LAND EVALUATION

PART I

PRINCIPLES IN LAND EVALUATION AND CROP PRODUCTION CALCULATIONS

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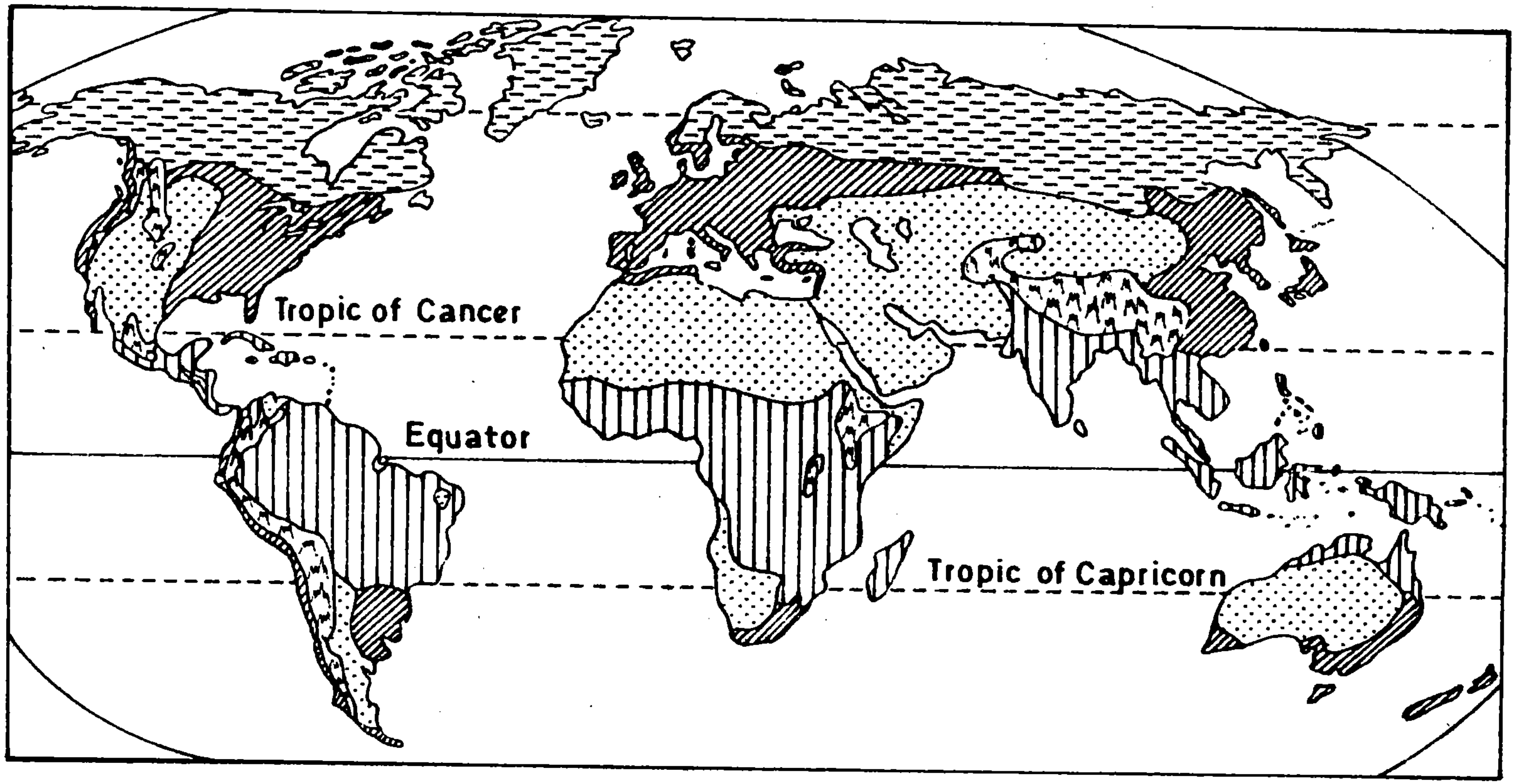
TABLE OF CONTENTS

1. GENERAL INTRODUCTION

Land evaluation is the assessment of land performance when used for specified purposes. As such it provides a rational basis for taking land-use decisions based on analysis of relations between land use and land, giving estimates of required inputs and projected outputs. Land evaluation deals with two major aspects of the land : physical resources such as soil, topography and climate, and socio-economic resources like farm size, management level, availability of manpower, market position and other human activities. The former can be considered as relatively stable properties, while the latter are much more variable and dependent on social and political decisions.

