 85.5 | 88.4 | 91.7 | 93.5 | 95.5 | 97.2 | 99.0 | |
| 250100.6 | 106.2 | 113.5 | 123.9 | 131.3 | 141.9 | 155.6 | 185.9 | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 500102.8 | 108.9 | 117.1 | 129.2 | 138.3 | 152.4 | 172.5 | 230.1 | |
| 1000 | 104.4 | 110.9 | 119.8 | 133.3 | 143.8 | 160.5 | 185.9 | 268.1 |
| 2500 | 106.0 | 112.9 | 122.4 | 137.2 | 149.1 | 168.4 | 199.0 | 306.6 |
| 5000 | 106.9 | 114.0 | 123.9 | 139.4 | 152.0 | 172.7 | 206.2 | 328.1 |
| 10000 | 107.5 | 114.8 | 125.0 | 141.0 | 154.2 | 176.0 | 211.7 | 344.5 |
| 16000 | 107.9 | 115.3 | 125.6 | 141.9 | 155.3 | 177.8 | 214.6 | 353.3 |

fine sand

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| CR:0.50 | 0.40 | 0.30 | 0.20 | 0.15 | 0.10 | 0.06 | 0.02 | |
| PSI: 20 | 19.7 | 19.7 | 19.8 | 19.9 | 19.9 | 19.9 | 20.0 | 20.0 |
| 5047.9 | 48.3 | 48.7 | 49.1 | 49.3 | 49.6 | 49.7 | 49.9 | |
| 10082.0 | 84.5 | 87.4 | 90.8 | 92.7 | 94.8 | 96.7 | 98.9 | |
| 25092.9 | 97.5 | 103.4 | 112.0 | 118.2 | 127.1 | 139.0 | 167.3 | |
| 50094.3 | 99.3 | 105.8 | 115.5 | 122.9 | 134.2 | 150.5 | 198.7 | |
| 1000 | 95.4 | 100.6 | 107.6 | 118.3 | 126.5 | 139.6 | 159.4 | 224.6 |
| 2500 | 96.5 | 101.9 | 109.4 | 120.9 | 130.0 | 144.8 | 168.2 | 250.5 |
| 5000 | 97.1 | 102.7 | 110.4 | 122.3 | 131.9 | 147.7 | 173.0 | 264.8 |
| 10000 | 97.5 | 103.2 | 111.1 | 123.4 | 133.4 | 149.9 | 176.6 | 275.7 |
| 16000 | 97.7 | 103.5 | 111.5 | 124.0 | 134.2 | 151.1 | 178.6 | 281.6 |

fine sandy loam

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| CR:0.50 | 0.40 | 0.30 | 0.20 | 0.15 | 0.10 | 0.06 | 0.02 | |
| PSI: 20 | 19.0 | 19.2 | 19.4 | 19.6 | 19.7 | 19.8 | 19.9 | 20.0 |
| 5046.2 | 46.9 | 47.7 | 48.4 | 48.8 | 49.2 | 49.5 | 49.8 | |
| 10085.4 | 87.8 | 90.5 | 93.3 | 94.9 | 96.5 | 97.9 | 99.3 | |
| 250127.9 | 136.1 | 146.6 | 161.1 | 171.1 | 184.6 | 200.1 | 225.9 | |
| 500131.7 | 140.9 | 152.9 | 170.5 | 183.4 | 202.5 | 228.3 | 293.4 | |
| 1000 | 134.4 | 144.2 | 157.3 | 177.1 | 192.1 | 215.5 | 249.6 | 351.8 |
| 2500 | 136.9 | 147.4 | 161.6 | 183.4 | 200.6 | 228.2 | 270.6 | 413.0 |
| 5000 | 138.3 | 149.1 | 163.9 | 186.9 | 205.3 | 235.2 | 282.2 | 447.6 |
| 10000 | 139.4 | 150.5 | 165.7 | 189.6 | 208.8 | 240.5 | 291.1 | 474.0 |
| 16000 | 140.0 | 151.2 | 166.7 | 191.0 | 210.8 | 243.3 | 295.8 | 488.2 |

