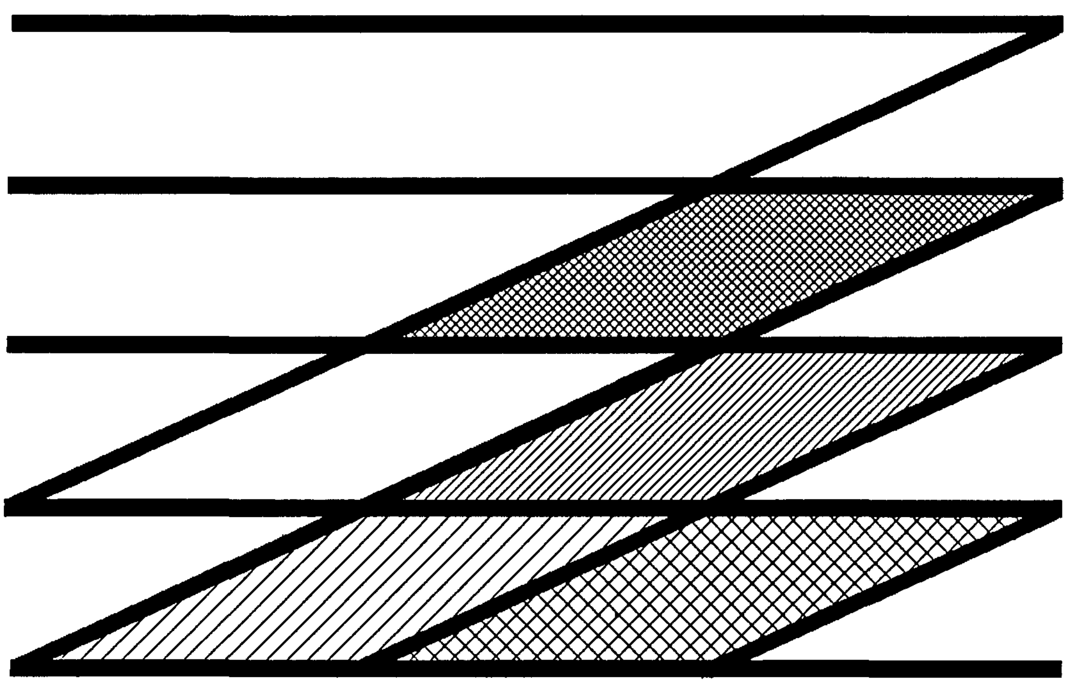
Land-use systems analysis



P.M. Driessen
N.T. Konijn

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Wageningen Agricultural University
Department of Soil Science & Geology
Duivendaal 10
6701 AR Wageningen The Netherlands

INRES
Cooperation between Universitas Brawijaya,
Wageningen Agricultural University and
State University Leyden
Jl. Mayor Jenderal Haryono 169
Malang 65113 Indonesia

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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 socio-economic 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 semi-quantitative 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 single-letter 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. Non-physical 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 single-land-use system is the configuration whose performance is analysed in assessment of land suitability.

Multiple-land-use systems (i.e. more than one crop on a field at one time) and **compound-land-use systems** (i.e. single or multiple systems in rotation) can be handled by combining analyses of single-land-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**. Non-permanent 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 basin-irrigated 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.

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 lower-case 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. e: erosion zie volgende bladzijde voor de afkortingen.

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 lower-case 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.

FAO classification scheme

Table 1.2. Structure of land suitability classification.

Order		**Class** degrees of suitability	**Subclass** kind of limitation	**Unit**
S	suitable	S1	S2m	S2e-1
		S2	S2e	S2e-2
		S3	S2me	etc.
		etc.	etc.	
	conditionally suitable	Sc3	Sc3m	
		etc.	etc.	
N	not suitable	N1	N1m	
		N2	N1e	
			etc.	

Subclass:
m = moisture availability
o = oxygen "
n = nutrient "
e = resistance to erosion
w = workability
c = climatic hazard

CHAPTER 2

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 single-land-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 single-land-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 single-land-use system with an annual crop.

	LAND-USE 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								

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** crop-specific. 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 small-scale mixed farming with intermediate technology (Nyandat & Muchena, 1978).

Table 2.3. Example of a simple conversion table.

Suitability class	Ratings					
	CLIMATE	MOISTURE	FERTILITY	EROSION	IMPLEMENTS	DRAINAGE
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

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. Sugar-cane and rice were not being grown in the Bura West area but were examined as options for land-use.

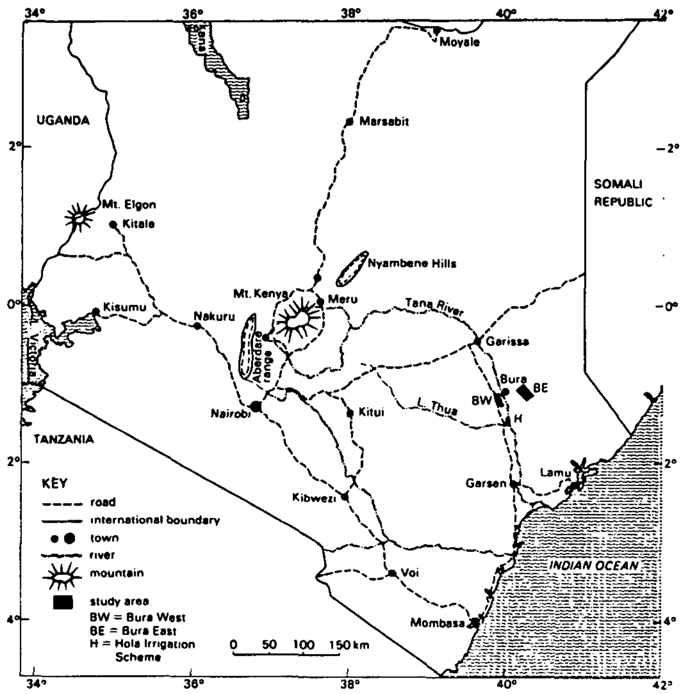


Fig. 2.1. Site of the Bura West irrigation scheme, Kenya (Muchena, 1987).

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

LUT-C: irrigated cotton

Management/technology. Smallholder plots of 1.25 ha within a government-owned, centrally managed settlement scheme. Surface irrigation with long furrows; anticipated cropping intensity 100%. Water supply on rotation at 14-day intervals. Land preparation mechanized but all other operations by hand except aerial sprays. Inputs high: farm inputs (seed; 80 to 120 kg fertilizer-N ha^{-1}; herbicides and pesticides) available on credit. Technical know-how 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 frost-free 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 salt-tolerant: 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.

LUT-M: irrigated maize

Management/technology. Smallholder plots of 0.625 ha within a government-owned, 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 subsistence-oriented. 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 frost-free 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.

LUT-R: irrigated rice

Management/technology. Plot sizes 1 ha or more. Basin irrigation of two crops per year in a large-scale commercial set-up. Land preparation mechanized; transplanting, weeding and harvesting by hand. Inputs high (HYV seed, fertilizers and pesticides); technical know-how 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.

LUT-S: irrigated sugar-cane

Management/technology. Large-scale 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 know-how moderate to high. Labour inputs high during planting and harvesting.

Crop requirements. Although sugar-cane 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. Sugar-cane 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. Sugar-cane is semi-tolerant to exchangeable sodium and can grow on soils with up to 40% adsorbed sodium ions.

LUT-P: irrigated cowpea

Management/technology. Smallholder plots of 0.625 ha in a government-owned, 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; know-how 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.

LUT-G: irrigated groundnut

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 know-how 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.

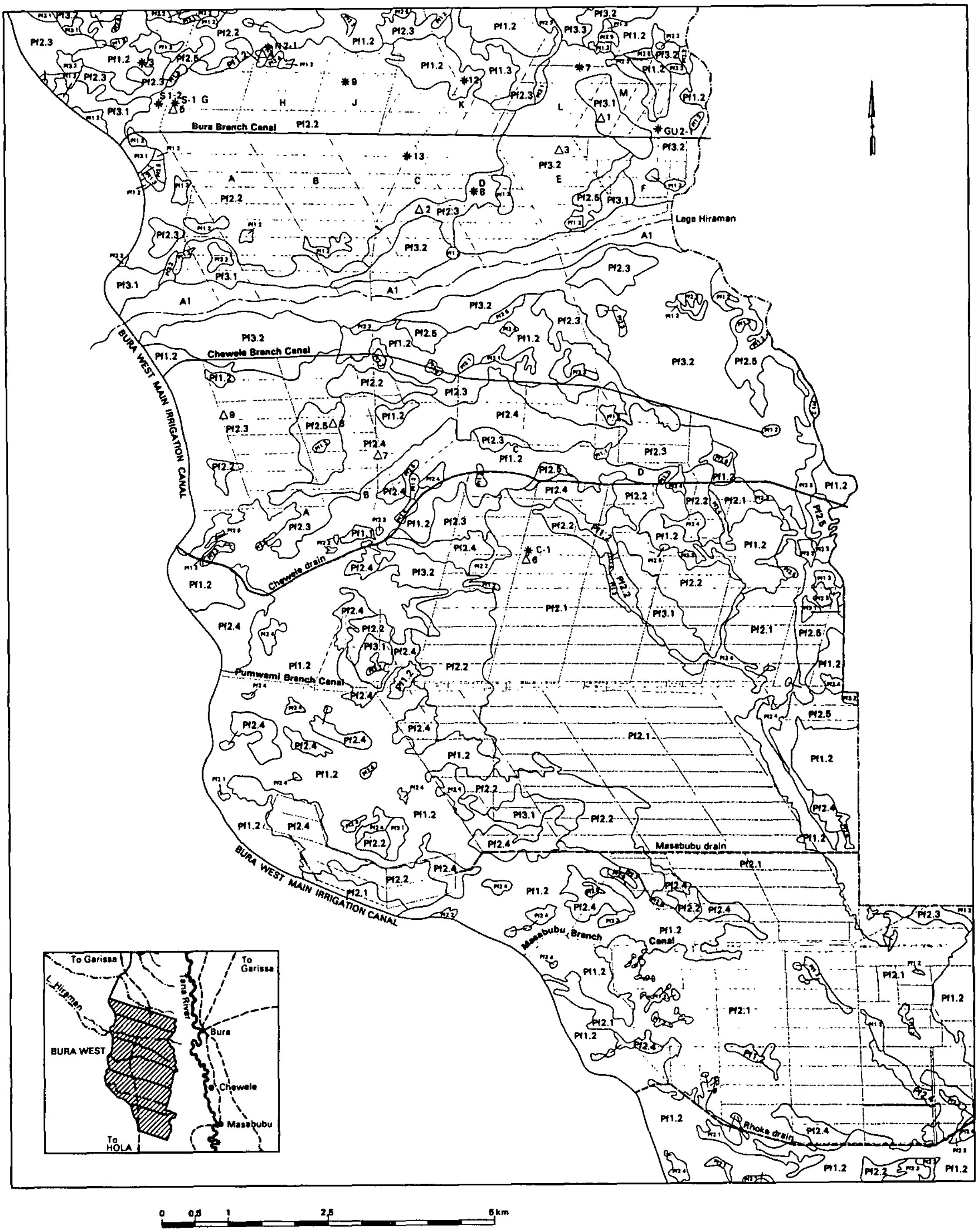


Fig.2.2. Soil map of the Bura West irrigation scheme (Muchena, 1987).

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 lime-free.	slightly to strongly saline at 70-115 cm.	moderately to strongly sodic at 50-90 cm.
Pf1.2	Moderately well to imperfectly drained, very deep, dark (reddish) brown, firm, sandy clay to clay.	0-15/40 cm lime-free.	strongly saline at 15-40 cm.	moderately to strongly sodic at 15-40 cm.
Pf1.3	The same as Pf1.2 but dark (greyish) brown.	0-10/15 cm lime-free.	strongly saline at 10-15 cm.	strongly sodic at 10-15 cm.
Pf2	**Lower-lying land**			
Pf2.1	Well drained, very deep, dark (reddish) brown, friable, (sandy) clay.	0-15/50 cm lime-free.	slightly saline at 100-125 cm.	slightly to strongly sodic at 60-125 cm.
Pf2.2	The same as Pf2.1 but friable to firm.	calcareous throughout.	moderately to strongly saline at 20-40 cm.	moderately to strongly sodic at 20-40 cm.

continued on next page

Symbol		CaCO$_3$	Salinity	Sodicity
Pf2.3	The same as Pf2.2.	calcareous throughout.	moderately to strongly saline at 10-20 cm.	moderately to strongly sodic at 10-20 cm.
Pf2.4	Well drained to moderately well drained, very deep, dark reddish brown, firm clay.	moderately to strongly calcareous >30 cm.	strongly saline at 60-70 cm.	strongly sodic at 15-30 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 40-50 cm.	strongly sodic at 10-15 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 20-60 cm.	moderately to strongly sodic at 20-30 cm.
Pf3.2	The same as Pf3.1, but firm to very firm.	As Pf3.1.	moderately to strongly saline at 15-30 cm.	moderately to strongly sodic at 10-15 cm.
Pf3.3	Imperfectly to poorly drained very deep, dark (greyish) brown, firm, cracking clay.	As Pf3.1.	moderately to strongly saline at 50-70 cm.	strongly sodic at 15-25 cm.
A Floodplain				
A1	Imperfectly drained, very deep, (dark) brown, (very) firm, stratified, cracking clay.	slightly to moderately calcareous >20-30 cm.	slightly to moderately saline at 70-100 cm.	moderately to strongly sodic at 20-30 cm.

Depth classes: 0-50 cm shallow; 50-80 cm moderately deep; 80-120 cm deep; >120 cm very deep.

Salinity classes: electrical conductivity of saturation extract (ECe) 0-4 mS cm^{-1} non-saline; 4-8 mS cm^{-1} slightly saline; 8-16 mS cm^{-1} moderately saline; >16 mS cm^{-1} strongly saline.

Sodicity classes: exchangeable sodium percentage (ESP) 0-5% non-sodic; 5-10% slightly sodic; 10-15% 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	1-2	4	4	2	2	5	
Pf1.2	1-3	4	4	2-3	4	4	4	2	4	
Pf1.3	1-3	5	5	2-3	4-5	4	5	3-5	4	
Pf2.1	2	1	2	1	2	2-3	1-2	2	2	2.1
Pf2.2	2-3	2-4	4	1	3	3	3	3	3	2.2
Pf2.3	2	3-4	4	1	3	3	4	3	3	
Pf2.4	2	2-4	4-5	1-2	3	3-4	3-4	4	4	
Pf2.5	2	2-4	4-5	1-2	4	4	4-5	5	4	
Pf3.1	3	3-4	3-4	2-3	3	3	3	3	3	
Pf3.2	3	3-4	3	2-3	3	3	3	4	3	
Pf3.3	3	3-4	3	3-4	4	4	3	4	3	
A1	3	1-3	3	3	3-4	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								
	Awc	**ASal**	**ASod**	**Oxy**	**Ger**	**Nut**	**Rts**	**Wrk**	**Drain**
LUT-C: 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
LUT-M: 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
LUT-R: 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
LUT-S: irrigated sugar-cane									
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
LUT-P: 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
LUT-G: 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

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	LUT-C	LUT-M	LUT-R	LUT-S	LUT-P	LUFG
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 cost-benefit 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

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 ('**single-factor valuation**' or '**indexing**')
- they combine all single-factor 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 Single-factor 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 crop-specific 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 single-factor indexes must be '**compounded**' in such a way that (most of) the interaction between the selected significant factors is accounted for.

Single-factor 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 single-factor 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: $PI = f(A) * f(B) * f(C) \quad \ldots * WF1$

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

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 single-factor 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 soil-productivity 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 non-soil 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 soil-productivity index reads:

$$\mathrm{PI}_{soil} = \sum_{i=1}^{n} (A_i * B_i * C_i * D_i * E_i * \mathrm{WF}_i) \qquad (3.1)$$

where

PI_{soil}	is soil-productivity 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.

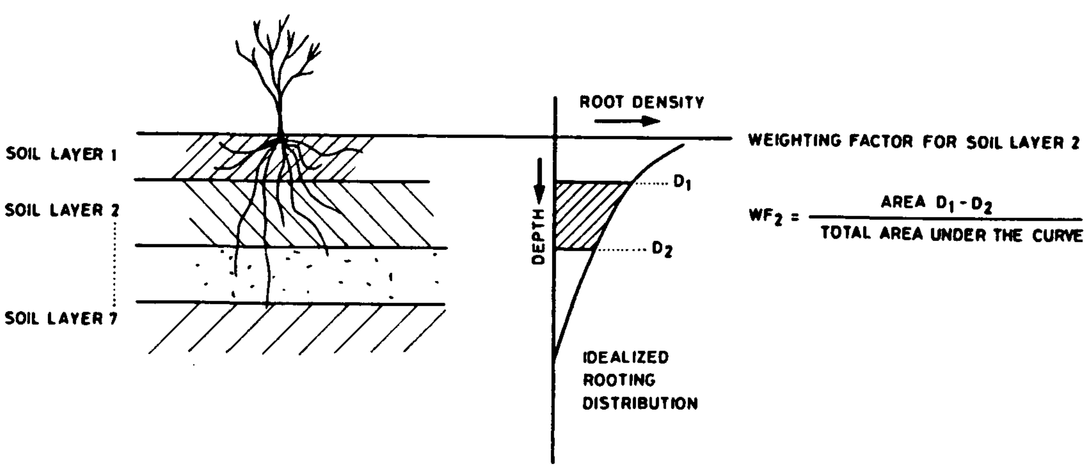


Fig. 3.1. Meaning of weighting factor (Rijsberman & Wolman, 1984).

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

$$WF_i = ((RDm - D_1)^2 - (RDm - D_2)^2) / RDm^2 \tag{3.2}$$

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 long-term 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:

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

where

PI_{soil}	is soil-productivity index
A_i	is sufficiency of water-holding 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.

0,17 + 0,5 * Dy AWC

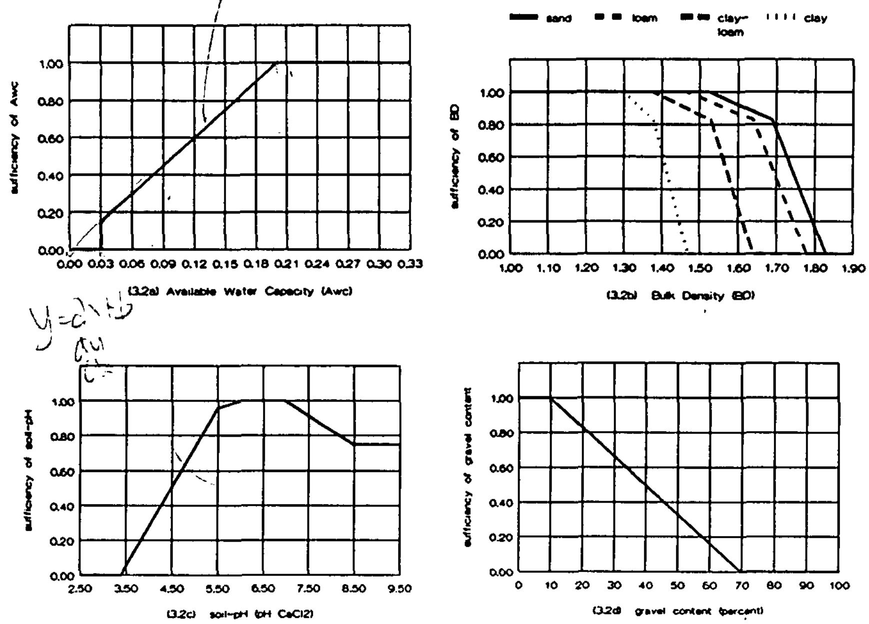


Fig. 3.2 a-d. Response curves of the single factors 'available water capacity' (Awc; Fig. 3.2a), bulk density (BD; Fig. 3.2b), pH (Fig. 3.2c) and gravel content (Fig. 3.2d).

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, single-factor 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):	$WF_{(0\text{-}25cm)} = ((100\text{-}0)^2 - (100\text{-}25)^2) / 100^2 = 0.438$	

Substitution of these values in Equation 3.3 produces the partial soil-productivity index for the upper layer:
$PI_{(0\text{-}25cm)} = 0.90 * 1.00 * 0.90 * 0.93 * 0.438 = 0.33$

For the 2nd layer:
$PI_{(25\text{-}50cm)} = 0.90 * 0.63 * 0.83 * 0.87 * 0.313 = 0.128$

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 maize-pigeon 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 rain-fed 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 curve-fitting produced approximate relationships between (calculated) PI_{soil} and (estimated) yield and production potentials:

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

where
Ym is maize (grain) yield of the maize-pigeon 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 maize-pigeon 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. Soil-productivity 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 (kg ha^{-1} year^{-1})	Ypp	TBP
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.)