The need for optimum use of land has never been greater than at present, when rapid population growth and urban expansion are making available for agriculture a relatively scarce commodity. The map of **Fifield and Pearcy (1966)** shows the areas of the world hospitable and hostile to man's occupancy and represents in a certain sense a first approximation of land evaluation at world scale (fig. 1). Each area can be considered as an equilibrium between socio-economic conditions and the physical environment.

The increasing demand for intensification of existing cultivation, especially in the areas with less favourable conditions implies that a new equilibrium has to be achieved between human factors, socio-economic conditions and the factors of the physical environment. The change of any equilibrium is always extremely difficult and therefore the realization of development programmes are very complex and requires very often high capital inputs.



LEGEND

- Favorable
- Too cold
  Arctic & Subarctic
- Too dry
  Desert & Semi-desert
- Too hot
  Wet Tropics & Savannah
- Too high
  Mt. Climates

Fig. 1 *Areas of the world hospitable and hostile to man's occupancy* (***Fifield and Pearcy, 1966***).

Table 1 illustrates how difficult it is to intensify agriculture if the compensation of the farmer for his work is even less than the salary of a casual labourer.

Table 1. Improvement of sorghum in the tropical Sudan zone of Senegal (Sys, 1978)

PRODUCTION FACTORS	QUANTIFICATION		
	Traditional agriculture	Improved farming	Potentiality
Labour	640 h	670 h	670 h
Seed (7 kg/ha) (US $)	1.2	1.2	1.2
Fertilizers (subsidized)	no	120 kg 10/21/21 11 US $	150 kg 10/21/21 13.6 US $ 100 kg ureum 9 US $
Amortization equipment	no	11 US $	28 US $
TOTAL (US $) (without labour)	1.2	23.2	51.8
YIELD			
kg/ha	500	1,200	3,000
Monetary value (US $)	85	203	509
NET REMUNERATION (US $)			
TOTAL	83.8	179.8	457.2
per hour work	0.13	0.27	0.66
Salary casual labourer : 3 US $/day			

The principal objective of land evaluation is to select the optimum land use for each defined land unit, taking into account both physical and socio-economic considerations and the conservation of environmental resources for future use. Detailed objectives vary considerably according to the purpose and scale of the land evaluation.

The introduction of new agronomic techniques or the reorganization of agriculture requires a serious planning in the field of land resources, socio-economic conditions, water resources, agricultural status and eco-climatological conditions.

The soil and land-use survey is only one aspect in the field of land evaluation, which has to be realized through an interdisciplinary team.

It is our aim to comment particularly the soil science, and land-use aspect of land evaluation; however, without neglecting completely the socio-economic factor.

A group of soil scientists, in order to keep all interpretation on the safe side, just consider their task as finished when the soil map is compiled. In areas under natural vegetation or without organized agriculture, they prefer to transfer the map to the agronomists who have to set up experimental plots on the different soil units in order to find out the most suitable agricultural practices for the different types of soils.

However this viewpoint is generally not accepted by officials and consultant firms, because in most projects time is the limiting factor and government officials request a rapid answer on practical soil use and management practices.

The information expected from the soil scientists after a survey are generally answers on the following questions :

(1) What kind of soils are present in the area ?

(2) Where are these soils situated ?

(3) What kind of crops are cultivated or can be grown on these soils ?

(4) What are the expected yields on the different soils ?

(5) What fertilizers and what amounts are to be used ?

(6) For arid lands; what is the irrigation practice to be recommended and what is the quantity of irrigation water necessary ?

(7) Whatever management practices are to be recommended ?

In order to answer these questions it is necessary to elaborate a system of land classification on which the evaluation of the land units is mainly based on information made available in the soil survey report supplemented by data on yields and available results obtained on similar soils under similar climatic and socio-economic conditions and management.