silt loam

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| CR:0.50 | 0.40 | 0.30 | 0.20 | 0.15 | 0.10 | 0.06 | 0.02 | |
| PSI: 20 | 18.3 | 18.6 | 18.9 | 19.3 | 19.4 | 19.6 | 19.8 | 19.9 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 5044.2 | 45.3 | 46.3 | 47.5 | 48.1 | 48.7 | 49.2 | 49.7 | |
| 10081.2 | 84.2 | 87.6 | 91.3 | 93.3 | 95.4 | 97.2 | 99.0 | |
| 250127.8 | 137.2 | 149.2 | 165.7 | 176.8 | 191.3 | 207.3 | 231.3 | |
| 500134.7 | 145.8 | 160.6 | 182.3 | 198.3 | 222.0 | 254.0 | 330.7 | |
| 1000 | 139.4 | 151.7 | 168.4 | 193.9 | 213.7 | 244.7 | 290.6 | 425.8 |
| 2500 | 144.0 | 157.4 | 176.0 | 205.2 | 228.7 | 267.2 | 327.7 | 531.2 |
| 5000 | 146.5 | 160.5 | 180.2 | 211.5 | 237.1 | 279.6 | 348.4 | 592.1 |
| 10000 | 148.4 | 162.9 | 183.3 | 216.2 | 243.4 | 289.1 | 364.2 | 639.1 |
| 16000 | 149.4 | 164.2 | 185.0 | 218.7 | 246.8 | 294.2 | 372.6 | 664.5 |

loam

| CR:0.50 | 0.40 | 0.30 | 0.20 | 0.15 | 0.10 | 0.06 | 0.02 | |
|---|---|---|---|---|---|---|---|---|
| PSI: 20 | 17.7 | 18.2 | 18.6 | 19.0 | 19.3 | 19.5 | 19.7 | 19.9 |
| 5042.2 | 43.5 | 45.0 | 46.5 | 47.3 | 48.2 | 48.9 | 49.6 | |
| 10074.0 | 77.7 | 82.1 | 87.0 | 89.8 | 92.9 | 95.6 | 98.5 | |
| 250102.5 | 111.0 | 122.1 | 137.8 | 148.8 | 164.0 | 182.0 | 214.3 | |
| 500104.7 | 113.8 | 125.9 | 143.3 | 156.1 | 174.7 | 199.3 | 258.6 | |
| 1000 | 106.2 | 115.6 | 128.3 | 146.9 | 160.9 | 181.9 | 211.1 | 292.3 |
| 2500 | 107.6 | 117.4 | 130.6 | 150.4 | 165.5 | 188.8 | 222.6 | 326.2 |
| 5000 | 108.3 | 118.3 | 131.8 | 152.3 | 168.1 | 192.6 | 228.9 | 345.1 |
| 10000 | 108.9 | 119.1 | 132.8 | 153.8 | 170.0 | 195.5 | 233.7 | 359.5 |
| 16000 | 109.2 | 119.4 | 133.3 | 154.5 | 171.0 | 197.0 | 236.3 | 367.3 |

loess loam

| CR:0.50 | 0.40 | 0.30 | 0.20 | 0.15 | 0.10 | 0.06 | 0.02 | |
|---|---|---|---|---|---|---|---|---|
| PSI: 20 | 18.9 | 19.1 | 19.3 | 19.5 | 19.7 | 19.8 | 19.9 | 20.0 |
| 5043.8 | 44.9 | 46.0 | 47.3 | 47.9 | 48.6 | 49.1 | 49.7 | |
| 10065.4 | 69.0 | 73.3 | 78.9 | 82.4 | 86.8 | 91.1 | 96.6 | |
| 25072.0 | 77.1 | 83.8 | 93.9 | 101.5 | 113.1 | 129.3 | 169.4 | |
| 50075.0 | 80.8 | 88.7 | 101.2 | 111.1 | 127.2 | 151.9 | 226.4 | |
| 1000 | 77.2 | 83.6 | 92.5 | 106.8 | 118.6 | 138.4 | 170.2 | 277.1 |
| 2500 | 79.4 | 86.3 | 96.1 | 112.2 | 125.9 | 149.2 | 188.2 | 329.7 |
| 5000 | 80.6 | 87.8 | 98.1 | 115.2 | 129.8 | 155.2 | 198.1 | 359.2 |
| 10000 | 81.5 | 88.9 | 99.6 | 117.5 | 132.9 | 159.7 | 205.6 | 381.8 |
| 16000 | 82.0 | 89.5 | 100.4 | 118.7 | 134.5 | 162.1 | 209.7 | 393.9 |