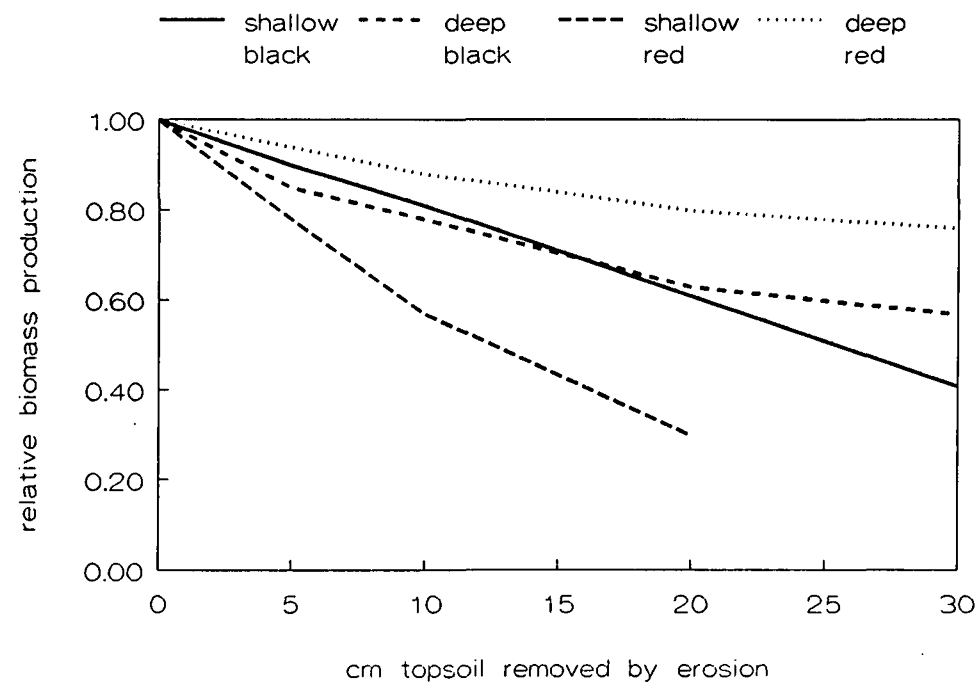


Fig. 3.3. Relative total production of biomass by land-use systems with intercropped maize and pigeon pea on shallow and deep, red and black soils, with various losses of surface soil by erosion.

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 single-factor 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 single-factor values on land-use system performance, are still far away.

CHAPTER 4

AGRO-ECOLOGICAL ZONING

4. AGRO-ECOLOGICAL ZONING

'**Agro-ecological zoning**' (AEZ) is a procedure of small-scale 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 (FAO-Unesco, 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 *de-facto* climate-related and soil-related **crop** requirements.

Steps in agro-ecological 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.

Step 1: Soil-related requirements of the 'major crops' selected are matched against the characteristics of all soil units distinguished on the Soil Map of the World. **Soil-unit ratings** for rain-fed cropping with 'high' and 'low' input are thus obtained.

Step 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 climate-related crop requirements in a model of **net biomass production** and **constraint-free yield**.

Step 5: The step from a potential ('constraint-free') 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 'high-input' and 'low-input' cropping). The outcome of this matching is the **agro-climatic suitability**.

Step 7: The soil-unit rating and the agro-climatic suitability determine the (preliminary) **land suitability class** for high-input and low-input rain-fed farming. The final land suitability class is obtained by correcting the preliminary land suitability class by a set of **phase, slope and texture rules**.

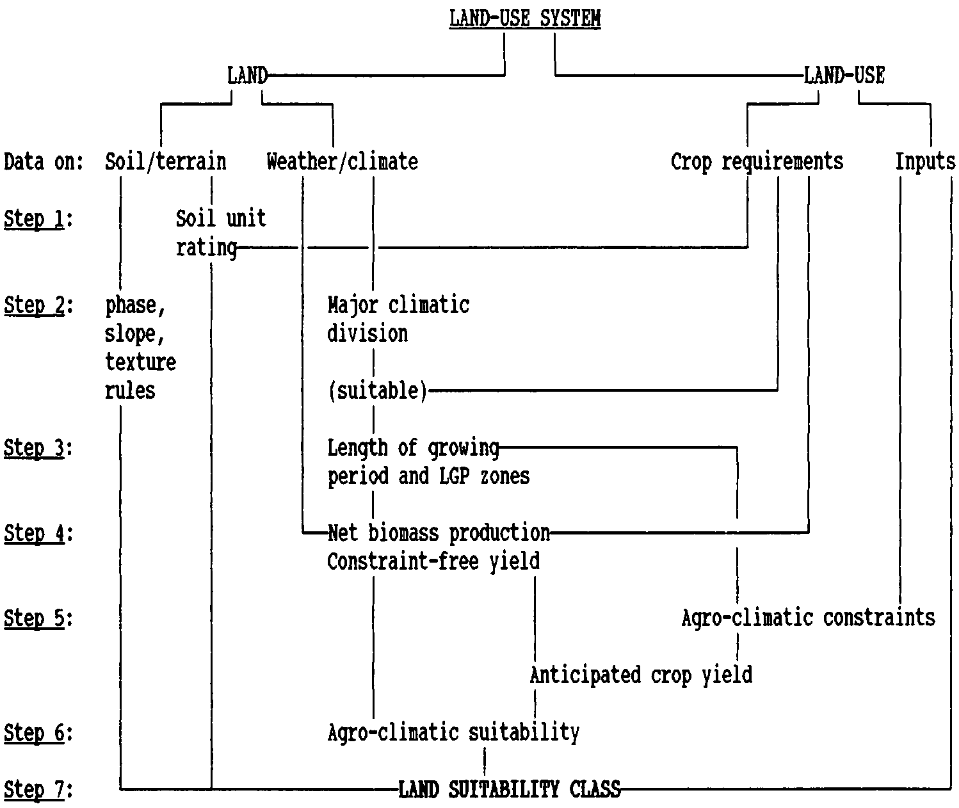


Fig. 4.1. All AEZ matching procedures in their relational context.

4.1 Soil-related crop requirements and soil-unit ratings

Soil-related crop requirements

Each soil unit in the legend of the FAO-Unesco 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 (soil-related) 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. Soil-related 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, silt-loam; CL, clay-loam.

requirements

Crop	Slope (%)		Soil depth (cm)		Drainage class		Texture class	
	opt.	marg.	opt.	marg.	opt.	range	opt.	range
maize	0-8	8-15	>50	10-50	mw-w	i-sed	SiL-CL	SL-MC
soybean	0-8	8-20	>75	50-75	mw-w	i-sed	SiL-CL	LS-KC
rice	0-4	4-8	>50	25-50	i-mw	vp-w	SiL-CL	SL-MC

	Fertility (level)	Salinity (mS/cm)		pH (1:2.5)		$CaCO_3$ (%)		Gypsum (%)	
		opt.	marg.	opt.	range	opt.	marg.	opt.	marg.
maize	moderate	0-4	4-6	5.5-8.2	5.2-8.5	0-15	15-25	0-.2	.2-2
soya	moderate	0-4	4-6	5.5-7.3	5.2-8.2	0-15	15-25	0-.2	.2-2
rice	low	0-2	2-4	5.5-7.5	5.2-8.2	0-15	15-25	0-.2	.2-2

Soil-unit 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 high-input and low-input rain-fed 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 sugar-cane. Table 4.2 presents an excerpt from the comprehensive rating table.

Table 4.2. Example of soil-unit 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

Climate-related 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 **crop-adaptability groups**, each with specific temperature and radiation requirements. Table 4.3 lists the climatic requirements of 'major crops' in each crop-adaptability group.

Table 4.3. Indicative climate-related crop requirements by crop-adaptability group. Source: FAO, 1978.

	Crop-adaptability 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})*	0.2-0.6	0.3-0.8	> 1.0	> 1.0
Crops in each crop-adaptability group	wheat potato bean	bean soya rice cotton cassava sw. potato	millet sorghum maize (sugar-cane)	maize sorghum

* 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 crop-adaptability groups I ('C3 crops') and IV ('C4 crops'). Tropical (lowland) cultivars belong to crop-adaptability 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. C3 C4

(Crop

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 agro-climatic 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 crop-adaptability 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 rain-fed 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 crop-adaptability group**	**mean 24-hour temperature in growth cycle** (°C)	**total area in Africa** (ha*10³)
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

GENERALIZED CLIMATIC INVENTORY - AFRICA

MAJOR CLIMATIC DIVISIONS AND LENGTHS OF GROWING PERIOD ZONES

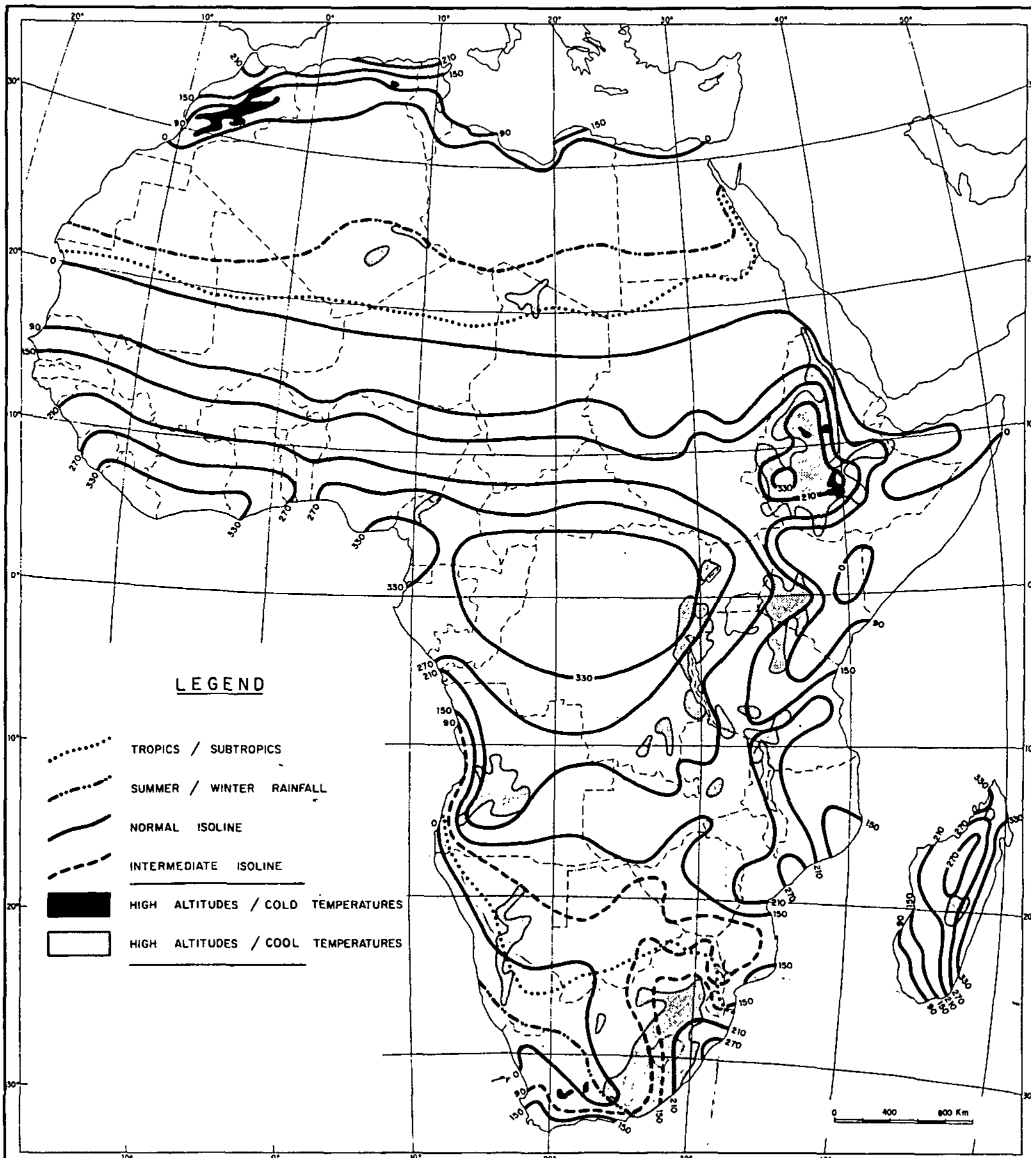


Fig. 4.2. Generalized survey of climatic resources of Africa: LGP zones and major climatic divisions. Source: FAO (1978).

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 24-hour mean temperature of less than 6.5 °C.

Regional aggregation of site-specific 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, constraint-free yield and anticipated yield

Net biomass production and constraint-free 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).

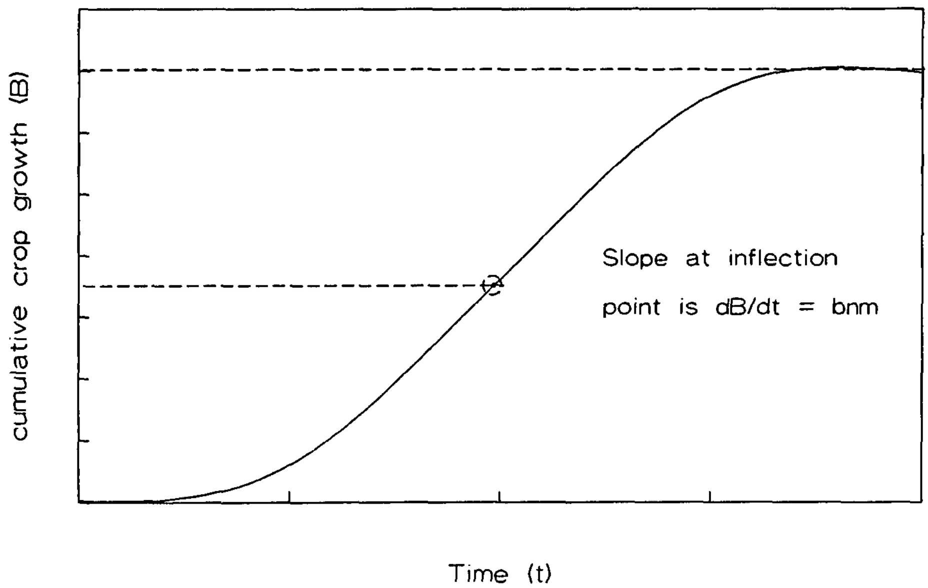


Fig. 4.3. Symmetrical cumulative growth curve.

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).

$$B_n = 0.5 * b_{nm} * Ng \tag{4.1}$$

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})

Ng 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

15.44

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

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

f cloud fraction

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

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

mmloed ^{c}/d cloud fraction

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 crop-adaptability groups and is also temperature-dependent. 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.

Crop-adaptability 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.

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

with

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

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_{gmu} 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 non-legumes. They suggested a quadratic relation to describe the temperature dependence of the maintenance respiration rate:

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

(maintenance resp. coef.

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 (24-hour 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:

$$b_{mr} = C_t * 0.5 * b_{nm} * Ng \tag{4.6}$$

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

$$b_{nm} = \mathrm{Ec} * b_{gma} \;/\; (1 + \mathrm{Ec} * C_t * Ng \;/\; 2) \tag{4.7}$$

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})

Ec is 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:

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

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.

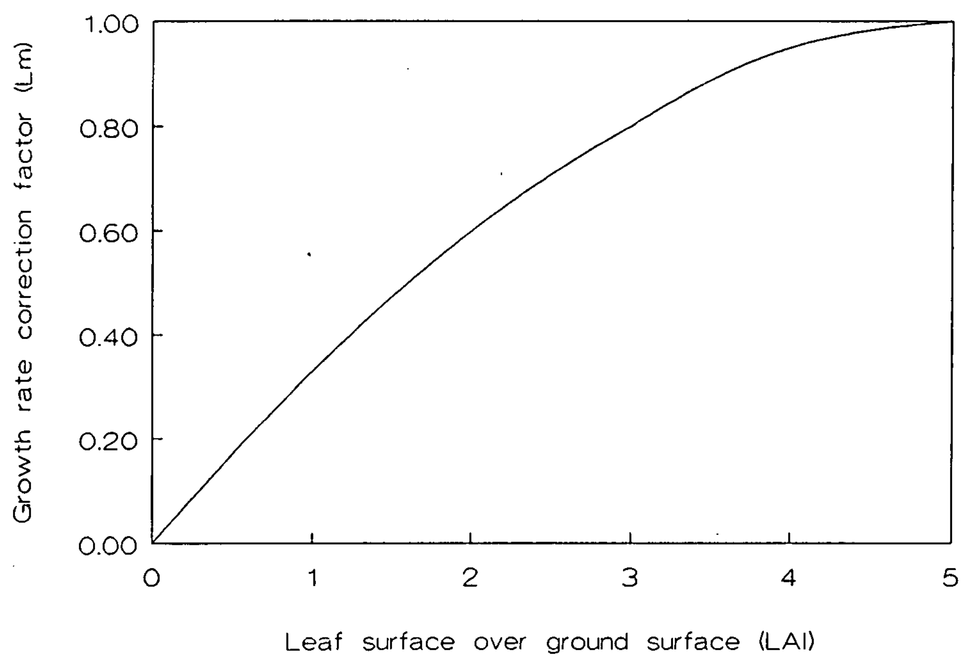


Fig 4.4. Correction factor for incomplete ground cover (L_m) as a function of the leaf area index (LAI) at the time of maximum growth.

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

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

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 **constraint-free crop yield** (B_{yu}) 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 high-yielding varieties of major crops under rain-fed 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
	sugar-cane (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 constraint-free crop yield amounts to

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

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

Agro-climatic constraints and anticipated crop yield

The net biomass production and constraint-free 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 **agro-climatic constraints** imposed by rainfall variability, climate-related 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 agro-climatic 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 constraint-free crop yield can serve as a reference but represents the high-input situation only; the yield reference for low-input farming was set to an arbitrary 25% of the calculated constraint-free 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 agro-climatic constraints is given in Appendix A4.)

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

LGP (d)	Ratings		
	low-input (abcd)	high-input (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	Leaf-spot, leaf-blight
330-364	0112	0112	Streak virus, wet produce
365	0222	0222	Workability

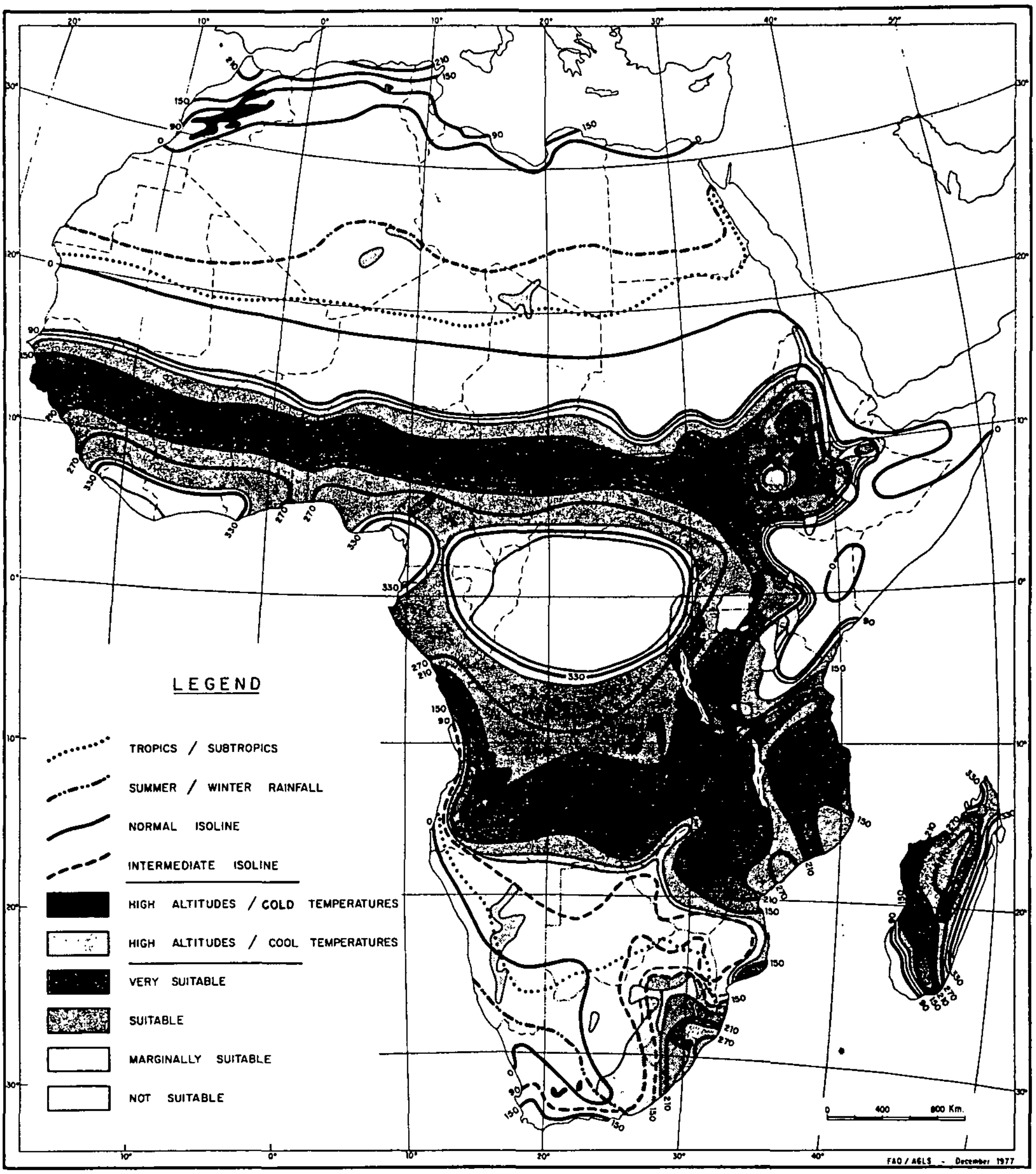
4.4 Classification of land suitability

Agro-climatic suitability

The ratio of the anticipated crop yield and the reference crop yield is an expression of the impact of agro-climatic 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 agro-climatic suitability map of Africa for rain-fed maize (FAO, 1978).



NOTE. THE ASSESSMENT IS FOR RAINFED PRODUCTION ONLY. A SEPARATE ASSESSMENT IS NECESSARY FOR IRRIGATED PRODUCTION

Fig. 4.5. Generalized agro-climatic suitability map of Africa for rain-fed maize. Source: FAO (1978).

Land suitability classification

The agro-climatic suitability classification is extended to a (preliminary) **land suitability classification** by combining it with information on individual soil units in each LGP zone (crop-specific and input-specific as in Table 4.2 and Appendix A2). The following rules apply.

- The land suitability class is the same as the agro-climatic suitability class if the (tabulated) soil-unit rating is S1.
- The land suitability class is one class less than the agro-climatic suitability class if the (tabulated) soil-unit rating is S2.
- Soil-unit ratings N1 and N2 imply that the land suitability class is NS.

Once the modifications for soil-unit 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 soil-unit ratings for individual soil mapping units, unmodified soil-unit 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 rain-fed 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 year-round 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 *ad-hoc* 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.105-106) 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 rain-fed maize.

Table 4.9. Land suitability of warm tropical lowlands in Africa for rain-fed 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

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: Af2-2/3b (FAO-Unesco, 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
ETO (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 (crop-adaptability 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 constraint-free 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. Soil-unit rating

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

Soil unit	**Input**	
	low	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 soil-unit ratings to establish a **soil** suitability rating for individual mapping unit components. This is, however, irrelevant to the present calculation.

Step 2. Major climatic division

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 crop-adaptability group III.

Step 3. Length of growing period

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.

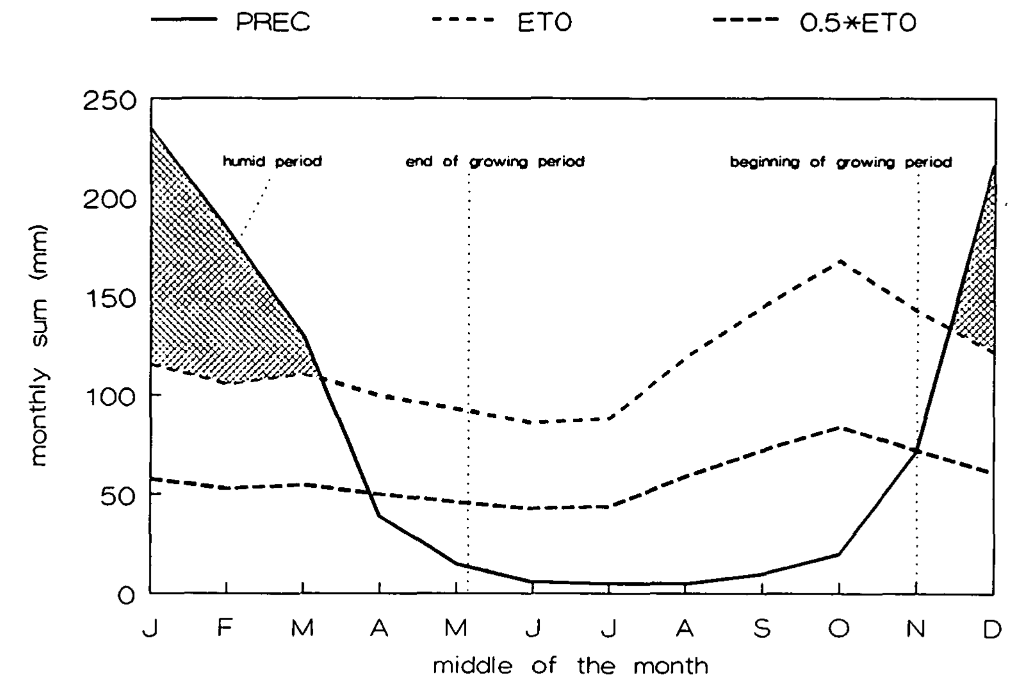


Fig. 4.6. Distribution of precipitation (PREC) and potential evapotranspiration (ET0) over the year and the beginning and end of the possible growing period.

Step 4. Net biomass production and constraint-free 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**: $P_{ma} = 65$ kg ha^{-1} h^{-1} (Table 4.6)
- **Correction factor for P_{ma} < > 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)
- **Constraint-free yield**:
  $B_{ya} = 20\,615 * 0.35 = 7\,215$ kg ha^{-1}. (Equation 4.10).

Step 5. Anticipated yield

The anticipated yield is obtained by making deductions for likely agro-climatic constraints. Table 4.8 and Appendix A4 indicate no constraint for maize in the LGP zone of 180-209 days. Consequently, the anticipated yield is assumed equal to the constraint-free yield.

Step 6. Agro-climatic suitability

The agro-climatic suitability criteria discussed in Section 4.4 stipulate that the **agro-climatic suitability class is 'very suitable' (VS)** because the anticipated yield is greater than 80% of the constraint-free yield (the reference yield for high-input farming).

Step 7. Land suitability class

The land suitability class is established by adjusting the agro-climatic 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 Af2-2/3b and high-input 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 Af2-2/3b 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 Af2-2/3b near Ulongue
- The slope of Af2-2/3b 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 two-thirds 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 Af2-2/3b land near Ulongue for high-input 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-use-system-specific 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 LAND-USE SYSTEMS: AN INTRODUCTION

5. DYNAMIC ANALYSIS OF LAND-USE SYSTEMS: AN INTRODUCTION

The procedure for agro-ecological 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 rain-fed 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 * ETO) 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** ETO (after a dry period) rather than 0.5 * ETO. 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 (ETO) 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.

$$\text{TASM} = (\text{SMFC} - \text{SMPWP}) * \text{RD} \tag{5.1}$$

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:

$$AASM = (SMPSI - SMPWP) * RD \qquad (5.2)$$

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).

$$\text{if } AASM > TASM \text{ then } AASM = TASM \qquad (5.2a)$$

and

$$\text{if } SMPSI < SMPWP \text{ then } AASM = 0 \qquad (5.2b)$$

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

$$SMCR = (1 - p) * (SMFC - SMPWP) + SMPWP \qquad (5.3)$$

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 ET-SMPSI relation is described by Equations 5.4 and shown in Figure 5.1.

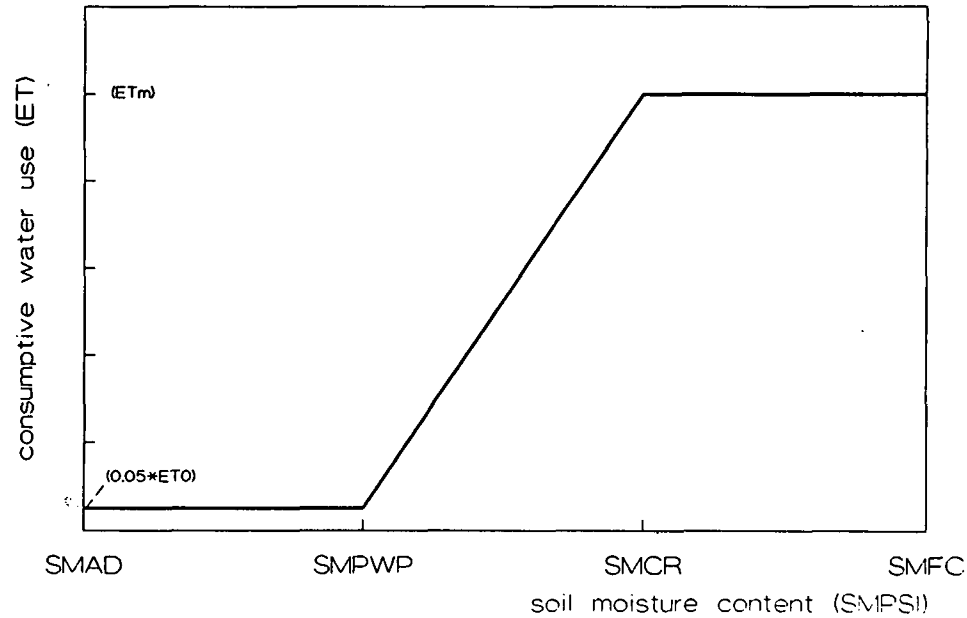


Fig. 5.1. Approximate relation of ET to SMPSI.

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

else if SMCR > SMPSI > SMPWP **then** (5.4b)
ET = (SMPSI-SMPWP) * (ETm-0.05 * ET0) / (SMCR-SMPWP) + 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

$$\boxed{ETm = kc * ET0} \tag{5.5}$$

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 kc-ranges 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	0.30-0.40	0.65-0.75	0.95-1.05	0.90-0.95	0.85-0.95
cabbage	0.40-0.50	0.70-0.80	0.95-1.10	0.90-1.00	0.80-0.95
cotton	0.40-0.50	0.70-0.80	1.05-1.25	0.80-0.90	0.65-0.70
groundnut	0.40-0.50	0.70-0.80	0.95-1.10	0.75-0.85	0.55-0.60
maize	0.30-0.50	0.70-0.85	1.05-1.20	0.80-0.95	0.55-0.60
onion	0.40-0.60	0.70-0.80	0.95-1.10	0.85-0.90	0.75-0.85
pea	0.40-0.50	0.70-0.85	1.05-1.20	0.65-0.75	0.25-0.30
peppers	0.40-0.50	0.70-0.80	0.95-1.10	0.90-1.00	0.80-0.90
potato	0.40-0.50	0.70-0.80	1.05-1.20	0.85-0.95	0.70-0.75
rice	1.10-1.15	0.10-1.15	1.10-1.30	0.95-1.05	0.95-1.05
safflower	0.30-0.40	0.70-0.80	1.05-1.20	0.65-0.70	0.20-0.25
sorghum	0.30-0.40	0.70-0.75	1.00-1.15	0.75-0.80	0.50-0.55
soya	0.30-0.40	0.70-0.80	1.00-1.15	0.70-0.80	0.40-0.50
sugar-beet	0.40-0.50	0.75-0.85	1.05-1.20	0.90-1.00	0.60-0.70
sugar-cane	0.40-0.60	0.75-1.20	1.05-1.30	0.80-1.05	0.60-0.75
sunflower	0.30-0.40	0.70-0.80	1.05-1.20	0.70-0.80	0.35-0.45
tobacco	0.30-0.40	0.70-0.80	1.00-1.20	0.90-1.00	0.75-0.85
tomato	0.40-0.50	0.70-0.80	1.05-1.25	0.80-0.95	0.60-0.65
water-melon	0.40-0.50	0.70-0.80	0.95-1.05	0.80-0.90	0.65-0.75
wheat	0.30-0.40	0.70-0.80	1.05-1.20	0.65-0.75	0.20-0.25

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	mid-season	late season
green bean	15-20	15-20	20-30	5-20
cabbage	20-30	30-35	20-30	10-20
cotton	20-30	40-50	50-60	40-55
groundnut	15-35	30-45	30-50	20-30
maize	15-30	30-45	30-45	10-30
onion	15-20	25-35	25-45	35-45
pea	10-25	25-30	25-30	20-30
peppers	25-35	30	30-60	30
potato	20-30	30-40	30-60	20-35
rice	30	30	40	30
safflower	20-35	35-75	45-65	25-40
sorghum	20-25	30-40	40-45	30
soya	20-25	25-35	45-65	20-30
sugar-beet	25-30	35-60	50-70	30-50
sugar-cane	30-60	90-120	180-330	30-60
sunflower	20-25	35-40	40-50	25-30
tobacco	10	20-30	30-35	30-40
tomato	10-15	20-30	30-40	30-40
water-melon	10-20	15-20	35-50	10-15
wheat	15-20	25-30	50-65	30-40

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 drought-tolerance 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, water-melon, wheat
4	cotton, maize, sorghum, soya, sugar-beet, sugar-cane, 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 rain-fed 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

State-variables

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 LUS-specific' 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 state-variable technique allows description of availability and consumptive needs for water in a dynamic way.

Choice of time interval (DT)

The state-variable technique views a crop cycle as a concatenation of time intervals; intervals have a user-defined 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 $1/30^{th}$ to, say, $1/500^{th}$ 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 10-days 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 mid-season 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 mid-season stage of crop development starts after L * DT = 50 d.

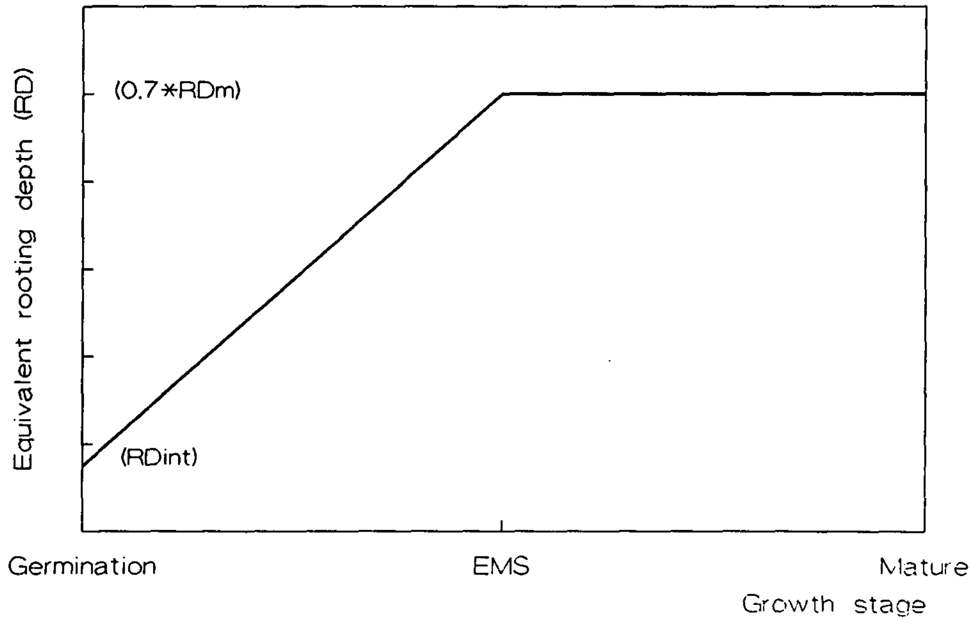


Fig. 5.2. Equivalent rooting depth (RD) over the growing season.

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

$$\textbf{if } L < \text{EMS} \textbf{ then } \text{RD} = \text{RDint} + (0.7 * \text{RDm} - \text{RDint}) * L \,/\, \text{EMS} \tag{5.6a}$$

$$\textbf{else } \text{RD} = 0.7 * \text{RDm} \tag{5.6b}$$

where

L	is number of intervals elapsed since emergence
EMS	is number of intervals between emergence and beginning of mid-season stage of crop development
RD	is equivalent rooting depth (cm)
RDm	is maximum rooting depth (cm)
RDint	is 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 day-sums 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)		Crop	Rooting depth (cm)	
	initial	maximum		initial	maximum
bean	7-10	100-150	safflower	5-10	100-200
cabbage	10	40-60	sorghum	5-10	100-200
cotton	5-10	100-170	soya	7-10	60-130
groundnut	7-10	50-100	sugar-beet	7-10	70-120
maize	10	100-170	sugar-cane	15-25	150-250
onion	4-10	30-50	sunflower	5-10	80-150
pea	7-10	60-100	tobacco	3-8	50-100
peppers	7-10	90	tomato	5-10	70-150
potato	10-15	40-60	water-melon	7-10	100-150
rice	10-15	80-100	wheat	7-10	125

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:

$$\text{(new)AASM} = (\text{SMPSI} - \text{SMPWP}) * \text{RD} + \text{PREC} * \text{DT} - \text{ET} * \text{DT} \qquad (5.7)$$

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 (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.

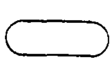
5.4 Pathway of calculation and data needs

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.

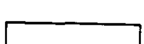
A proper sequence of calculation instructions and transfer functions is an '**algorithm**'. The internal structure of an algorithm can be depicted in a '**flow chart**'. In a notation that can be understood by a calculating device, the algorithm becomes a '**program**'. It is beyond the scope of this text to discuss principles of computer programming but the construction of simple flow charts deserves some attention.

Flow charts

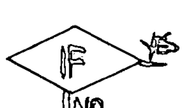
A flow chart is essentially a diagram in which the calculation procedure is presented in discrete steps. The order in which these steps are taken is indicated by arrow signs; the steps themselves are represented by symbols. The shape of a symbol indicates the type of action that it represents. In this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



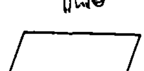
terminals mark the beginning and end of the calculations



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.

relation AEZ / symphony

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

ET0 : pot rate ET

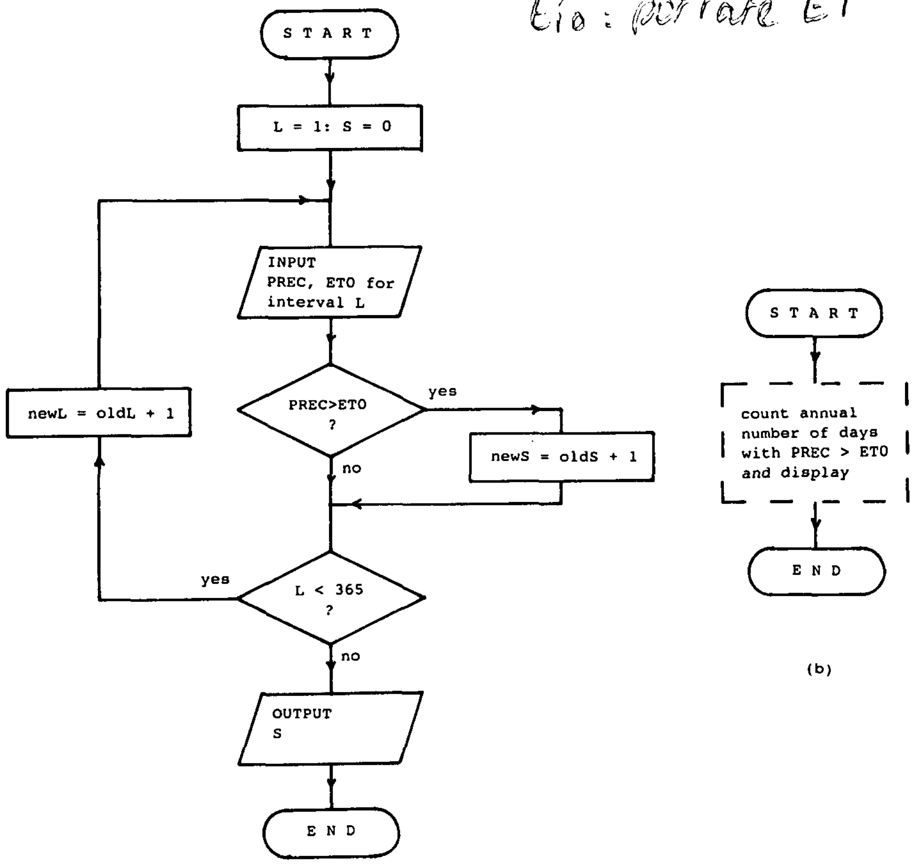


Fig. 5.3. Flow diagram of a procedure to count the annual number of days with a precipitation surplus (S).