sandy clay loam

| CR:0.50 | 0.40 | 0.30 | 0.20 | 0.15 | 0.10 | 0.06 | 0.02 | |
|---|---|---|---|---|---|---|---|---|
| PSI: 20 | 19.4 | 19.5 | 19.6 | 19.8 | 19.8 | 19.9 | 19.9 | 20.0 |
| 5047.3 | 47.8 | 48.3 | 48.9 | 49.1 | 49.4 | 49.7 | 49.9 | |
| 10085.1 | 87.5 | 90.1 | 93.0 | 94.6 | 96.3 | 97.7 | 99.2 | |
| 250110.2 | 116.5 | 124.8 | 136.5 | 144.9 | 156.9 | 172.1 | 203.6 | |
| 500114.6 | 122.0 | 132.0 | 147.2 | 158.9 | 177.3 | 204.3 | 279.5 | |
| 1000 | 118.0 | 126.2 | 137.6 | 155.5 | 169.9 | 193.6 | 230.9 | 351.2 |
| 2500 | 121.2 | 130.2 | 143.0 | 163.6 | 180.7 | 209.7 | 257.4 | 427.8 |
| 5000 | 123.0 | 132.5 | 145.9 | 168.0 | 186.6 | 218.6 | 272.2 | 471.5 |
| 10000 | 124.3 | 134.1 | 148.2 | 171.4 | 191.1 | 225.3 | 283.4 | 504.9 |
| 16000 | 125.1 | 135.1 | 149.4 | 173.2 | 193.5 | 228.9 | 289.4 | 523.0 |

silty clay loam

| CR:0.50 | 0.40 | 0.30 | 0.20 | 0.15 | 0.10 | 0.06 | 0.02 | |
|---|---|---|---|---|---|---|---|---|
| PSI: 20 | 14.0 | 14.9 | 15.9 | 17.1 | 17.7 | 18.4 | 19.0 | 19.7 |
| 5031.0 | 33.5 | 36.5 | 40.0 | 42.1 | 44.4 | 46.5 | 48.8 | |
| 10048.1 | 53.1 | 59.4 | 67.9 | 73.3 | 80.0 | 86.6 | 94.9 | |
| 25059.5 | 66.9 | 77.1 | 92.5 | 103.9 | 120.6 | 142.3 | 187.3 | |
| 50064.2 | 72.8 | 84.9 | 103.9 | 118.8 | 142.3 | 176.4 | 266.9 | |
| 1000 | 67.8 | 77.3 | 90.8 | 112.8 | 130.6 | 159.8 | 204.8 | 342.9 |
| 2500 | 71.2 | 81.6 | 96.6 | 121.4 | 142.1 | 177.0 | 233.2 | 424.6 |
| 5000 | 73.1 | 84.0 | 99.8 | 126.2 | 148.5 | 186.5 | 249.0 | 471.3 |
| 10000 | 74.6 | 85.8 | 102.2 | 129.8 | 153.3 | 193.7 | 261.0 | 507.2 |
| 16000 | 75.4 | 86.8 | 103.5 | 131.7 | 155.9 | 197.6 | 267.4 | 526.5 |

clay loam

| CR:0.50 | 0.40 | 0.30 | 0.20 | 0.15 | 0.10 | 0.06 | 0.02 | |
|---|---|---|---|---|---|---|---|---|
| PSI: 20 | 12.1 | 13.1 | 14.3 | 15.8 | 16.7 | 17.7 | 18.5 | 19.5 |
| 5025.6 | 28.3 | 31.7 | 36.0 | 38.6 | 41.7 | 44.7 | 48.1 | |
| 10037.6 | 42.4 | 48.8 | 57.7 | 63.8 | 71.8 | 80.3 | 92.0 | |
| 25043.6 | 49.7 | 58.2 | 71.2 | 80.9 | 95.2 | 113.7 | 153.9 | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 50043.9 | 50.1 | 58.7 | 71.9 | 81.8 | 96.5 | 116.0 | 160.5 | |
| 1000 | 44.0 | 50.3 | 59.0 | 72.3 | 82.4 | 97.4 | 117.4 | 164.7 |
| 2500 | 44.2 | 50.5 | 59.2 | 72.7 | 82.9 | 98.2 | 118.7 | 168.8 |
| 5000 | 44.3 | 50.6 | 59.4 | 72.9 | 83.2 | 98.6 | 119.5 | 171.0 |
| 10000 | 44.4 | 50.7 | 59.5 | 73.1 | 83.4 | 99.0 | 120.0 | 172.7 |
| 16000 | 44.4 | 50.7 | 59.6 | 73.2 | 83.6 | 99.1 | 120.4 | 173.6 |

light clay

| CR:0.50 | 0.40 | 0.30 | 0.20 | 0.15 | 0.10 | 0.06 | 0.02 | |
|---|---|---|---|---|---|---|---|---|
| PSI: 20 | 17.1 | 17.6 | 18.1 | 18.7 | 19.0 | 19.3 | 19.6 | 19.9 |
| 5040.8 | 42.4 | 44.0 | 45.8 | 46.8 | 47.8 | 48.7 | 49.5 | |
| 10073.5 | 77.4 | 81.9 | 87.0 | 89.9 | 93.0 | 95.6 | 98.5 | |
| 250114.5 | 124.7 | 137.9 | 156.0 | 168.3 | 184.5 | 202.4 | 229.3 | |
| 500122.5 | 134.6 | 150.8 | 174.8 | 192.6 | 219.1 | 254.6 | 337.3 | |
| 1000 | 128.0 | 141.5 | 159.9 | 188.4 | 210.6 | 245.5 | 297.0 | 445.3 |
| 2500 | 133.4 | 148.2 | 168.8 | 201.7 | 228.3 | 271.9 | 340.4 | 567.4 |
| 5000 | 136.3 | 151.8 | 173.7 | 209.0 | 238.1 | 286.5 | 364.7 | 638.8 |
| 10000 | 138.5 | 154.6 | 177.4 | 214.6 | 245.5 | 297.6 | 383.2 | 693.9 |
| 16000 | 139.7 | 156.1 | 179.4 | 217.6 | 249.5 | 303.6 | 393.1 | 723.7 |

silty clay

| CR:0.50 | 0.40 | 0.30 | 0.20 | 0.15 | 0.10 | 0.06 | 0.02 | |
|---|---|---|---|---|---|---|---|---|
| PSI: 20 | 12.3 | 13.3 | 14.5 | 15.9 | 16.8 | 17.7 | 18.6 | 19.5 |
| 5022.3 | 24.8 | 28.0 | 32.3 | 35.2 | 38.8 | 42.4 | 47.1 | |
| 10028.5 | 32.3 | 37.5 | 45.3 | 51.0 | 59.2 | 69.0 | 85.6 | |
| 25035.0 | 40.3 | 48.0 | 60.5 | 70.5 | 86.5 | 109.3 | 163.0 | |
| 50038.7 | 44.9 | 54.1 | 69.5 | 82.4 | 103.9 | 136.8 | 230.1 | |
| 1000 | 41.5 | 48.4 | 58.8 | 76.5 | 91.7 | 117.7 | 159.4 | 291.8 |
| 2500 | 44.2 | 51.8 | 63.3 | 83.3 | 100.7 | 131.2 | 181.7 | 356.7 |
| 5000 | 45.7 | 53.7 | 65.8 | 87.0 | 105.7 | 138.6 | 194.1 | 393.4 |
| 10000 | 46.9 | 55.1 | 67.7 | 89.8 | 109.5 | 144.3 | 203.5 | 421.5 |
| 16000 | 47.5 | 55.9 | 68.7 | 91.3 | 111.5 | 147.3 | 208.6 | 436.7 |

heavy clay

| CR:0.50 | 0.40 | 0.30 | 0.20 | 0.15 | 0.10 | 0.06 | 0.02 | |
|---|---|---|---|---|---|---|---|---|
| PSI: 20 | 4.7 | 5.5 | 6.7 | 8.6 | 10.0 | 12.0 | 14.3 | 17.6 |
| 507.9 | 9.5 | 11.7 | 15.5 | 18.5 | 23.1 | 29.0 | 39.8 | |
| 1009.4 | 11.3 | 14.1 | 19.0 | 23.1 | 29.6 | 38.9 | 60.5 | |
| 25010.6 | 12.7 | 16.1 | 21.9 | 26.9 | 35.3 | 48.1 | 84.7 | |
| 50011.2 | 13.6 | 17.2 | 23.5 | 29.1 | 38.5 | 53.3 | 99.8 | |
| 1000 | 11.7 | 14.2 | 18.0 | 24.8 | 30.7 | 40.9 | 57.4 | 111.7 |
| 2500 | 12.2 | 14.8 | 18.8 | 25.9 | 32.3 | 43.3 | 61.3 | 123.4 |
| 5000 | 12.4 | 15.1 | 19.2 | 26.6 | 33.1 | 44.5 | 63.4 | 129.8 |
| 10000 | 12.6 | 15.3 | 19.5 | 27.1 | 33.8 | 45.5 | 65.0 | 134.7 |
| 16000 | 12.7 | 15.5 | 19.7 | 27.3 | 34.1 | 46.0 | 65.9 | 137.3 |