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 ET0-values 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 'dry-interval 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 'growth-cycle 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.

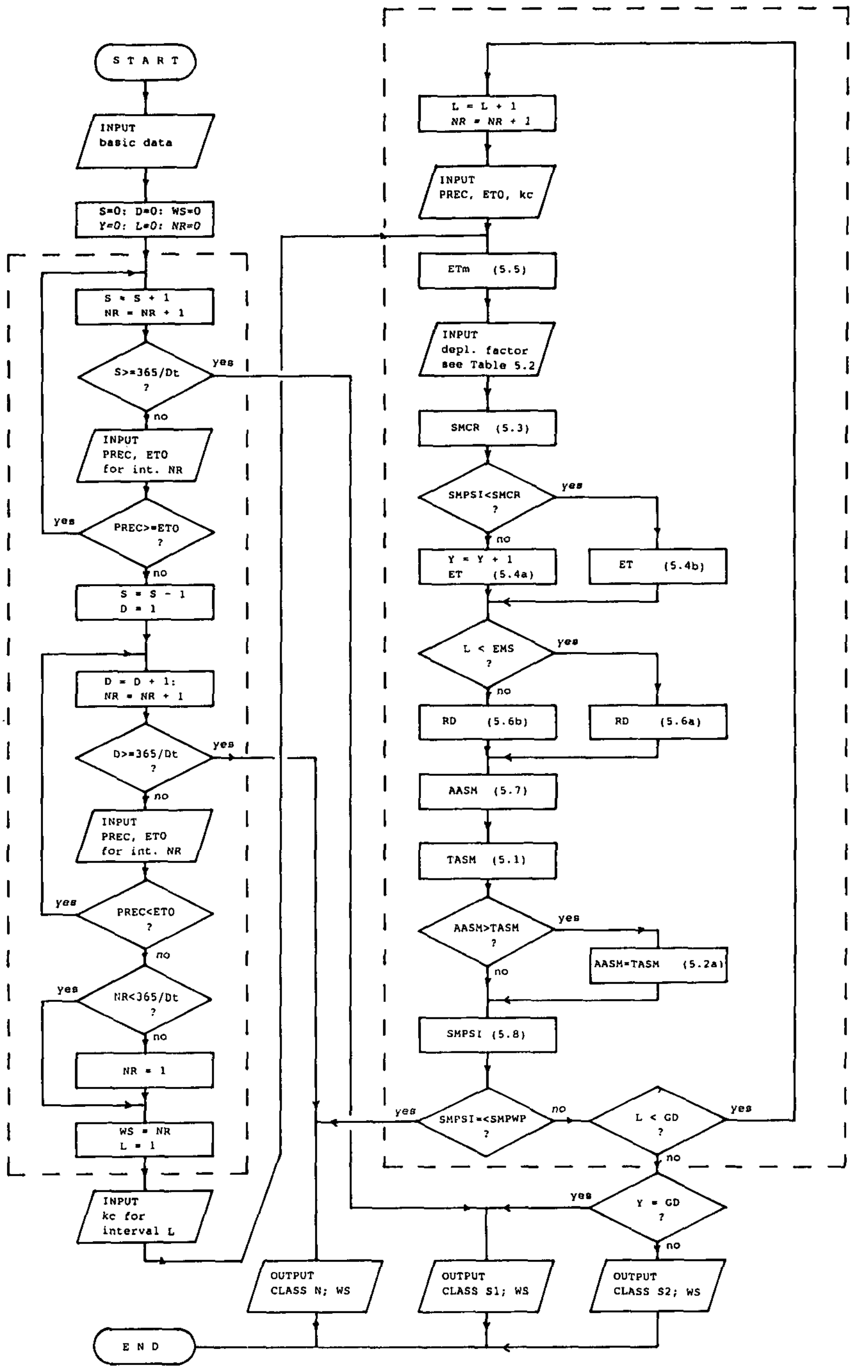


Fig. 5.4. Flow diagram of an analysis which (1) identifies the beginning of a growing season, and (2) determines the land suitability class as conditioned by the availability of soil moisture.

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 rain-fed 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 'growing-cycle 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.

Soil and terrain data:

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 ($cm^3\ cm^{-3}$).

Weather/climate data:

PREC	rate of precipitation (cm d^{-1}; meteorological reports)
ET0	rate of potential evapotranspiration (cm d^{-1}; meteorological reports).

Crop data:

Crop group	(see Table 5.2A)
EMS	early mid-season 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).

Management/technology data:

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 hand-calculator. 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 rain-fed 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.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
NR	ETO * Dt	PREC * Dt	S	S>=365/Dt ?	PREC>=ETO ?	D	D>=365/Dt ?	PREC<ETO ?	WS	L	INPUT kc	ETm * Dt	INPUT 'p'	SMCR	SMPSI<SMCR ?	ET * Dt	Y	L<EMS ?	RD	AASM	TASM	AASM>TASM ?	(new)AASM	SMPSI	SMPSI=<SMPWP ?	L < GD ?	Y = GD ?	OUTPUT CLASS, WS
init			0			0			0	0							0		7					0.26				
1	3.5	0.4	0	no	no	1																						
2	3.7	0.8				2	no	yes																				
3	4.3	1.6				3	no	yes																				
4	4.4	3.3				4	no	yes																				
5	4.4	5.6				5	no	no	5	1	0.3	1.32	0.87	0.13	no	1.32	1	yes	21	7.64	5.25	yes	5.25	0.35	no	yes		
6	4.0	6.4								2	0.5	2.0	0.87	0.13	no	2.0	2	yes	35	13.2	8.75	yes	8.75	0.35	no	yes		
7	3.6	6.9								3	0.7	2.52	0.84	0.14	no	2.52	3	yes	49	16.6	12.3	yes	12.3	0.35	no	yes		
8	4.0	5.6								4	0.8	3.2	0.78	0.15	no	3.2	4	yes	63	18.2	15.8	yes	15.8	0.35	no	yes		
9	4.2	3.2								5	0.9	3.78	0.72	0.17	no	3.78	5	yes	77	18.7	19.3	no	18.7	0.34	no	yes		
10	4.3	1.8								6	1.05	4.52	0.65	0.19	no	4.52	6	no	91	19.3	22.8	no	19.3	0.31	no	yes		
11	4.3	0.9								7	1.15	4.95	0.61	0.20	no	4.95	7	no	91	15.3	22.8	no	15.3	0.27	no	yes		
12	4.4	0.8								8	1.05	4.62	0.64	0.19	no	4.62	8	no	91	11.5	22.8	no	11.5	0.23	no	yes		
13	4.4	0.6								9	1.0	4.40	0.66	0.18	no	4.40	9	no	91	7.67	22.8	no	7.67	0.18	no	yes		
14	4.4	0.4								10	0.9	3.96	0.70	0.17	no	3.96	10	no	91	4.08	22.8	no	4.08	0.15	no	yes		
15	4.4	0.3								11	0.75	3.30	0.77	0.16	yes	2.66	10	no	91	1.74	22.8	no	1.74	0.12	no	yes		
16	4.4	0.1								12	0.55	2.42	0.84	0.14	yes	1.40	10	no	91	0.42	22.8	no	0.42	0.11	no	no	no →	CLASS S2 (from interval # 5)
17																												

BASIC DATA SET

General:

Dt: 10 d

Weatner/climate:

ETO * Dt: (in cm; col. 2)
PREC * Dt: (in cm; col. 3)

Soil:

Soil texture: loam
SMFC: 0.35 $cm^3\ cm^{-3}$
SMPWP: 0.10 $cm^3\ cm^{-3}$
initial SMPSI: 0.26 $cm^3\ cm^{-3}$

Crop: maize cv

EMS: 6 intervals
GD: 12 intervals
RDm: 130 cm
initial RD: 7 cm

L:	1	2	3	4	5	6	7	8	9	10	11	12
kc:	0.3	0.5	0.7	0.8	0.9	1.05	1.15	1.05	1.0	0.9	0.75	0.55

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 rain-fed maize which germinates in the 5th 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

CALCULATING SUFFICIENCY: SINGLE-FACTOR RATINGS

6. CALCULATING SUFFICIENCY: SINGLE-FACTOR 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 non-saline, 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:

$$ETm = TRM + EM \tag{6.1}$$

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:

$$ETm = kc * ET0 \tag{5.5}$$

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 one-third of the potential rate (ET0) at the moment of germination, when transpiration is still negligible. ETm is greater than ET0 during the mid-season 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(?)	sugar-cane	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 variety-specific Tsum-value.

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.

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

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.

$$(new)RDS = (old)RDS + DRDS \tag{6.3}$$

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 mid-season 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

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

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.

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

where
TC is momentary turbulence coefficient
kc_{ref} is momentary reference-crop 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 mid-season 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.

$$kc = kc_{ref} * TC \tag{6.6}$$

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 mid-season stage, when kc has its highest value. Interpolation between these values results in:

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

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:

$$EM = ETm - TRM \tag{6.8}$$

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)

PWP pF=4.2
FC pF=2

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 field-grown 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.

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

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.

$$\text{if } MUR >= TRM \text{ then } TR = TRM \tag{6.10a}$$

$$\text{else } TR = MUR \tag{6.10b}$$

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:

$$INTSUFF = TR / TRM \tag{6.11}$$

where
INTSUFF is sufficiency of water availability. van 0 tot 1

voldoende

6.4 Auxiliary relations

Matching demand against supply in a single-land-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.

SMPSI-PSI relations are used to convert soil moisture content into matric suction and vice versa. Several theoretical SMPSI-PSI 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) mid-season 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	sugar-cane	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) KPSI-values explains the frequent use of theoretical or semi-empirical KPSI-PSI 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 KPSI-PSI relation for PSI greater than a soil-specific 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 texture-specific 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 texture-specific geometry constant (cm^{-1})
AK is texture-specific 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 KPSI-PSI curve for sandy clayloam; indicative values for KPSI can be calculated for the relevant PSI-range with the parameter values suggested in Table 6.4.

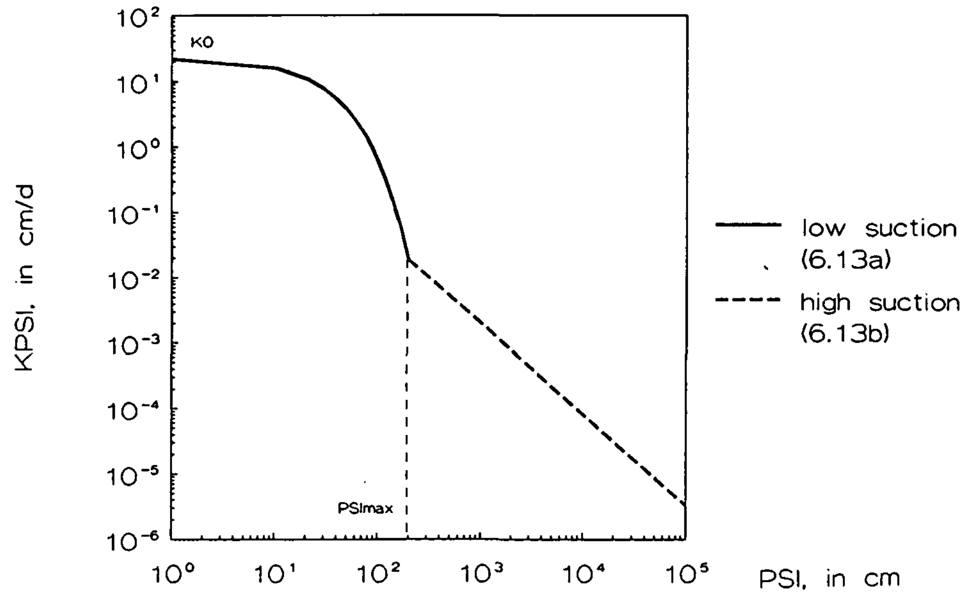


Fig. 6.1. Indicative KPSI-PSI curve for sandy clayloam.

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

Texture	**SMO** ($cm^3\ cm^{-3}$)	**GAM** (cm^{-2})	**PSI_{max}** (cm)	**KO** ($cm\ d^{-1}$)	**ALFA** (cm^{-1})	**AK** ($cm^{-2.4}\ d^{-1}$)
coarse sand	0.395	0.1000	80	1120	0.244	0.08
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

SMPSI-PSI relation

pF-curves of Dutch reference soil materials (single-grain material with rigid geometry) are reasonably well described with one generic SMPSI-PSI relation.

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

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 texture-specific constant (cm^{-2}; see Table 6.4).

Conversely:

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

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).

$$(new)SMPSI = (old)SMPSI + (TRICKLE - TR - EA) * DT / RD \tag{6.15}$$

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)

Water-saturated 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:

$$PSIMUL = (PSI + PSIATM) / 2 \tag{6.16}$$

Campbell (1985) describes the relative humidity of air in (equilibrium with) air-dry 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 °C 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:

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

where
PSIATM is matric suction of air-dry soil (cm)
T_{24h} is average daily temperature (°C).

Campbell (1985) uses a default RHA-value of 0.5 in his calculations; the corresponding matric suction of 'air-dry' 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:

$$F = \text{KPSI} * (\text{PSI} + G) / L_x \qquad (6.17)$$

Darcy

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.

$$\text{DMMUL} = \text{KMUL} * (\text{PSIATM} - \text{PSI}) / (\text{EM} + \text{KMUL}) \qquad (6.18)$$

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).

$$\text{if PSIMUL} < \text{PSI}_{max} \text{ then KMUL} = \text{K0} * \exp(-\text{ALFA} * \text{PSIMUL}) \qquad (6.19a)$$

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

where

PSIMUL	is equivalent matric suction of the mulch layer (cm)
PSI_{max}	is texture-specific 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 texture-specific geometry constant (cm^{-1}; see Table 6.4)
AK	is texture-specific 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.

$$\mathrm{MULWAT} = \mathrm{DMMUL} * \mathrm{SMMUL} + \mathrm{PREC} * \mathrm{DT} \tag{6.20}$$

with

$$\mathrm{SMMUL} = \mathrm{SM0} * \mathrm{PSIMUL}^{(-\mathrm{GAM}*\ln(\mathrm{PSIMUL}))} \tag{6.20.1}$$

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

$$\mathrm{TRICKLE} = (\mathrm{MULWAT} - \mathrm{DMMUL} * \mathrm{SMPSI}) / \mathrm{DT} \tag{6.21a}$$

$$\text{else } \mathrm{TRICKLE} = 0 \tag{6.21b}$$

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).

$$\mathrm{VAPFLUX} = \mathrm{AIRDIFF} * \mathrm{DMDA} * \mathrm{SVAP} * (\mathrm{RHMUL} - \mathrm{RHA}) / \mathrm{DMMUL} \tag{6.22}$$

where

VAPFLUX	is 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 DMDA-values 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).

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

Actual rate of evaporation

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
WATSUPPLY is rate of upward water flow to the lower boundary of the mulch layer (cm d^{-1})
RD is 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
VAPSUPPLY is 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 water-saturated soil is allowed to drain.

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

where

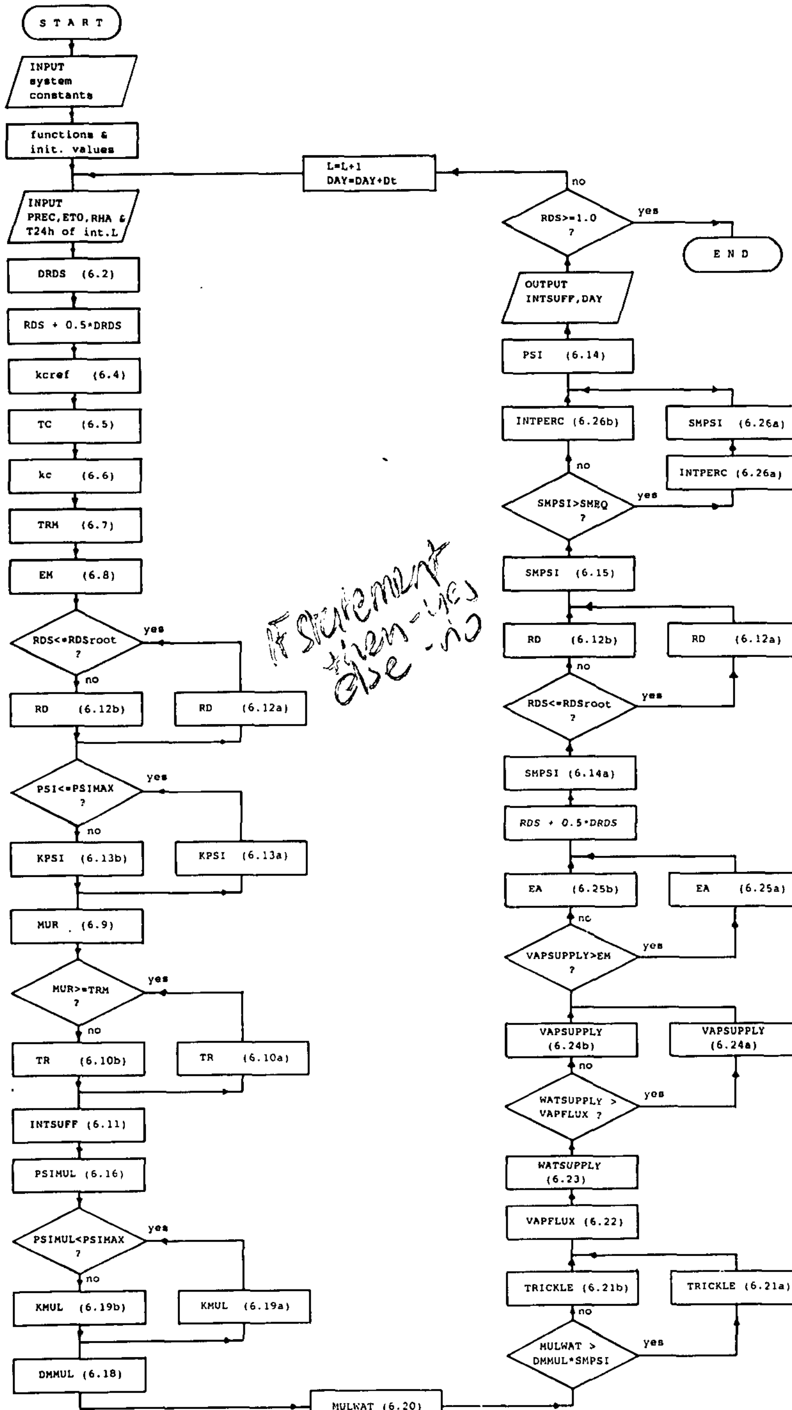
SM0	is total pore fraction ($cm^3\ cm^{-3}$; see Table 6.4)
GAM	is texture-specific constant (cm^{-2}; see Table 6.4).

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.**



If statement
then - yes
else - no

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:

	KPSI-PSI relation	(soil reports; hydrology reports)
	SMPSI-PSI relation	(soil reports)
	SMFC	(soil reports; SMPSI-PSI 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 rain-fed maize germinating on 1 June on loess loam in Xuzhou was successful in 1987 but very poor in 1988.