peat

| CR:0.50 | 0.40 | 0.30 | 0.20 | 0.15 | 0.10 | 0.06 | 0.02 | |
|---|---|---|---|---|---|---|---|---|
| PSI: 20 | 15.4 | 16.1 | 16.9 | 17.8 | 18.3 | 18.8 | 19.3 | 19.7 |
| 5022.9 | 24.8 | 27.1 | 30.4 | 32.7 | 35.8 | 39.3 | 45.0 | |
| 10024.6 | 26.8 | 29.8 | 34.4 | 37.8 | 43.1 | 50.3 | 67.7 | |
| 25026.2 | 28.9 | 32.6 | 38.4 | 43.1 | 50.9 | 62.8 | 99.4 | |
| 50027.1 | 30.0 | 34.1 | 40.7 | 46.1 | 55.3 | 70.1 | 120.1 | |
| 1000 | 27.8 | 30.9 | 35.2 | 42.4 | 48.4 | 58.7 | 75.8 | 136.6 |
| 2500 | 28.5 | 31.7 | 36.3 | 44.0 | 50.6 | 62.0 | 81.3 | 152.9 |
| 5000 | 28.8 | 32.1 | 36.9 | 44.9 | 51.8 | 63.8 | 84.3 | 161.9 |
| 10000 | 29.1 | 32.5 | 37.4 | 45.6 | 52.7 | 65.2 | 86.5 | 168.8 |
| 16000 | 29.3 | 32.7 | 37.6 | 46.0 | 53.2 | 65.9 | 87.8 | 172.4 |

== NOTES ==

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LIST OF SYMBOLS AND ABBREVIATIONS

LIST OF SYMBOLS AND ABBREVIATIONS

**$a$ is coefficient in Angström equation**
**AASM is actual (momentary) amount of available moisture (cm)**
**$A_c$ is** theoretical **photosynthetically active radiation on clear day (cal cm$^2$ d$^1$) See Table 4.5.**
**$A_i$ is sufficiency of available water capacity of layer i**
**AIRDIFF is vapour diffusion coefficient in air (cm$^2$ d$^{-1}$ mbar$^{-1}$)**
**ALFA is texturespecific geometry constant (cm$^{-1}$)**
**AMAX is maximum rate of assimilation at actual temperature (kg ha$^{-1}$ h$^{-1}$)**
**AK is texturespecific empirical constant (cm$^{-2.4}$ d$^{-1}$)**
**ASSC is actual surface storage capacity (cm)**
**Awc is available water capacity (cm$^3$ cm$^{-3}$)**
**$b$ is coefficient in Angström equation**
**$b_c$ daily gross assimilation rate (areic mass rate of $CH_2O$, kg ha$^{-1}$ d$^{-1}$) of reference crop canopy on clear day**
**BD is bulk density (Mg m$^{-3}$)**
**$b_{gm}$ is gross assimilation rate of reference crop (kg ha$^{-1}$ d$^{-1}$)**
**$b_{gma}$ is gross assimilation rate of field crop with closed canopy at maximum growth and constant assimilation rate $P_{max}$ (kg ha$^{-1}$ d$^{-1}$)**
**$B_i$ is sufficiency of aeration of layer i**
**$b_{mr}$ is average rate of maintenance respiration (kg ha$^{-1}$ d$^{-1}$)**
**$B_n$ is total areic mass of dry matter produced (kg ha$^{-1}$)**
**$b_{nm}$ is average rate of biomass production by a field crop (kg ha$^{-1}$ d$^{-1}$)**
**$b_o$ daily gross rate of assimilation of reference crop canopy on overcast days (kg ha$^{-1}$ d$^{-1}$)**
**BU(el) is base uptake of element 'el' (kg ha$^{-1}$)**
**$B_{ya}$ is constraintfree yield (kg ha$^{-1}$)**
**cf(temp) is correction factor for suboptimum daily temperature (from 0 to 1.0)**
**cf(water) is correction factor for suboptimum availability of water (= 1.0 in PS1)**
**$C_i$ is sufficiency of bulk density of layer i**
**CR is rate of capillary rise (cm d$^{-1}$)**
**$C_t$ is mass fraction rate of gross assimilate production (as $CH_2O$) lost by maintenance respiration with respect to dry crop mass at temperature $T_{24h}$ (kg kg$^{-1}$ d$^{-1}$)**
**CY is yield from unfertilized field (kg ha$^{-1}$)**
**$C_{30}$ is average gross rate of maintenance respiration at 30 °C, set to 0.0283 kg kg$^{-1}$ d$^{-1}$ for leguminous crops and 0.0108 kg kg$^{-1}$ d$^{-1}$ for other**

crops
$D$is rate of percolation from rooting zone to groundwater (cm $d^{-1}$)
DAYis Julian day number on northern hemisphere, or Julian day number plus or minus 182 on southern hemisphere
DECis declination of the sun (degree)
DELTZTis change in phreatic level (cm)
$D_i$ is sufficiency of pH of layer i

DMDA is ratio of diffusion coefficients of mulch layer and air
DMMULis equivalent depth of mulch layer (cm)
dris surface roughness or furrow depth (cm)
DRDS is increase in relative development over a time interval
DSis rate at which surfacestored water sags into the rooting zone (cm $d^{-1}$)
DT is length of interval (d)
DWI(org)is increase of dry organ mass in a time interval (kg $ha^{-1}$)
$D_1$ is depth of upper boundary of layer i (cm)
$D_2$ is depth of lower boundary of layer i (cm)
EA is actual rate of evaporation (cm $d^{-1}$)
$E_{bare}$is rate of evaporation from bare soil (cm $d^{-1}$)
Ecis efficiency of conversion (generic value = 0.72 kg $kg^{-1}$)
EC(el)is mass fraction of nutrient 'el' in fertilizer 'f' (kg $kg^{-1}$)
Ec(org)is efficiency of assimilate conversion in plant part 'org' (kg $kg^{-1}$)
$E_d$is efficiency of application
$E_f$is field canal efficiency
EFFis light use efficiency at low light intensity (= 0.5 kg $ha^{-1}$ $h^{-1}$ / J $m^{-2}$ $s^{-1}$)
$E_i$ is sufficiency of electrical conductivity of layer i
$E_i$is efficiency of conveyance
EM is maximum rate of evaporation (cm $d^{-1}$)
EMSis number of intervals between emergence and beginning of midseason stage of crop development
ET is actual rate of evapotranspiration (cm $d^{-1}$)
ETm is maximum rate of evapotranspiration (cm $d^{-1}$)
ET0 is potential rate of evapotranspiration (cm $d^{-1}$)
E0is potential rate of evaporation (cm $d^{-1}$)
$F$ is rate of water flow (cm $d^{-1}$)
Fgassis gross rate of assimilate production by a field crop (kg $ha^{-1}$ $d^{-1}$)
Fgcis gross rate of $CO_2$reduction by a closed reference crop (kg $ha^{-1}$ $d^{-1}$)
FR(f)is fertilizer requirement (kg $ha^{-1}$)
fr(org)is mass fraction of Fgass allocated to organ 'org'. (See Appendix A5 and Figure 8.3)

f0 is time fraction of cloud cover (d $d^{-1}$)
*G*is gravity component of hydraulic head, equal to negative vertical distance between points of flow (cm)
GAA(org)is gross rate of assimilate supply to plant part 'org' (kg $ha^{-1}$ $d^{-1}$)
GAM is texturespecific constant ($cm^{-2}$; see Table 6.4)
$G_i$ is sufficiency of gravel content of layer i
GROSSUPis gross rate of water supply to upper boundary of rooting zone (cm $d^{-1}$)
hi is harvest index (0 - 1)
IEis effective rate of irrigation (cm $d^{-1}$)
IGis gross rate of water release at project headworks (cm $d^{-1}$)
IMis actual infiltration rate (cm $d^{-1}$)
INTPERCis equivalent rate of percolation from rooted surface soil (cm $d^{-1}$)
INTSUFFis sufficiency of water availability during time interval (0 1)
kc is crop coefficient