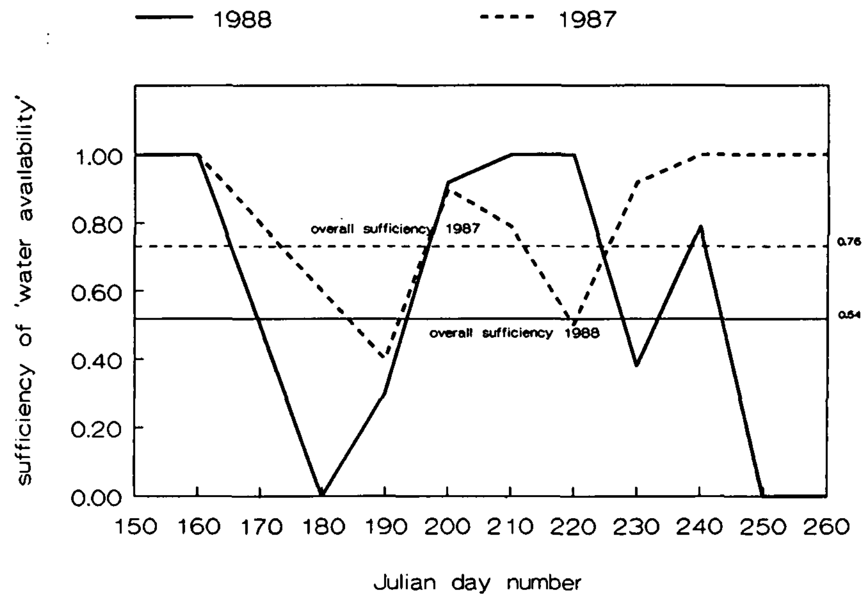


Fig. 6.3. Sufficiency of the land quality 'water availability' in land-use systems with rain-fed maize on loess loam near Xuzhou, P.R. of China. In both scenarios (1987 and 1988) the crop germinates on 1 June and on soil with a moisture potential of 1000 cm.

Note that a system-dependent rate of water supply (MUR) was matched against the transpiration needs of a constraint-free 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 stress-free crop, even after the period of stress had long passed. The sufficiencies calculated in the previous section are likely to be too pessimistic.

Single-factor 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.

Single-factor ratings can perhaps indicate major differences between dry and wet years and between drought-sensitive and tolerant crops. However they must not be used for other than comparative studies of an exploratory nature.

CHAPTER 7

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 PS-3. 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 (PS-1) 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 PS-1 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 (PS-2), 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 PS-2 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 PS-2 analysis is the **water-limited production potential**.

At the third hierarchical level (PS-3), 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 PS-1 are still simple; simulation of production situation PS-2 is already quite difficult. Calculating production potential as a function of temperature(s), available radiation, water, **and** nutrients (PS-3) is not really practicable. A change in strategy is needed.

From PS-3 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' (PS-3), an additional 'herbicide requirement' (PS-4), and so forth, in addition to the calculated water-limited production potential.

Note that only production situations PS-1, PS-2 and PS-3 will be discussed in this book.

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

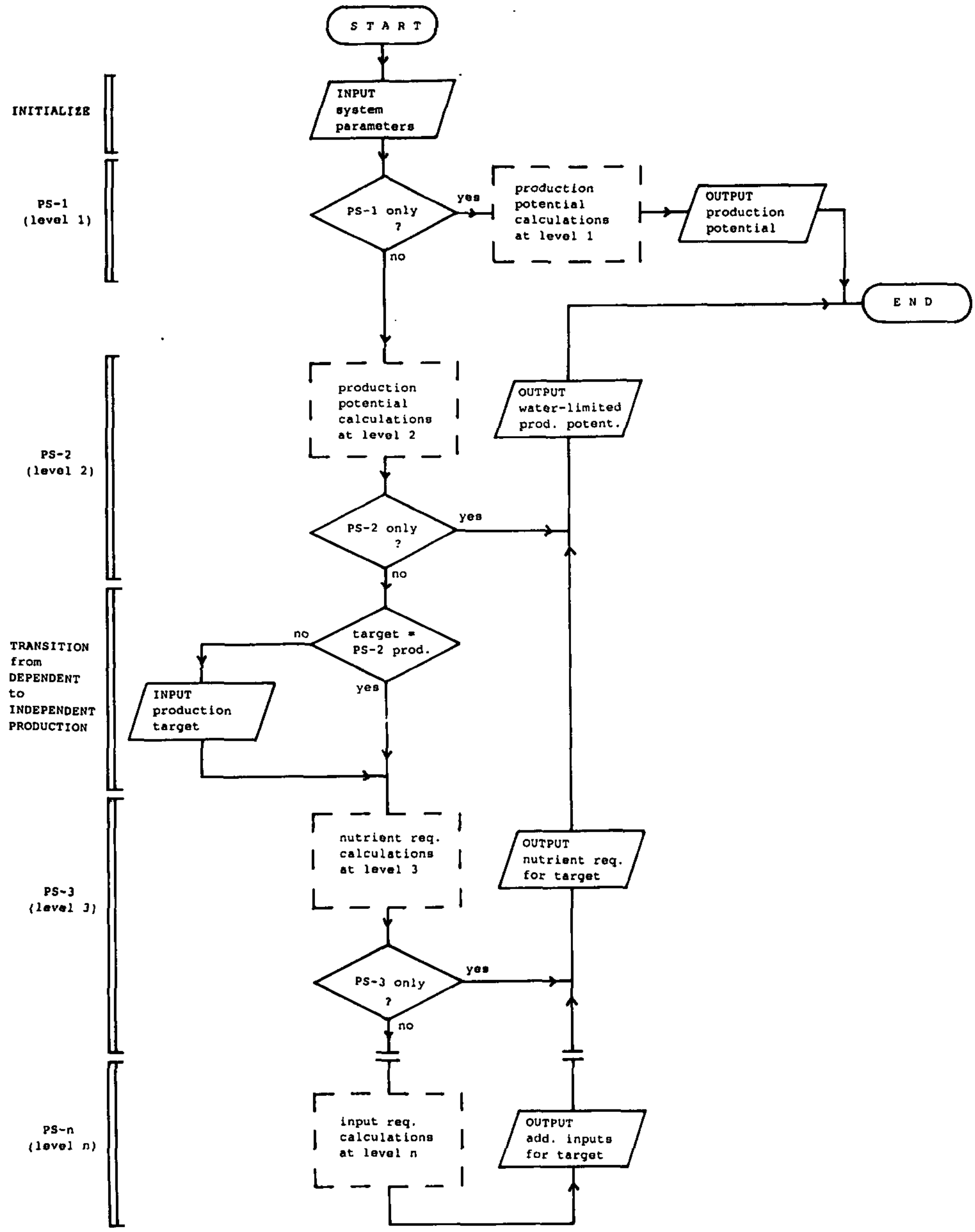


Fig. 7.1. Relational diagram of production situations.

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 2[nd] 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.

On-farm 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 non-agricultural sector are just as important. Studies of farming systems **must** consider the socio-economic constraints to farming.

A two-stage analysis of on-farm production possibilities results if objective(s) and constraints identified in socio-economic studies are combined with (sets of) activities, physical constraints, inputs and production figures generated in multiple analysis of production situations. Interactive multiple-goal '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' socio-economic optimation model has proven to be particularly difficult.

CHAPTER 8

PS-1: BIOPHYSICAL PRODUCTION POTENTIAL

8. PS-1: BIOPHYSICAL PRODUCTION POTENTIAL

Production situation PS-1 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 PS-1 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 PS-1 is based on the same principles as calculation of net biomass production for agro-ecological 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:

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

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.

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

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 **C3-plants** 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 **C4-plants**.

An important difference between C3-plants and C4-plants is that respiration in the sunlit photosynthetic organs (**photorespiration**) is considerable in C3-plants and negligible in C4-plants.

Losses of assimilates incurred in photorespiration increase with temperature and intensity of light. This has practical consequences.

- C4-plants make more efficient use of intercepted solar radiation than C3-plants at high light intensity (there is little difference at low light intensity)
- C4-plants reach their maximum rate of assimilation rate between 25 and 35 °C whereas C3-plants perform best between 15 and 25 °C (Black, 1973).

Not surprisingly, C4-plants stem predominantly from the tropics. Most C3-crops (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 C4-crops than for C3-crops. AMAX is strongly temperature-dependent; EFF decreases by only 1% for every degree of temperature increase in C3-plants, and even less in C4-plants. 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).

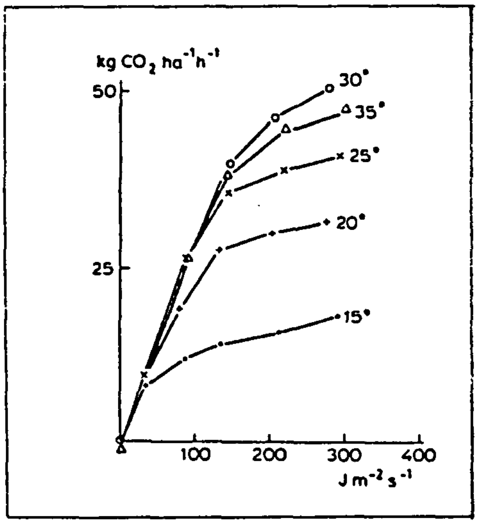


Fig. 8.1. Light response curves of maize leaves at several temperatures (de Wit et al., 1978).

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 field-grown 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 **crop-adaptability groups** with different AMAX-to-temperature relations. The response curves in Figure 8.2 resemble those used by the AEZ team (FAO, 1978).

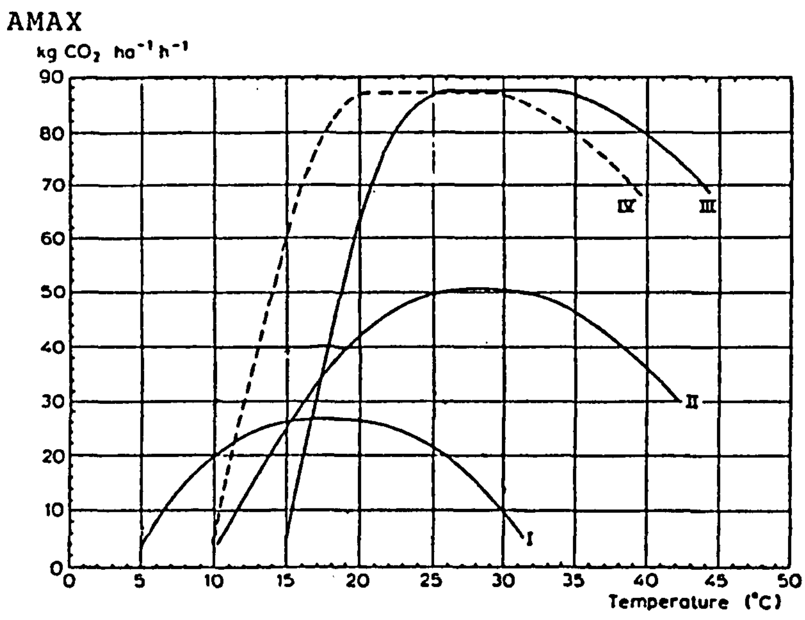


Fig. 8.2. Generic AMAX-to-temperature response curves (Versteeg & van Keulen, 1986).
Legend: I = C3-crops in cool and temperate climates; II = C3-crops in warm climates; III = C4-crops in warm climates; IV = C4-crops in cool climates.

Note that Figure 8.2 is a simplification; the optimum temperature for assimilation by a C3-crop cannot be a steady 18 °C in cool climates and 27 °C in the tropics if it is co-determined 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 AMAX-to-temperature relation for C3-crops.

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

Approximate AMAX-to-temperature relations for C4-crops 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
$$AMAX = 110 - 2 * (T_{day} - Tref) \qquad (8.2c)$$

$$\textbf{if } AMAX > 88 \text{ then } AMAX = 88 \qquad (8.2d)$$

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

AMAX-to-temperature 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).

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

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.

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

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.

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

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

$$DL = 12 * (PI + 2 * asin(SSCC)) / PI \qquad (8.4)$$

with

$$SSCC = SSIN / CCOS \qquad (8.4.1)$$
$$SSIN = sin(LAT * RAD) * sin(DEC * RAD) \qquad (8.4.2)$$
$$CCOS = cos(LAT * RAD) * cos(DEC * RAD) \qquad (8.4.3)$$
$$DEC = -23.45 * cos(2 * PI * (DAY+10) / 365) \qquad (8.4.4)$$

where

RAD is a conversion factor (degree to radian; RAD = PI / 180)
LAT is latitude of the site (degree)
DEC is declination of the sun (degree)
DAY is 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:

$$PAR = 0.5 * [SC * (1 + 0.033 * cos(2 * PI * DAY / 365))] * RDN \qquad (8.5)$$

with

$$RDN = SSIN + 24 * CCOS * (1 - (SSCC)^2)^{0.5} / (DL * PI) \qquad (8.5.1)$$

where

PAR is 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})
RDN is 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).

$$PARCAN = PAR * TRANS \tag{8.6}$$

where

PARCAN	is photosynthetically active radiation at the top of the canopy ($J\ m^{-2}\ s^{-1}$)
PAR	is photosynthetically active radiation at the outer extremity of the atmosphere ($J\ m^{-2}\ s^{-1}$)
TRANS	is atmospheric transmission.

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

$$TRANS = a + b * SUNH / DL \tag{8.6.1}$$

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.

$$a = 0.29 * \cos(RAD * LAT) \tag{8.6.2}$$

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).

$$b = 1.25 - RHA \qquad (r^2 = 0.85) \tag{8.6.3}$$

where

RHA is 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).

$$Fgc = DL * (AMAX / ke) * \ln[(AMAX + CC) / (AMAX + CC * EXP(-LAI * ke))] \quad (8.7)$$

with

$$CC = EFF * ke * PARCAN \quad (8.7.1)$$

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})
PARCAN	is 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 co-determined 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	18-23 (22)	0.8	0.012	0.010	0.004	0.003
chickpea	C3	15-20 (13)	0.5*	0.030	0.010	0.015	0.009
cotton	C3	16-24 (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	28-33 (31)	0.5*	0.015	0.010	0.015	-
lentil	C3	32-37 (33)	0.5*	0.015	0.010	0.015	0.013
maize	C4	14-35 (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	20-30 (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	25-32 (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	21-30 (23)	0.5*	0.015	0.010	0.015	0.012
sorghum	C4	11-21 (20)	0.5	0.015	0.010	0.010	0.010
soya	C3	15-23 (26)	0.4	0.015	0.010	0.015	0.017
sugar-cane	C4	8-12 (10)	0.3	0.0134	0.010	0.0029	-
sunflower	C3	25-30 (nd)	0.8	0.015	0.010	0.0075	0.023
sweet potato	C3	14-20 (22)	0.45	0.028	0.025	0.020	0.005
tobacco	C3	10-31 (16)	0.5*	0.015	0.010	0.015	-
wheat	C3	16-24 (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.

$$\text{Fgass} = \text{Fgc} * 30/44 * \text{cf(water)} \quad (8.10)$$

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 PS-1).

Note that production situation PS-1 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)).

$$\text{GAA(org)} = \text{Fgass} * \text{fr(org)} \quad (8.11)$$

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 RDS-to-fr(org) relations for common annual crops. Linear interpolation between tabulated combinations of RDS and fr(org) is allowed.

Figure 8.3 presents the RDS-to-fr(org) curves for maize cv. Pioneer 3183. (Danalatos, in press).

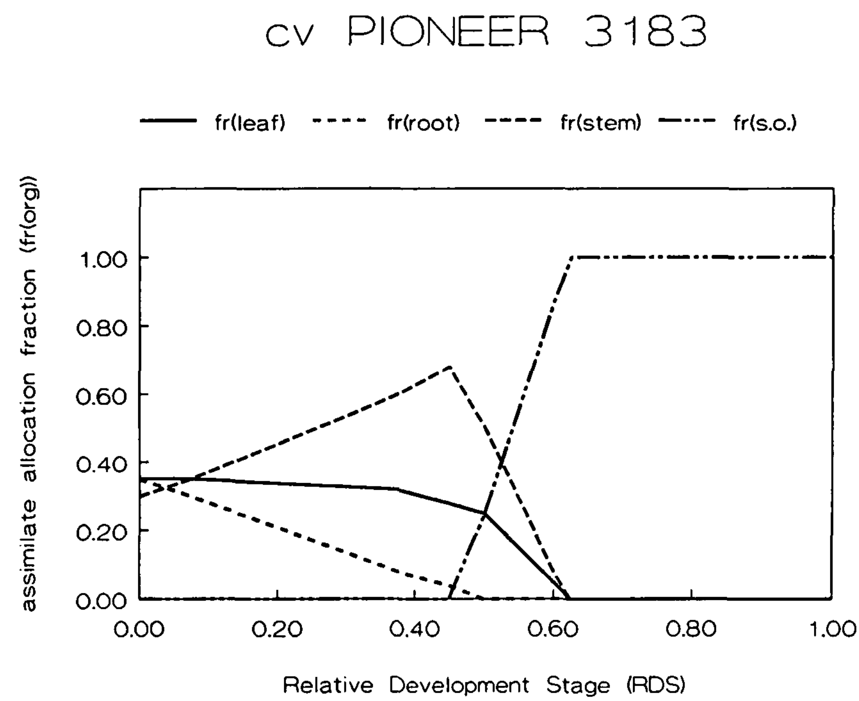


Fig 8.3. RDS-to-fr(org) relations for maize cv. Pioneer 3183. (Danalatos, in press).

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.)

Organ-specific **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 PS-1 conditions and at the reference temperature.

$$MRRref(org) = r(org) * S(org) \quad (8.12)$$

where

MRRref(org)	is maintenance respiration rate of **living** plant part 'org' at the reference temperature (kg ha^{-1} d^{-1})
r(org)	is organ-specific 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 temperature-dependent. A **temperature correction factor** (cf(temp)) expresses maintenance respiration at ambient temperature as a fraction of maintenance respiration at reference temperature.

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

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

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 PS-1 maintenance respiration needs are likely to decrease when water flow and energy demanding transport processes slow down in times of drought.

$$\text{MRR(org)} = \text{MRRref(org)} * \text{cf(temp)} * \text{cf(water)} \tag{8.14}$$

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 PS-1).

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 organ-specific 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** (°C d)	**Ec(org)**			
		leaf	root	stem	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
sugar-cane	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)).

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

$$\textbf{else } livS(leaf) = (new)S(leaf) \qquad (8.17b)$$

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).

$$\text{TDM} = \text{S(leaf)} + \text{S(root)} + \text{S(stem)} + \text{S(s.o.)} \tag{8.18}$$

$$\text{TLDM} = \text{livS(leaf)} + \text{S(root)} + \text{S(stem)} + \text{S(s.o.)} \tag{8.19}$$

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 PS-1.

Complete analysis of production situation PS-1 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 PS-1. The data items are arranged in four categories: General data, Management data, Crop data and Weather data.

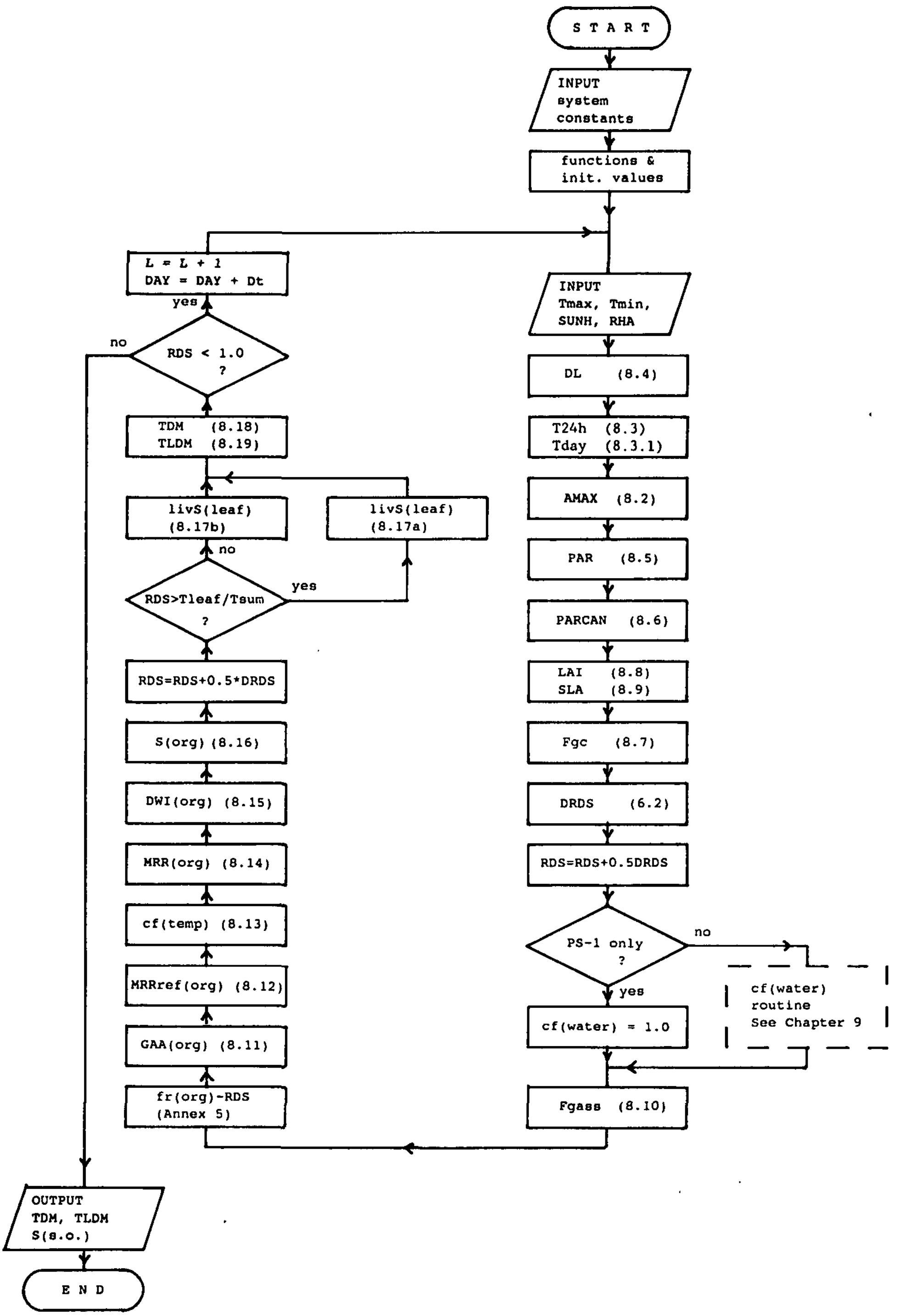


Fig. 8.4. Flow diagram for analysis of production situation PS-1.

Table 8.3. Data needs for analysis of production situation PS-1.

General data:		
	DT	(typically DT = 1 d)
	LAT	
Management data:		
	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.)).
Crop data:		
	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 PS-1.)

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 150th 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 one-third of the fertile seed mass is respired in germination and the remaining two-thirds 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.

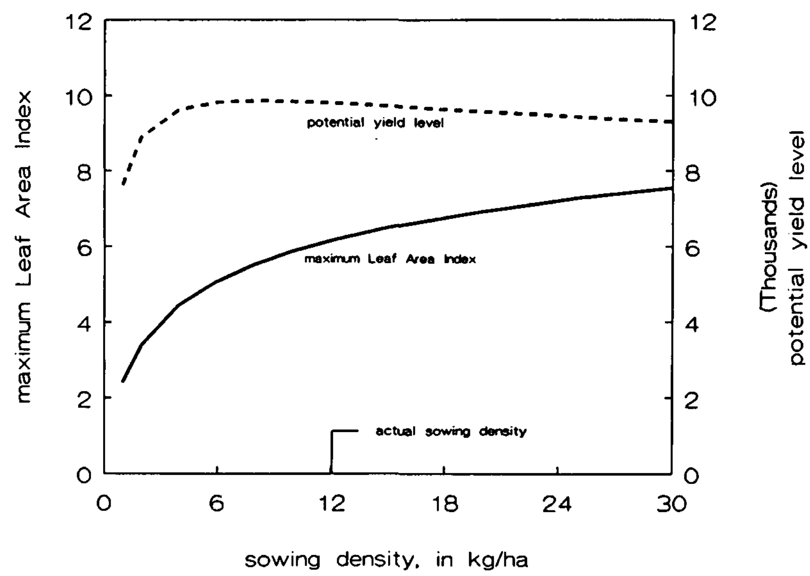


Fig. 8.5. Calculated maximum LAI and biophysical yield potential of maize near Xuzhou (1988) as a function of sowing density. (Dry seed; seed mortality is set to 10%).

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 PS-1 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 poor-quality seed, weeds, pests and diseases in actual farming are mitigated by (chosing) a higher sowing density than needed in production situation PS-1. 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 constraint-free 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 PS-1 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 mid-season 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 grain-filled cobs and just enough root mass to keep the crop standing in anticipation of the harvester.

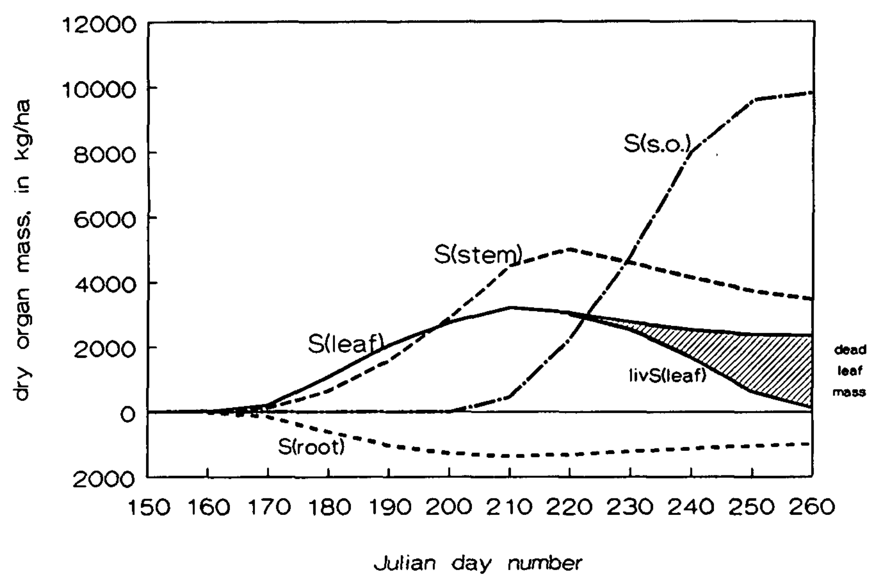


Fig. 8.6. Potential growth of maize near Xuzhou, North China Plain, calculated with the PS123 model. The maize is a local cultivar sown to 12 kg ha^{-1} (10% seedling mortality); it germinated on 1 June 1988.

8.4 Role of production situation PS-1 in land-use systems analysis

Recall that FAO's agro-ecological zoning is based on calculations of the 'potential net biomass production' of field crops (B_{n}; Equation 4.9). Potential production multiplied by a tabulated harvest index gives an estimated 'constraint-free yield' (B_{y}; Equation 4.10) which serves as the **reference yield level** for high-input farming. The reference yield level for low-input farming was arbitrarily set to 25% of the calculated

constraint-free yield. An estimate of the 'anticipated crop yield' was obtained by applying correction factors for agro-climatic 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 PS-1 has the same function as the constraint-free 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

PS-2: WATER-LIMITED PRODUCTION POTENTIAL

9. PS-2: WATER-LIMITED PRODUCTION POTENTIAL

Production situation PS-2 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 PS-2 is already a much more complex situation than PS-1 but still less complex than the production environment of many farmers in developing countries. Advanced farmers may examine alternative PS-2 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.

$$\mathrm{RSM} = [\mathrm{UPFLUX} + (\mathrm{CR} + D) - \mathrm{TR}] / \mathrm{RD} \qquad (9.1)$$

where

RSM	is rate of change of volume fraction of moisture in the rooting zone (d^{-1})
UPFLUX	is 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})
TR	is actual rate of transpiration (cm d^{-1})
RD	is 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.

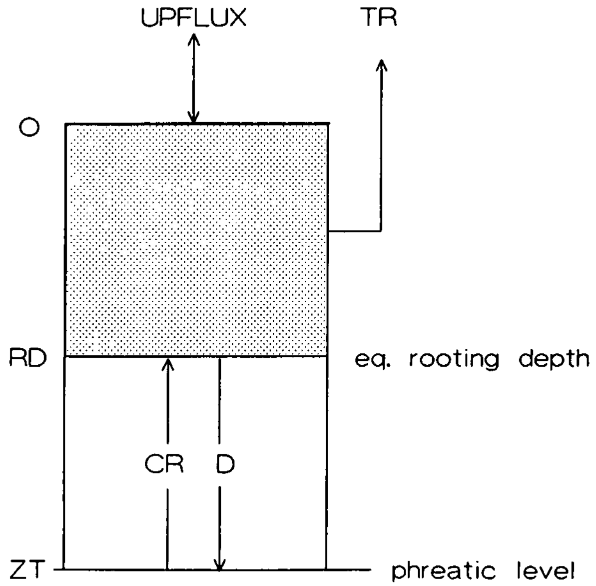


Fig 9.1. Water fluxes conditioning the volume fraction of moisture in the rooting zone.

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).

$$cf(water) = TR / TRM \tag{9.2}$$

where

cf(water)	is relative rate of transpiration by plants exposed to water stress
TR	is actual rate of transpiration (cm d^{-1})
TRM	is maximum rate of transpiration (cm d^{-1}).

The difference between analyses of production situation PS-1 and production situation PS-2 is that cf(water) in Equations 8.10 (Fgass) and 8.14 (MRR(org)) is 1.0 in production situation PS-1, and between 0 and 1.0 in production situation PS-2 (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).

$$GROSSUP = PREC + IE - EA \tag{9.3}$$

where

GROSSUP	is gross rate of water supply to the upper boundary of the rooting zone (cm d^{-1})
PREC	is gauged rate of precipitation (cm d^{-1})
IE	is effective rate of irrigation (cm d^{-1})
EA	is 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).

$$IE = IG * E_i * E_f * E_d \tag{9.4}$$

where

IE	is effective rate of irrigation (cm d^{-1})
IG	is 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).

$$E_{bare} = E0 * (RHS - RHA) / (1 - RHA) \tag{9.5}$$

with

$$RHS = \exp(-2.1649 * 10^{-4} * PSI / (273 + T_{24h})) \tag{9.5.1}$$

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).

$$EM = E_{bare} * \exp(-LAI * ke) \tag{9.6}$$

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).

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

where

WATSUPPLY	is rate of upward flow to the lower boundary of the mulch layer, (cm d^{-1})
KPSI	is hydraulic conductivity (cm d^{-1})
PSIMUL	is equivalent matric suction of the mulch layer (cm)
RD	is equivalent rooting depth (cm)
DMMUL	is 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

KPSI	is hydraulic conductivity of soil with matric suction PSI (cm d^{-1})
PSI_{max}	is texture-specific suction boundary (cm; see Table 6.4)
K0	is saturated hydraulic conductivity (cm d^{-1}; see Table 6.4)
ALFA	is texture-specific geometry constant (cm^{-1}; see Table 6.4)
AK	is texture-specific 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 (crop-specific) relative development stage at which root growth ceases (RDS_{root}).

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 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 air-dry soil (PSIATM).

$$PSIMUL = (PSI + PSIATM) / 2 \qquad (6.16)$$

with

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

where

PSIMUL	is equivalent matric suction of the mulch layer (cm)
PSI	is matric suction of the root zone (cm)
PSIATM	is matric suction of air-dry soil (cm)
RHA	is 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.

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

where

DMMUL	is equivalent depth of the mulch layer (cm)
KMUL	is 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 texture-specific suction boundary (cm; see Table 6.4)
K0	is saturated hydraulic conductivity (cm d^{-1}; see Table 6.4)
ALFA	is texture-specific geometry constant (cm^{-1}; see Table 6.4)
AK	is texture-specific 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.

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

where

VAPFLUX	is 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 of air (mbar)
RHMUL	is relative humidity of air in the mulch layer (0 - 1)
RHA	is relative humidity of atmospheric air (0 - 1).

with

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

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

$$SMMUL = SM0 * PSIMUL^{(-GAM * \ln(PSIMUL))} \quad (6.14a)$$

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

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

where

T_{24h} is average daily temperature (°C)
SM0 is total pore fraction of soil material ($cm^3\ cm^{-3}$)
SMMUL is volume fraction of moisture in the mulch layer ($cm^3\ cm^{-3}$)
GAM is texture-specific constant (cm^{-2}; see Table 6.4)
PSIMUL is 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

VAPSUPPLY is 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

SS is 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
MULWAT is calculated (maximum) amount of water in the mulch layer (cm)
NETSUP is 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

NETSUP	is net rate of water supply to the upper boundary of the rooting zone (cm d^{-1})
IM	is actual infiltration rate (cm d^{-1})
ASSC	is actual surface storage capacity (cm)
SS	is actual surface storage (cm)
DS	is rate at which water on top of the soil sags into the rooting zone (cm d^{-1})
SR	is rate of surface runoff (cm d^{-1})
DT	is 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.

Percolation (*D*)

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.

$$\textbf{if } PSI =< (ZT - RD) \textbf{ then } D = KPSI * (PSI / (ZT - RD) - 1) \quad (9.11a)$$

$$\textbf{else } D = 0 \quad (9.11b)$$

where
D is rate of percolation from the rooting zone to the groundwater (cm d^{-1})
KPSI is hydraulic conductivity (cm d^{-1}; see Equation 6.13)
PSI is soil suction in the rooting zone (cm)
ZT is depth of phreatic level (cm)
RD is equivalent depth of the rooting zone (cm).

Capillary rise (CR)

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 CR-PSI 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

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).

Maximum rate of transpiration rate (TRM)

In chapter 6, TRM was calculated by simply multiplying the potential rate of evapotranspiration (ETO) by the crop coefficient of a hypothetical reference crop (kc_{ref}) and a turbulence coefficient (TC).

Note that assimilation is a function of **transpiration** (TRO) and NOT of *evapo*transpiration. Potential transpiration by a Penman-type 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:

$$TR0 = ET0 - E_{bare} * \exp(-(5 \text{ to } 6) * ke)$$

or

$$TR0 = ET0 - 0.05 * E0 \quad (9.12.1)$$

where

TR0 is potential rate of transpiration (cm d^{-1})
ET0 is potential rate of evapotranspiration (cm d^{-1})
E0 is 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 mid-season development stage of adequately watered crops.

$$TC = 1 + (TCM - 1) * (1 - \exp(-LAI * ke)) \quad (9.12.2)$$

where

TC is turbulence coefficient
TCM is (tabulated) maximum value for the turbulent coefficient
LAI is leaf area index
ke is 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 non-laminar flow.

$$TRM = TR0 * (1 - \exp(-LAI * ke)) * TC \quad (9.12)$$

Optimum availability of soil moisture

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 set-up.

A critically low moisture content occurs when the maximum rate of water uptake (MUR) is just equal to the theoretical transpiration needs (TRM).

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

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

with

$$R_{plant} = 680 + 0.53 * PSI_{leaf} \qquad (6.9.1)$$

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

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)
KPSI	is hydraulic conductivity (cm d^{-1})
RD	is equivalent rooting depth (cm).

The actual rate of transpiration (TR) can now be calculated for soil moisture fractions between SM0 and $SMPSI_{leaf}$.

$$\text{if } SMPSI >= (SM0 - 0.04) \text{ then } TR = 0 \qquad (9.13a)$$

$$\text{if } (SM0 - 0.04) > SMPSI > (SM0 - 0.08) \text{ then}$$
$$TR = TRM * (SM0 - 0.04 - SMPSI) / 0.04 \qquad (9.13b)$$

$$\text{else if } MUR >= TRM \text{ then } TR = TRM \qquad (9.13c)$$

$$\text{else } TR = MUR \qquad (9.13d)$$

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.

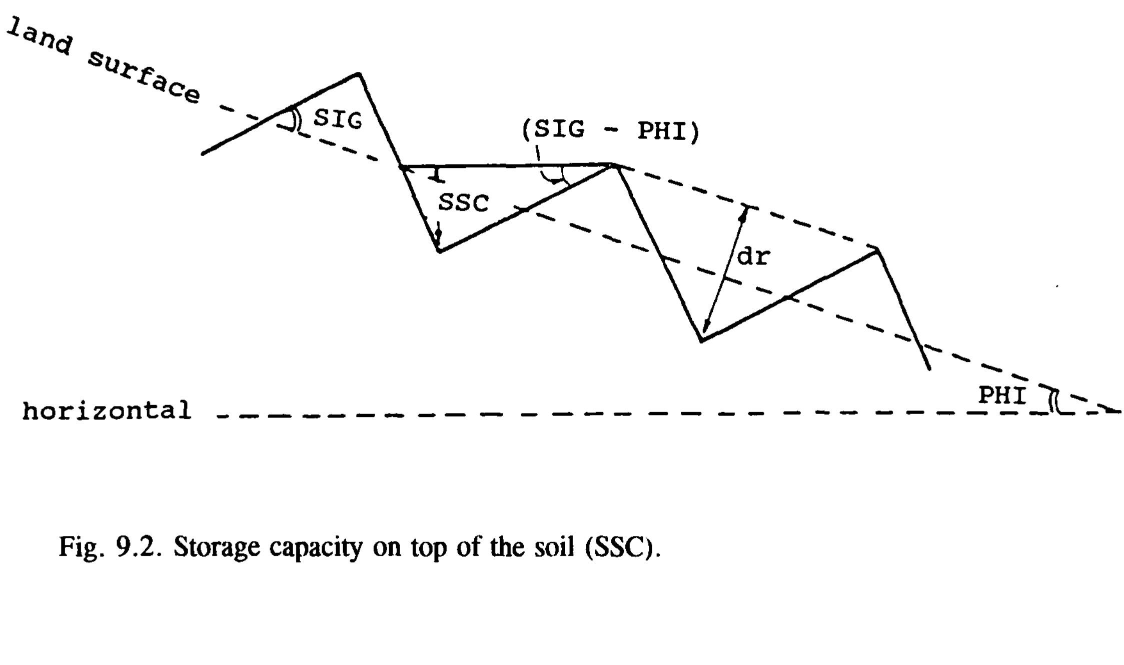


Fig. 9.2. Storage capacity on top of the soil (SSC).

$$SSC = 0.5 * dr * \frac{\sin^2(SIG - PHI)}{\sin(SIG)} * \frac{\cotan(SIG + PHI) + \cotan(SIG - PHI)}{2 * \cos(SIG) * \cos(PHI)} \qquad (9.14)$$

where

SSC	is equivalent surface storage capacity (cm)
dr	is surface roughness or furrow depth (cm)
SIG	is clod angle or furrow angle (degree)
PHI	is 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 contour-ploughed 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.

$$SPSI = S0 * (1 - SMPSI / SM0) \tag{9.15.1}$$

where

SPSI	is actual sorptivity (cm $d^{-0.5}$)
S0	is reference sorptivity (cm $d^{-0.5}$)
SMPSI	is volume fraction of moisture in the rooting zone (cm^3 cm^{-3})
SM0	is 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.

$$IM = SPSI * DT^{-0.5} + K_{tr} \tag{9.15}$$

where

IM	is equivalent rate of infiltration (cm d^{-1})
SPSI	is actual sorptivity (cm $d^{-0.5}$)
K_{tr}	is hydraulic permeability of transmission zone (cm d^{-1})
DT	is length of interval (d).

Table 9.3. Indicative values for standard sorptivity (SO) and permeability of the transmission zone (K_{tr}) of reference soil materials.

Texture class	SO ($cm\ d^{-0.5}$)	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

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.

$$\text{(new)SMPSI} = \text{(old)SMPSI} + \text{RSM} * \text{DT} \tag{9.16}$$

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

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.

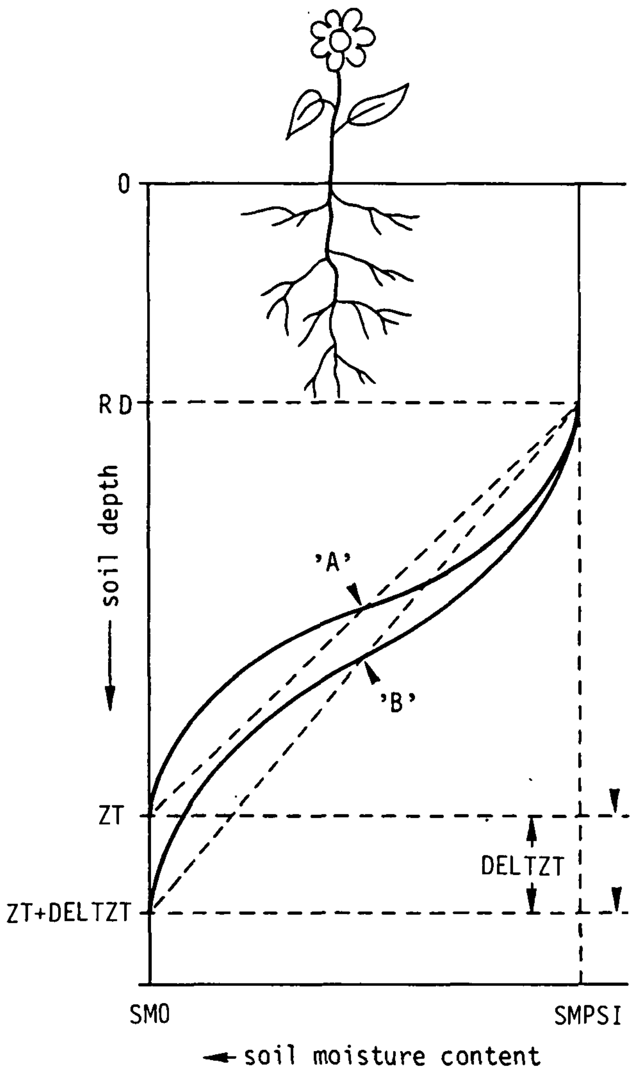


Fig. 9.3. Simplified soil moisture profiles before (line 'A') and after (line 'B') capillary rise.