$kc_{ref}$ is crop coefficient of short green reference crop
KMULis hydraulic conductivity of mulch layer (cm $d^{-1}$)
KPSI is hydraulic conductivity of soil with matric suction PSI (cm $d^{-1}$)
$K_{tr}$is hydraulic permeability of transmission zone (cm $d^{-1}$)
$K_x$ is temperature of environment 'x' (K)
K0 is saturated hydraulic conductivity (cm $d^{-1}$)
*L*is number of intervals elapsed since emergence
LAIis leaf area index
LATis latitude of site (degree)
LCHRis land characteristic
livS(leaf)is dry mass of all living leaves (kg $ha^{-1}$)
$L_m$is correction factor for incomplete ground cover
LQis land quality
LUis landunit
LURis land-use requirement
LUSis land-use system
LUTis land utilization type
$L_x$ is distance of flow (cm)
MCSTR(el)is minimum concentration of element 'el' in crop residue (kg $kg^{1}$)
MCY(el)is minimum concentration of element 'el' in economic produce (kg $kg^{-1}$)
MRRref(org)is maintenance respiration rate of living plant part 'org' at reference temperature (kg $ha^{-1}$ $d^{-1}$)

MRR(org)is rate of maintenance respiration of plant part 'org' at actual (daily) temperature and actual availability of water (kg $ha^{-1}$ $d^{-1}$)
MSis 'marginally suitable'; agroclimatic suitability class, anticipated yield 20 40% of reference yield
MULWATis calculated amount of water in mulch layer at end of interval (cm)
MUR is maximum rate of water uptake by roots (cm $d^{-1}$)
Mw is mass of water (kg $mole^{-1}$)
Nis 'not suitable'
NETSUPis net rate of water supply to upper boundary of rooting zone (cm $d^{-1}$)
*Ng*is length of growing cycle (d)
NRis 'not relevant'
NSis 'not suitable'; agroclimatic suitability class, anticipated yield < 20% of reference yield
NUR(el)is nutrient uptake requirement, i.e. net quantity of nutrient 'el' that must be taken up for target production (kg $ha^{-1}$)
N1is 'currently not suitable'
N2is 'permanently not suitable'
*p* is depletion fraction (Tables 5.2)
PARis photosynthetically active radiation at the outer extremity of the atmosphere (J $m^{-2}$ $s^{-1}$)
PARCANis photosynthetically active radiation at top of canopy (J $m^{-2}$ $s^{-1}$)
PHIis average slope of land (degree)
PI is a constant (PI = 3.14159)
$PI_{soil}$ is soilproductivity index

$P_{max}$is maximum assimilation rate of field crop (kg $ha^{-1}$ $h^{-1}$). See Table 4.6
PREC is gauged rate of precipitation (cm $d^{-1}$)
PSI is matric suction of rooted soil (cm)
PSIATMis matric suction of airdry soil (cm)
PSIatuis moisture potential of soil in equilibrium with atmosphere (J $kg^{-1}$)
$PSI_{cr}$is critically high soil matric suction (cm)
PSIintis matric suction at planting or germination (cm)
$PSI_{leaf}$ is critical leaf water head (cm)
$PSI_{max}$ is texturespecific suction boundary (cm)
PSIMULis equivalent matric suction of mulch layer (cm)
$Q_{10}$is factor by which process speed increases if temperature rises 10 °C ($Q_{10}$ = 2 for enzymatic processes)

RADis a conversion factor (degree to radian; RAD = PI / 180)
RD is equivalent depth of uniformly rooted surface layer (cm)
RDintis equivalent rooting depth at planting or emergence (cm)
RDm is maximum depth of rooting system (cm)
RDNis fraction of SC at latitude LAT and day DAY
RDS is relative development stage
$RDS_{root}$ is (tabulated) RDS at which root growth ceases (see Table 6.3)
RF(el)is recovery fraction of fertilizernutrient 'el' (kg $kg^{-1}$)
$R_g$ is gass constant (J $mole^{-1}$ $K^{-1}$)
$R_g$ is measured total incoming radiation (cal $cm^{-2}$ $d^{-1}$)
RHA is relative humidity of atmosphere (0 - 1)
RHMULis relative humidity of air in equilibrium with soil material with suction PSIMUL (0 1)
RHSis relative humidity of air in soil (0 1)
r(org)is organspecific relative maintenance respiration rate (kg $kg^{-1}$ $d^{-1}$)
$R_{plant}$ represents resistance to flow in the plant (d)
$R_{root}$ represents resistance to flow to the roots (d)
RSMis rate of change of volume fraction of moisture in rooting zone ($d^{-1}$)
Sis 'suitable'; anticipated yield 40 80% of reference yield
SC is solar constant (SC = 1 353 J $m^{-2}$ $s^{-1}$)
SD is depth of soil (cm)
SDI is soil depth index
SEIis soil erodability index
SIGis clod angle or furrow angle (degree)
SLA is specific leaf area ($m^2$ $kg^{-1}$)
$SLA_{max}$is maximum specific leaf area ($m^2$ $kg^{-1}$)
$SLA_{min}$is minimum specific leaf area ($m^2$ $kg^{-1}$)
$S(leaf)_{LRDS}$is living leaf mass when RDS is ((present)RDS - Tleaf / Tsum) (kg $ha^{-1}$)
SMCR is critical volume fraction of moisture in soil ($cm^3$ $cm^{-3}$)
SMEQis soil moisture equivalent, i.e. volume fraction of moisture in soil with matric suction PSI = 333 cm or pF 2.52 ($cm^3$ $cm^{-3}$)
SMFC is volume fraction of moisture in soil at field capacity ($cm^3$ $cm^{-3}$)
SMMULis moisture content of mulch at beginning of interval ($cm^3$ $cm^{-3}$)
SMPSI is volume fraction of moisture in soil with suction PSI ($cm^3$ $cm^{-3}$)