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.

$$\text{DELTZT} = 2 * (\text{CR} + D) * \text{DT} \,/\, (\text{SM0} - \text{SMPSI}) \qquad (9.17.1)$$

where
DELTZT is 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.

$$(new)ZT = (old)ZT + DELTZT \tag{9.17}$$

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)

$$(new)SS = (old)SS - DS * DT \tag{9.18}$$

where
SS is actual surface storage (cm)
DS is 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 PS-1 to an analysis of situation PS-2. The routine bypasses the operation 'cf(water) = 1' in the calculations at PS-1 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 PS-1.

Data needs

Table 9.4 lists the **additional** data needs for analyses of production situation PS-2. 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.

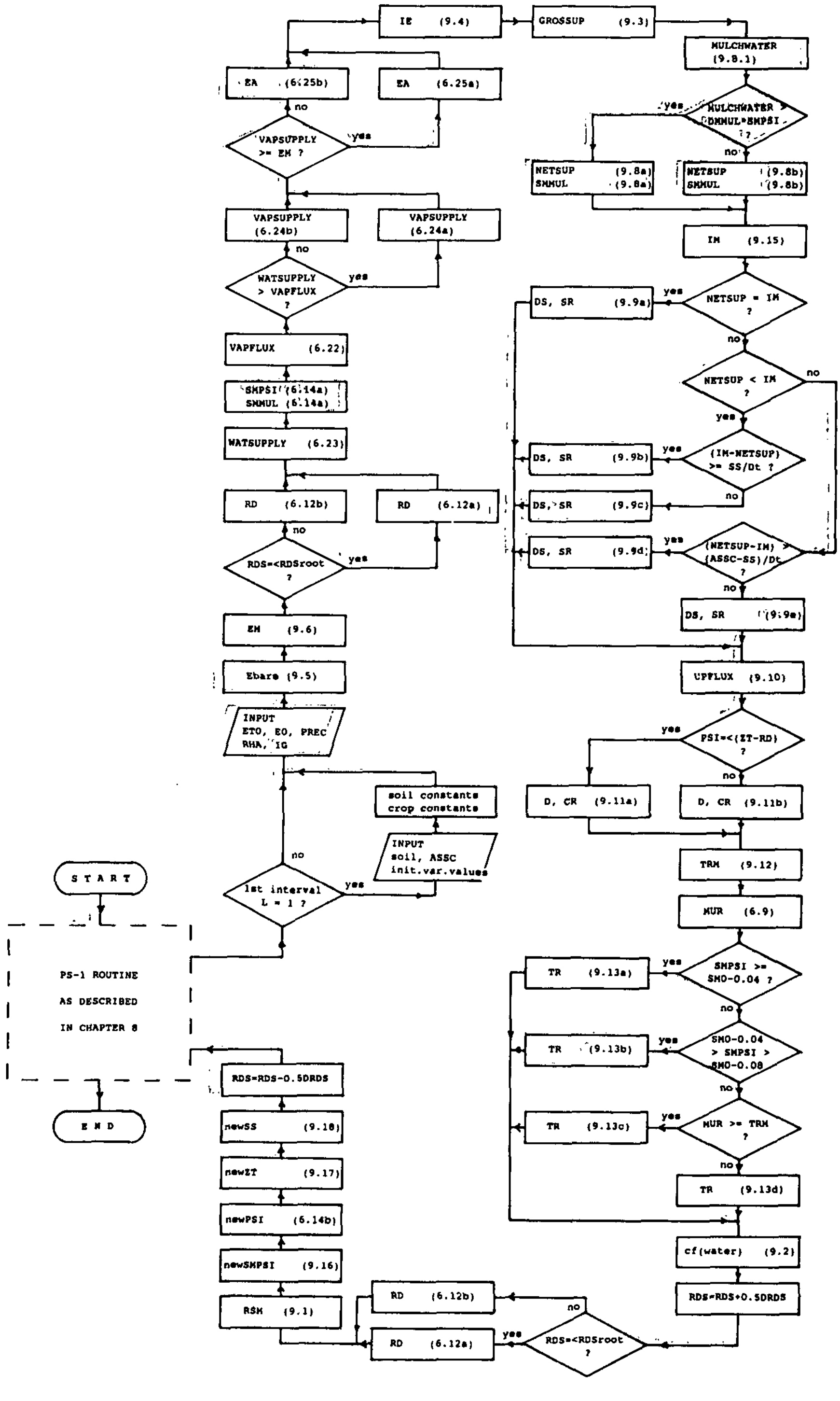


Fig. 9.4. Flow diagram of a routine to calculate cf(water). Substitution in Figure 8.4 extends the analysis of production situation PS-1 to an analysis of situation PS-2.

Table 9.4. Additional data needs for analyses of production situation PS-2.

General data:		
	--	
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).
Soil and terrain data:		
	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).

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 rain-fed 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 rain-fed 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** constraint-free 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 PS-2 level**. Using class boundaries as suggested by FAO (1978), one would classify the land unit of Table 9.5 as 'very suitable' for rain-fed cotton, 'not suitable' for rain-fed peppers, and 'suitable' for rain-fed maize in normal years (1987 and 1988) but 'not suitable' for rain-fed maize in dry years (1986).

Running scenarios with different specifications reveals the merits of defined management packages. The low yield of rain-fed 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 10-days averages to keep the output concise.

Table 9.6A. Indicators of crop performance in production situation PS-2. The values were generated for rain-fed 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.

DAY	LAI	LIVSLEAF	SLEAF	SROOT	SSTEM	SSO	TDM	CFWATER
150	0.01	3	3	4	2	0	9	1.00
160	0.06	33	33	30	19	0	82	1.00
170	0.41	221	221	158	130	0	509	1.00
180	2.49	1376	1376	746	837	0	2958	1.00
190	6.07	2890	2890	1404	2334	0	6627	0.16
200	6.00	2989	3016	1450	2526	0	6992	0.21
210	2.33	1064	3076	1442	2805	337	7660	1.00
220	0.21	117	3081	1358	2880	1141	8460	1.00
230	0.11	62	3072	1260	2589	1308	8229	1.00
240	0.09	53	3066	1171	2330	1436	8003	1.00
250	0.07	45	3061	1090	2101	1513	7763	1.00
254	0.07	43	3059	1067	2039	1510	7675	1.00

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.

DAY	LAI	LIVSLEAF	SLEAF	SROOT	SSTEM	SSO	TDM	CFWATER
150	0.01	3	3	4	2	0	9	1.00
160	0.06	33	33	30	19	0	82	1.00
170	0.41	221	221	158	130	0	509	1.00
180	2.49	1376	1376	746	837	0	2958	1.00
190	6.07	2895	2895	1406	2342	0	6644	0.92
200	8.13	4073	4073	1806	4527	0	10406	0.04
210	7.16	3449	4085	1808	4572	11	10476	0.41
220	2.17	1119	4015	1747	4669	1483	11914	0.90
230	0.00	0	3965	1645	4301	2604	12515	0.00
240	0.00	0	3965	1645	4301	2604	12515	0.00
250	0.00	0	3965	1645	4301	2604	12515	0.00
254	0.00	0	3965	1645	4301	2604	12515	0.00

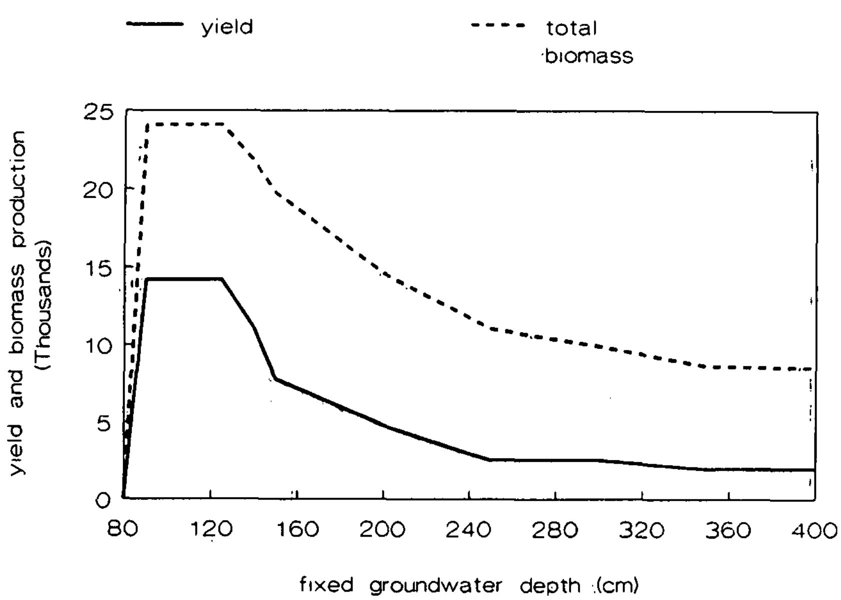


Fig. 9.5. Water-limited yield and production potentials of rain-fed maize as a function of phreatic depth. Other system specifications are as in previous calculations.

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 PS-2 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 PS-2 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 PS-2. Their production environment is far too complex to be modelled. See Figure 9.6.

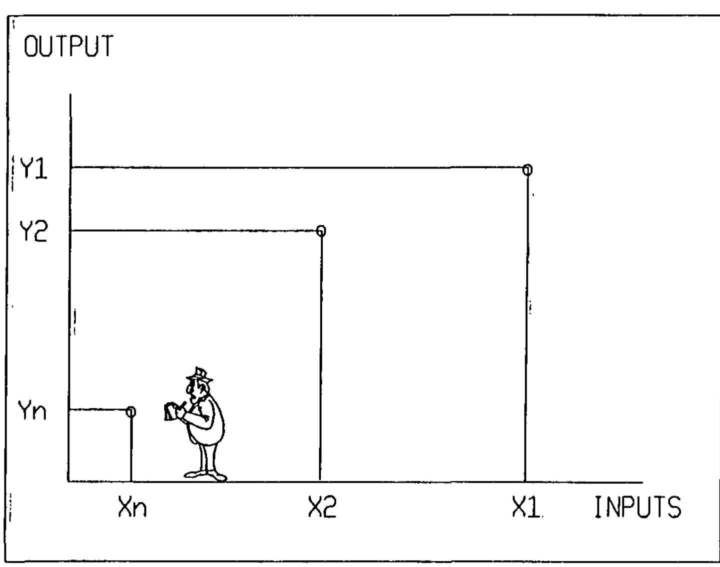


Fig. 9.6. Input-output relations for production situations PS-1 (X1-Y1) and PS-2 (X2-Y2), and for a poor farmer (Xn-Yn) who has no unused resources and whose actual yield and production represent the potential. PS-n is too complex to be handled with simulation techniques.

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 long-term 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

PS-3: ASSESSING FERTILIZER REQUIREMENTS

10. PS-3: ASSESSING FERTILIZER REQUIREMENTS

Production situation PS-3 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 organo-mineral 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})

Ytarget is (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.

Yield-uptake 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, yield-uptake curves can be broken down into two linear trajecta.

Figure 10.1 shows the theoretical maize-yield-to-nitrogen-uptake 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.**

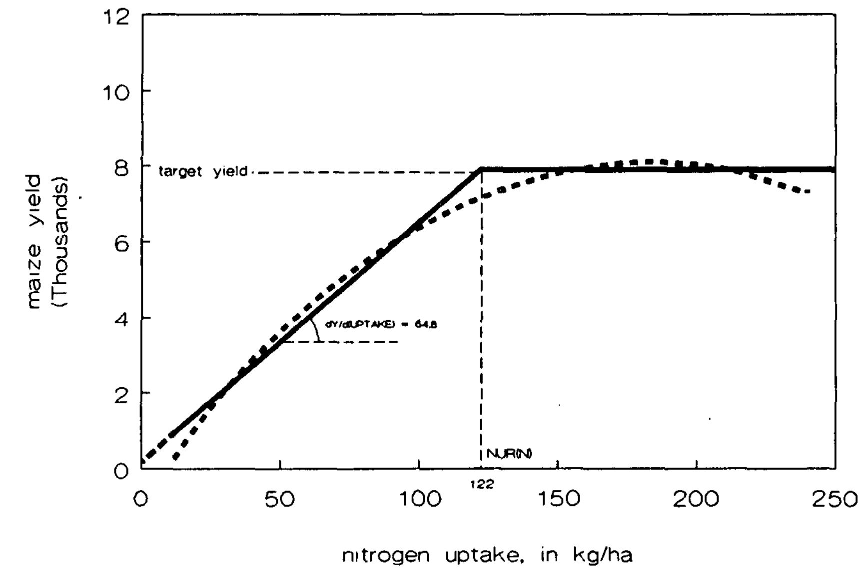


Fig. 10.1. Theoretical maize-yield-to-nitrogen-uptake response curve.

Base uptake (BU(el))

Fertilizer trials are conducted under PS-3 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 yield-to-nitrogen-uptake 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}.

$$BU(el) = CY / (Ytarget / NUR(el)) \tag{10.2}$$

where

BU(el)	is base uptake of nutrient 'el' (kg ha^{-1})
CY	is control yield (kg ha^{-1}).

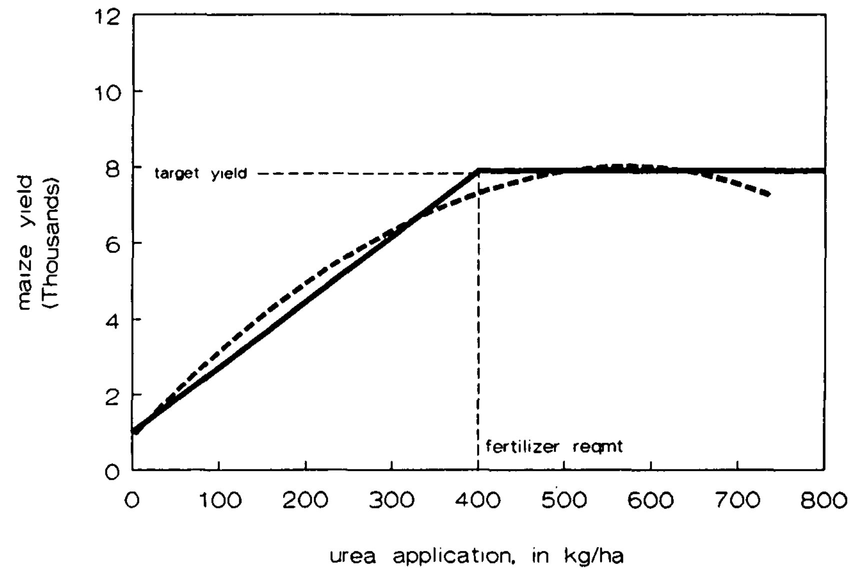


Fig. 10.2. Observed yield-to-nitrogen-fertilizer response curve.

Note that farmers' fields are not cropped to PS-3 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 fertilizer-nitrogen, 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 N-compounds 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 K-fertilizers (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
K-Mg 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 urea-nitrogen 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 urea-N 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 oxygen-poor layer raises RF(N) from less than 0.2 to 0.5 or more because urea-N is converted only to NH_4^+-ions. These are not reduced to gaseous N-forms 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, near-neutral alluvial clay
.	Near-neutral, (strongly) humic soil material
.	Weakly to medium acid, well-structured 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

10.2 Fertilizer requirement

The relation between nutrient uptake, yield, and fertilizer application is depicted in a 4-quadrant 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)).

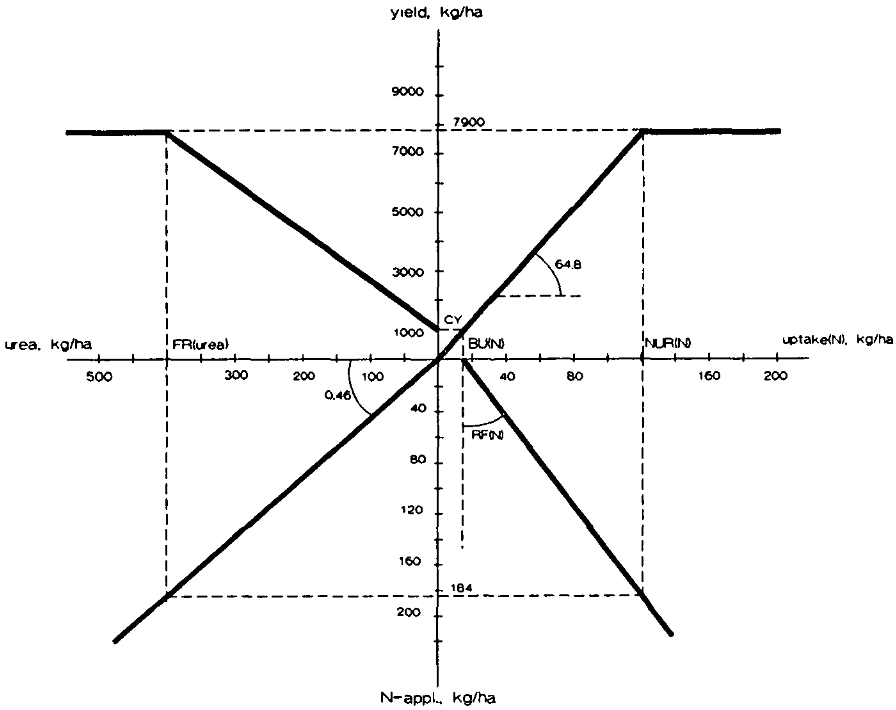


Fig. 10.3. Maize yield, application of urea, application of nitrogen, and uptake of nitrogen in the sample PS-3 scenario.

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}.

$$FR(f) = (NUR(el) - BU(el)) / (EC(el) * RF(el)) \qquad (10.3)$$

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 fertilizer-nutrient '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 phosphorus-fixing soil. Application of a low dose of P-fertilizer 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 PS-3 (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 N-concentrations in living tissue could vary sixteenfold; in practice P/N-ratios vary only fourfold, between P/N = 0.04 and P/N = 0.15.

When the P/N-ratio is close to 0.04, **absolute** phosphorus shortage inhibits further uptake of nitrogen (even if it is present in the soil). When the P/N-ratio is close to 0.15, **relative** phosphorus shortage (induced by absolute nitrogen shortage) inhibits further uptake of phosphorus. The P/N-ratio 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 P-fertilizer 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 phosphorus-fixing soils normally use rock phosphate or basic slag as a phosphorus fertilizer. Table 10.2 shows that rock phosphate has a P-content 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 phosphorus-fixing 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 P-fertilizer 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 (yield-to-(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 P-deficiency 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 P-concentration 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 N-shortage); the overall P/N-ratio 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/straw-ratio of the control crop is between the yield/straw-ratio 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 constraint-free short-straw 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	1= no risk
2	12.1-16.0	2= slight
3	8.1-12.0	3= moderate
4	4.0-8.0	4= strong
5	<4.0	5= very strong

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: 0-30 cm (where most of the roots are present), and 30-100 cm.

Rating	ASal; the highest ECe reading within:	
	0-30 cm	30-100 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 0-30 cm and '2' within 30-100 cm, then the final rating is '2'.

Absence of sodicity (ASod)

Separate ratings are given for two depths: 0-30 cm and 30-100 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:	
	0-30 cm	30-100 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 P-Olsen value. The negative effects of salinity and sodicity on soil fertility are taken into account in separate ratings for ASal and ASod.