SMPWPis volume fraction of moisture at permanent wilting point ($cm^3$ $cm^{-3}$)

SM0 is total pore fraction ($cm^3$ $cm^{-3}$; see Table 6.4)
S(org)is dry mass of living plant part 'org' (kg $ha^{-1}$)
SPSIis actual sorptivity (cm $d^{-0.5}$)
SRis rate of surface runoff (cm $d^{-1}$)
SSis equivalent depth of water on flooded or ponded land (cm)
SSCis equivalent surface storage capacity (cm)
SSintis actual surface storage at planting or emergence (cm)
SUNH is number of sun hours (h $d^{-1}$)
SVAP is saturated vapour pressure (mbar)
S0is reference sorptivity (cm $d^{-0.5}$)
S1is 'highly suitable'
S2is 'moderately suitable'
S3is 'marginally suitable'
TASM is maximum possible amount of available moisture (cm)
TBP is total biomass production (kg $ha^{-1}$ $year^{-1}$)
TC is momentary turbulence coefficient
TCM is (tabulated) maximum turbulence coefficient
$T_{day}$ is daytime temperature (°C)
TDMis total dry mass (kg $ha^{-1}$)
TDMtargetis set production target (kg $ha^{-1}$)
TLDMis total living dry mass (kg $ha^{-1}$)
Tleafis heat requirement for full leaf development (°C d)
Tmainis reference temperature for maintenance respiration (°C)
Tmax is maximum daily temperature (°C)
Tmin is minimum daily temperature (°C)
TR is actual rate of transpiration (cm $d^{-1}$)
TRANSis atmospheric transmission
Tref is reference temperature (°C)
TRICKLEis rate of precipitation trickling down into the soil (cm $d^{-1}$)
TRM is maximum rate of transpiration (cm $d^{-1}$)
TR0is potential rate of transpiration (cm $d^{-1}$)
Tsum is heat requirement for full development of plant (°C d)
T0 is threshold temperature for development (°C)
$T_{24h}$is average daily temperature (°C)
UPFLUXis net rate of water (vapour) flow through upper boundary of rooting zone (cm $d^{-1}$)
VAPFLUXis maximum vapour flux through mulch layer (cm $d^{-1}$)
VAPSUPPLY is maximum rate of water vapour supply to upper boundary of mulch
layer (cm $d^{-1}$)
VSis 'very suitable'; agroclimatic suitability class, anticipated yield > 80% of reference yield

WATSUPPLY is rate of upward water flow to lower boundary of mulch layer (cm $d^{-1}$)
$WF_i$ is weighting factor for layer i
$x$ is cropspecific coefficient ($cm^{-1}$)

$y$represents the difference between maximum assimilation rate of a field crop ($P_{max}$) and fixed reference assimilation rate (20 kg $ha^{-1}$ $h^{-1}$)
$Y$is 'ET = ETm counter'
Ym is maize (grain) yield of maizepigeon pea intercrop (kg $ha^{-1}$ $year^{-1}$)
Ypp is pigeon pea (grain) yield (kg $ha^{-1}$ $year^{-1}$)
Ytargetis set yield target (kg $ha^{-1}$)
ZTis depth of phreatic level (cm)
ZTintis depth of phreatic level at planting or emergence (cm).