Rating	CEC (cmol/kg)	orgC (%)	av.P (ppm)	K	Ca	Mg	pH (1:2.5)
				(------cmol/kg-------)			
1 (high)	>16	>2	>20	>0.5	>6	>3	5.6-6.8
2 (moderate)	6-16	1-2	11-20	0.2-0.5	3-6	1-3	6.9-7.5
3 (low)	3-6	0.5-1	5-10	0.1-0.2	1-3	0.5-1	7.6-8.7
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 (0-30 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	3.5-7.0
3	0.2-0.5	or	7.1-11.0
4	0.1-0.2	or	11.1-12.5
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; 82-85)

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		Sugar-cane		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		Sugar-cane		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		Sugar-cane		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 low	Wheat high	Sorghum low	Sorghum high	Millet low	Millet high	Beans low	Beans high
All Rendzinas:	S2N2	S2N2	S2	S2	S2	S2	S2N2	S2N2

	Maize low	Maize high	Soya low	Soya high	Cotton low	Cotton high	Wh. Potato low	Wh. Potato high
All Rendzinas:	S2N2	S2N2	S2N2	S2N2	S2N2	S2N2	S2N2	S2N2

	Sw. Potato low	Sw. Potato high	Sugar-cane low	Sugar-cane high	Cassava low	Cassava high	Rice low	Rice 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 low	Wheat high	Sorghum low	Sorghum high	Millet low	Millet high	Beans low	Beans 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 low	Maize high	Soya low	Soya high	Cotton low	Cotton high	Wh. Potato low	Wh. Potato 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 low	Sw. Potato high	Sugar-cane low	Sugar-cane high	Cassava low	Cassava high	Rice low	Rice 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		Sugar-cane		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		Sorghum		Millet		Beans	
	low	high	low	high	low	high	low	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		Soya		Cotton		Wh. Potato	
	low	high	low	high	low	high	low	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		Sugar-cane		Cassava		Rice	
	low	high	low	high	low	high	low	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 low	Sw. Potato high	Sugar-cane low	Sugar-cane high	Cassava low	Cassava high	Rice low	Rice 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 low	Wheat high	Sorghum low	Sorghum high	Millet low	Millet high	Beans low	Beans 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 low	Maize high	Soya low	Soya high	Cotton low	Cotton high	Wh. Potato low	Wh. Potato 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 low	Sw. Potato high	Sugar-cane low	Sugar-cane high	Cassava low	Cassava high	Rice low	Rice 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		**Sugar-cane**		**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		Sugar-cane		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		Sugar-cane		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		Sugar-cane		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		Sugar-cane		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 low	Wheat high	Sorghum low	Sorghum high	Millet low	Millet high	Beans low	Beans 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 low	Maize high	Soya low	Soya high	Cotton low	Cotton high	Wh. Potato low	Wh. Potato 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 low	Sw. Potato high	Sugar-cane low	Sugar-cane high	Cassava low	Cassava high	Rice low	Rice 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 low	Wheat high	Sorghum low	Sorghum high	Millet low	Millet high	Beans low	Beans high
Eutric P-luvisol	S2	S1	na	na	na	na	S1	S1
Dystric P-luvisol	N1	S2	na	na	na	na	S2	S1
Gleyic P-luvisol	N1	N1N2	na	na	na	na	N2	N1N2

	Maize		Soya		Cotton		Wh. Potato	
	low	high	low	high	low	high	low	high
Eutric P-luvisol	S2S1	S1	S2S1	S1	na	na	S1	S1
Dystric P-luvisol	S2	S1	S2	S1	na	na	S2	S1
Gleyic P-luvisol	N2	N1N2	S2N2	S2N1	na	na	N2	N1N2

	Sw. Potato		Sugar-cane		Cassava		Rice	
	low	high	low	high	low	high	low	high
Eutric P-luvisol	S1	S1	S1	S1	na	na	na	na
Dystric P-luvisol	S2	S1	S2	S1	na	na	na	na
Gleyic P-luvisol	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		Sugar-cane		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		Sugar-cane		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		Sugar-cane		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		Sugar-cane		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 low	Wheat high	Sorghum low	Sorghum high	Millet low	Millet high	Beans low	Beans 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 low	Maize high	Soya low	Soya high	Cotton low	Cotton high	Wh. Potato low	Wh. Potato 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 low	Sw. Potato high	Sugar-cane low	Sugar-cane high	Cassava low	Cassava high	Rice low	Rice 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 low	Wheat high	Sorghum low	Sorghum high	Millet low	Millet high	Beans low	Beans 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 low	Maize high	Soya low	Soya high	Cotton low	Cotton high	Wh. Potato low	Wh. Potato 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		Sugar-cane		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. PHASE-SLOPE-TEXTURE RULES FOR MODIFYING SOIL RATINGS

(Source: FAO World Soil Resources Report 48; 86-89)

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 (FAO-Unesco, 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 sugar-cane 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 sugar-cane 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 sugar-cane, 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 sugar-cane 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 60-100 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 high-input (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, one-third remain unchanged, one-third is decreased by one class and the remaining one-third 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, one-third remain unchanged and the remaining two-thirds are downgraded to N2 because mechanized cultivation is not considered possible on some two-thirds 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 AGRO-CLIMATIC CONSTRAINTS

(Condensed from: FAO World Soil Resources Report 48, 95-97)

Constraints:

'a' water stress,
'b' weeds, pests and/or diseases,
'c' defective yield formation/quality,
'd' impeded workability/harvesting.

Severity:

'0' no or slight; no yield loss,
'1' moderate; 25 % yield loss,
'2' severe; 50 % yield loss.

I. Crops in crop-adaptability 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
90-119	1000	1000	2100	2000	2110	2010	2010	2010
120-149	0000	0000	1100	1000	1100	1000	1000	1000
150-179	0000	0000	0000	0000	0000	0000	0000	0000
180-209	0100	0100	0000	0000	0000	0000	0100	0000
210-239	0110	0111	0110	0011	0100	0001	0110	0001
240-269	0221	0222	0121	0022	0101	0002	0110	0002
270-299	0221	0222	0221	0122	0101	0102	0111	0102
300-329	0221	0222	0221	0222	0101	0102	0211	0112
330-364	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
90-119	2010	2010	2110	2000	2010	2010	2010	2010
120-149	1000	1000	1110	1000	1001	1001	1011	1011
150-179	0000	0000	0110	0000	0000	0000	1101	1001
180-209	0100	0000	0110	0000	0000	0000	0100	0000
210-239	0110	0001	0110	0110	0000	0000	0100	0000
240-269	0210	0002	0110	0111	0010	0000	0100	0000
270-299	0211	0102	0121	0121	0010	0001	0100	0000
300-329	0211	0112	0221	0122	0020	0012	0100	0000
330-364	0222	0122	0222	0222	0020	0012	0110	0011
365	0222	0222	0222	0222	0021	0022	0111	0012

II. Crops in crop-adaptability groups I and IV in tropical and subtropical areas

	spring wheat			winter wheat
altitude (m):	1500-2000	2000-2500	2500-3000	0-1500
temperature (°C):	17.5-20.0	15.0-17.5	12.5-15.0	
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
90-119	2000 2000	2010 2010	2010 2010	2010 2010
120-149	1000 1000	1000 1000	2010 2010	2000 2000
150-179	0000 0000	0000 0000	1000 1000	1000 1000
180-209	0000 0000	0000 0000	0000 0000	0000 0000
210-239	0110 0011	0100 0101	0000 0000	0100 0100
240-269	0111 0111	0110 0111	0110 0111	0100 0100
270-299	0221 0222	0221 0222	0211 0212	-- --
300-329	0221 0222	0221 0222	0221 0222	-- --
330-364	0222 0222	0222 0222	0222 0222	-- --
365	0222 0222	0222 0222	0222 0222	-- --

	beans			potato
altitude (m):	1500-2000	2000-2500	2500-3000	1500-3000
temperature (°C):	17.5-20.0	15.0-17.5	12.5-15.0	12.5-20.0
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
90-119	2010 2010	2020 2020	2020 2020	2010 2010
120-149	1000 1000	2010 2010	2020 2020	1001 1001
150-179	0000 0000	0000 0000	1010 1010	0000 0000
180-209	0100 0000	0100 0000	0100 0000	0000 0000
210-239	0110 0001	0110 0001	0110 0000	0100 0101
240-269	0211 0001	0210 0001	0210 0001	0111 0111
270-299	0211 0102	0211 0102	0211 0102	0211 0212
300-329	0211 0112	0211 0112	0211 0112	0221 0222
330-364	0222 0122	0222 0122	0222 0122	0222 0222
365	0222 0222	0222 0222	0222 0222	0222 0222

maize

altitude (m):	1500-1600		1900-2000		2400-2500	
temperature (°C):	19.5-20.0		17.0-17.5		15.0-15.5	
inputs:	low	high	low	high	low	high
constraint:	abcd	abcd	abcd	abcd	abcd	abcd
LGP: 75- 89	2120	2020	2120	2020	2120	2020
90-119	2110	2010	2120	2020	2120	2020
120-149	1100	1000	2120	2020	2120	2020
150-179	0000	0000	1010	1010	2020	2020
180-209	0000	0000	1000	1000	2020	2020
210-239	0100	0001	0000	0000	2010	2010
240-269	0101	0002	0000	0000	2010	2010
270-299	0101	0102	0100	0001	1100	1001
300-329	0101	0102	0101	0102	0101	0101
330-364	0112	0112	0112	0112	0112	0112
365	0222	0222	0222	0222	0222	0222

sorghum

altitude (m):	1500-1600		1900-2000		2400-2500	
temperature (°C):	19.5-20.0		17.0-17.5		15.0-15.5	
inputs:	low	high	low	high	low	high
constraint:	abcd	abcd	abcd	abcd	abcd	abcd
LGP: 75- 89	2120	2020	2120	2020	2120	2020
90-119	2110	2010	2120	2020	2120	2020
120-149	1100	1000	2120	2020	2120	2020
150-179	0000	0000	1010	1010	2020	2020
180-209	0000	0000	1000	1000	2020	2020
210-239	0110	0011	0000	0000	2020	2020
240-269	0121	0022	0100	0001	2010	2010
270-299	0221	0122	0111	0012	1010	1011
300-329	0221	0222	0221	0122	0111	0112
330-364	0222	0222	0222	0222	0222	0222
365	0222	0222	0222	0222	0222	0222

A5. TENTATIVE RDS-fr(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 RDS-fr(org) relations, PS-1 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 chinese cv	RDS	0	0.39	0.46	0.83	>0.87	
	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 generic	RDS	0	0.32	0.51	0.63	0.77	>0.86
	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 generic	RDS	0	0.03	0.08	0.27	0.86	1
	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 generic	RDS	0	0.20	0.30	0.50	1	
	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 generic	RDS	0	0.30	0.60	1		
	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 cv 'Arjuna'	RDS	0	0.21	0.37	0.53	0.69	
	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 generic	RDS	0	0.12	0.24	0.40	0.70	
	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 generic	RDS	0	0.22	0.34	0.56	0.61	
	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 generic	RDS	0	0.24	0.40	0.48	0.61	>0.74
	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

sugar-cane generic	RDS	0	0.14	0.45	0.90	>0.91	
	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 generic	RDS	0	0.40	0.53	0.56	0.68	>0.75
	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 generic	RDS	0	0.48	1			
	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 generic	RDS	0	0.10	0.50	1		
	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 generic	RDS	0	0.11	0.20	0.35	0.47	>0.56
	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 chinese cv	RDS	0	0.08	0.30	0.31	0.46	>0.55
	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
50	34.3	35.3	36.5	38.2	39.4	41.0	42.9	46.3
100	34.4	35.4	36.7	38.6	39.8	41.7	44.0	49.0
250	34.5	35.5	36.8	38.6	39.9	41.8	44.1	49.5
500	34.5	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
50	47.2	47.7	48.3	48.8	49.1	49.4	49.6	49.9
100	82.9	85.5	88.4	91.7	93.5	95.5	97.2	99.0
250	100.6	106.2	113.5	123.9	131.3	141.9	155.6	185.9
500	102.8	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
50	47.9	48.3	48.7	49.1	49.3	49.6	49.7	49.9
100	82.0	84.5	87.4	90.8	92.7	94.8	96.7	98.9
250	92.9	97.5	103.4	112.0	118.2	127.1	139.0	167.3
500	94.3	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
50	46.2	46.9	47.7	48.4	48.8	49.2	49.5	49.8
100	85.4	87.8	90.5	93.3	94.9	96.5	97.9	99.3
250	127.9	136.1	146.6	161.1	171.1	184.6	200.1	225.9
500	131.7	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
50	44.2	45.3	46.3	47.5	48.1	48.7	49.2	49.7
100	81.2	84.2	87.6	91.3	93.3	95.4	97.2	99.0
250	127.8	137.2	149.2	165.7	176.8	191.3	207.3	231.3
500	134.7	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
50	42.2	43.5	45.0	46.5	47.3	48.2	48.9	49.6
100	74.0	77.7	82.1	87.0	89.8	92.9	95.6	98.5
250	102.5	111.0	122.1	137.8	148.8	164.0	182.0	214.3
500	104.7	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
50	43.8	44.9	46.0	47.3	47.9	48.6	49.1	49.7
100	65.4	69.0	73.3	78.9	82.4	86.8	91.1	96.6
250	72.0	77.1	83.8	93.9	101.5	113.1	129.3	169.4
500	75.0	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
50	47.3	47.8	48.3	48.9	49.1	49.4	49.7	49.9
100	85.1	87.5	90.1	93.0	94.6	96.3	97.7	99.2
250	110.2	116.5	124.8	136.5	144.9	156.9	172.1	203.6
500	114.6	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
50	31.0	33.5	36.5	40.0	42.1	44.4	46.5	48.8
100	48.1	53.1	59.4	67.9	73.3	80.0	86.6	94.9
250	59.5	66.9	77.1	92.5	103.9	120.6	142.3	187.3
500	64.2	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
50	25.6	28.3	31.7	36.0	38.6	41.7	44.7	48.1
100	37.6	42.4	48.8	57.7	63.8	71.8	80.3	92.0
250	43.6	49.7	58.2	71.2	80.9	95.2	113.7	153.9
500	43.9	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
50	40.8	42.4	44.0	45.8	46.8	47.8	48.7	49.5
100	73.5	77.4	81.9	87.0	89.9	93.0	95.6	98.5
250	114.5	124.7	137.9	156.0	168.3	184.5	202.4	229.3
500	122.5	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
50	22.3	24.8	28.0	32.3	35.2	38.8	42.4	47.1
100	28.5	32.3	37.5	45.3	51.0	59.2	69.0	85.6
250	35.0	40.3	48.0	60.5	70.5	86.5	109.3	163.0
500	38.7	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
50	7.9	9.5	11.7	15.5	18.5	23.1	29.0	39.8
100	9.4	11.3	14.1	19.0	23.1	29.6	38.9	60.5
250	10.6	12.7	16.1	21.9	26.9	35.3	48.1	84.7
500	11.2	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
50	22.9	24.8	27.1	30.4	32.7	35.8	39.3	45.0
100	24.6	26.8	29.8	34.4	37.8	43.1	50.3	67.7
250	26.2	28.9	32.6	38.4	43.1	50.9	62.8	99.4
500	27.1	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

LIST OF SYMBOLS AND ABBREVIATIONS

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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 texture-specific geometry constant (cm^{-1})
AMAX	is maximum rate of assimilation at actual temperature (kg $ha^{-1} h^{-1}$)
AK	is texture-specific 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_{yx}	is constraint-free 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 PS-1)
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})
DAY	is Julian day number on northern hemisphere, or Julian day number plus or minus 182 on southern hemisphere
DEC	is declination of the sun (degree)
DELTZT	is 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
DMMUL	is equivalent depth of mulch layer (cm)
dr	is surface roughness or furrow depth (cm)
DRDS	is increase in relative development over a time interval
DS	is rate at which surface-stored 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})
Ec	is 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
EFF	is 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})
EMS	is number of intervals between emergence and beginning of mid-season 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})
E0	is potential rate of evaporation (cm d^{-1})
F	is rate of water flow (cm d^{-1})
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})
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 texture-specific constant (cm^{-2}; see Table 6.4)
G_i	is sufficiency of gravel content of layer i
GROSSUP	is gross rate of water supply to upper boundary of rooting zone (cm d^{-1})
hi	is harvest index (0 - 1)
IE	is effective rate of irrigation (cm d^{-1})
IG	is gross rate of water release at project headworks (cm d^{-1})
IM	is actual infiltration rate (cm d^{-1})
INTPERC	is equivalent rate of percolation from rooted surface soil (cm d^{-1})
INTSUFF	is sufficiency of water availability during time interval (0 - 1)
kc	is crop coefficient

kc_{ref}	is crop coefficient of short green reference crop
KMUL	is 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
LAI	is leaf area index
LAT	is latitude of site (degree)
LCHR	is land characteristic
livS(leaf)	is dry mass of all **living** leaves (kg ha^{-1})
L_m	is correction factor for incomplete ground cover
LQ	is land quality
LU	is land-unit
LUR	is land-use requirement
LUS	is land-use system
LUT	is 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})
MS	is 'marginally suitable'; agro-climatic suitability class, anticipated yield 20 - 40% of reference yield
MULWAT	is 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 $mole^{-1}$)
N	is 'not suitable'
NETSUP	is net rate of water supply to upper boundary of rooting zone (cm d^{-1})
Ng	is length of growing cycle (d)
NR	is 'not relevant'
NS	is 'not suitable'; agro-climatic 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})
N1	is 'currently not suitable'
N2	is 'permanently not suitable'
p	is depletion fraction (Tables 5.2)
PAR	is photosynthetically active radiation at the outer extremity of the atmosphere (J m^{-2} s^{-1})
PARCAN	is photosynthetically active radiation at top of canopy (J m^{-2} s^{-1})
PHI	is average slope of land (degree)
PI	is a constant (PI = 3.14159)
PI_{soil}	is soil-productivity 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)
PSIATM	is matric suction of air-dry soil (cm)
PSIatu	is moisture potential of soil in equilibrium with atmosphere (J kg^{-1})
PSI_{cr}	is critically high soil matric suction (cm)
PSIint	is matric suction at planting or germination (cm)
PSI_{leaf}	is critical leaf water head (cm)
PSI_{max}	is texture-specific suction boundary (cm)
PSIMUL	is 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)
RAD	is a conversion factor (degree to radian; RAD = PI / 180)
RD	is equivalent depth of uniformly rooted surface layer (cm)
RDint	is equivalent rooting depth at planting or emergence (cm)
RDm	is maximum depth of rooting system (cm)
RDN	is 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 fertilizer-nutrient '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)
RHMUL	is relative humidity of air in equilibrium with soil material with suction PSIMUL (0 - 1)
RHS	is relative humidity of air in soil (0 - 1)
r(org)	is organ-specific 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)
RSM	is rate of change of volume fraction of moisture in rooting zone (d^{-1})
S	is '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
SEI	is soil erodability index
SIG	is 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})
SMEQ	is 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})
SMMUL	is 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})

SMPWP	is 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' ($kg\ ha^{-1}$)
SPSI	is actual sorptivity ($cm\ d^{-0.5}$)
SR	is rate of surface runoff ($cm\ d^{-1}$)
SS	is equivalent depth of water on flooded or ponded land (cm)
SSC	is equivalent surface storage capacity (cm)
SSint	is actual surface storage at planting or emergence (cm)
SUNH	is number of sun hours ($h\ d^{-1}$)
SVAP	is saturated vapour pressure (mbar)
S0	is reference sorptivity ($cm\ d^{-0.5}$)
S1	is 'highly suitable'
S2	is 'moderately suitable'
S3	is '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)
TDM	is total dry mass ($kg\ ha^{-1}$)
TDMtarget	is set production target ($kg\ ha^{-1}$)
TLDM	is total living dry mass ($kg\ ha^{-1}$)
Tleaf	is heat requirement for full **leaf** development (°C d)
Tmain	is reference temperature for maintenance respiration (°C)
Tmax	is maximum daily temperature (°C)
Tmin	is minimum daily temperature (°C)
TR	is actual rate of transpiration ($cm\ d^{-1}$)
TRANS	is atmospheric transmission
Tref	is reference temperature (°C)
TRICKLE	is rate of precipitation trickling down into the soil ($cm\ d^{-1}$)
TRM	is maximum rate of transpiration ($cm\ d^{-1}$)
TR0	is 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)
UPFLUX	is net rate of water (vapour) flow through upper boundary of rooting zone ($cm\ d^{-1}$)
VAPFLUX	is maximum vapour flux through mulch layer ($cm\ d^{-1}$)
VAPSUPPLY	is maximum rate of water vapour supply to upper boundary of mulch layer ($cm\ d^{-1}$)
VS	is 'very suitable'; agro-climatic 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 crop-specific 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 maize-pigeon pea intercrop (kg ha^{-1} $year^{-1}$)
Ypp	is pigeon pea (grain) yield (kg ha^{-1} $year^{-1}$)
Ytarget	is set yield target (kg ha^{-1})
ZT	is depth of phreatic level (cm)
ZTint	is depth of phreatic level at planting or emergence (cm).