In areas where an organized agriculture is present one may apply some widely accepted principles for the interpretation of soil suitability. The "Soil Survey Manual" (**USDA, 1951**) suggests a :

$$\text{Productivity rating index} : \frac{\text{Expected yields per acre}}{\text{Standard yield per acre}} \times 100$$

This index is based on measured or estimated yields and has to be defined for the different soil types.

At present there is a tendency to rely this productivity index with a combination of a series of ratings suggested for the different land characteristics and land qualities. For each land characteristic or quality the intensity of the limitation has to be evaluated. A general review of the land characteristics/qualities and their limitations is then used to determine land capability classes.

Some systems have even suggested numeral ratings for each soil characteristic or quality and the calculation of a land capability index.

A "Land Capability Classification" implies a characterization and a regroupment of soil units in capability classes for their present (actual) and future (potential) general use. Although there is an important difference between "land" and "soil" as well as between "land classification" and "soil classification" we should be aware of the fact that soil is still an important factor in regional land evaluation. "Land" may have a very wide meaning and "soil" a more restricted one, but every crop growing on "land" is planted or sawn into "soil" and it makes a big difference whether this soil is good or bad.

Classification with regard to the following aspects of applied soil science may be formulated :

(1) PLANT GROWTH
- kind of plants
- production and yields
- management

(2) SOIL
- natural fertility
- erosion control
- workability and related management practices

(3) TOWN AND COUNTRY PLANNING

- roads and highways
- capability to support buildings
- capability to grow ornamental plants
- corrosive action for a variety of materials (cement, uncoated stud pipes, cast-iron, ...)
- capability for sewage design

(4) PROTECTION OF THE ENVIRONMENT

- soil retention for nitrates, heavy metals
- pollution of groundwater tables
- alternative land uses

The present publication has to be considered as a practical manual on land evaluation for agricultural purposes. Besides the explanation of the principles in land evaluation, the publication provides the necessary guidelines for crop production calculations and for the most important practical methods in land evaluation useful to anyone engaged in assessing the suitability of land for agricultural development.

2. PRINCIPLES IN LAND EVALUATION AS A BASIS FOR LAND-USE PLANNING

2.1. Introduction

According to **Vink (1975)**, land use is any kind of permanent or cyclic human intervention to satisfy human needs; for a complex of natural and artificial resources which together are called "land". Land use is therefore the application of human control of natural ecosystems, in a relatively systematic manner, in order to derive benefit from it. Man as an inherent part of the ecosystem tries to manipulate it.

Land use involves always specific surface areas and can be considered as a geographic concept. It is the result of a continuous field of tension created between available resources and human needs.

The activities in land evaluation that are specifically concerned with the land use comprise two parts : description of the kinds of land use, and assessment of the land-use requirements.

Except in very generalized reconnaissance surveys, the kinds of land use considered in an evaluation are described as land utilization types. In the case of rainfed agriculture, the land utilization types may consist of individual crops within a specified socio-economic setting. They may also consist of crop combinations, or farming systems described in more detail.

2.2. Land-use planning

2.2.1. PROJECT IDENTIFICATION

Before starting any project, it is necessary that an identification of the project is made by means of a clear formulation of the objectives to be obtained.

This identification may include references to the national and regional requests in order to estimate their dimensions and to evaluate them in their physical and socio-economic context.

The project identification should define the responsibilities for the project, the availability of funds and suggest a first outline and time-table of the activities involved. The time-table and the terms of reference for the first phase should be given in detail, because these data are needed for the budgeting of this phase and the choice and recruitment of the experts.

Such a project identification is generally realized by a State Planning Unit, composed of an interdisciplinary team of Heads of Departments (agriculture, drainage and irrigation, soils, socio-economics, ...). If necessary, they may be assisted by consultants.

2.2.2. PHASES IN AGRICULTURAL LAND-USE PLANNING

Beek and Bennema (1972) have formulated a theoretical planning model for agricultural development projects, which consists of three phases :

A : the pre-project study

B : the reconnaissance study

C : the detailed study

Table 2 gives a summary of the model, which has to be considered as a guide-line; in many cases this theoretical approach has to be adapted to the local conditions.

Quantitative data related to the best use of the physical resources under the given socio-economic conditions become available with greater precision and detail during each consecutive phase.

During the realization of the project three main questions have to be answered :

(1) Should the project be executed or not ?
(2) What are the feasibilities ?
(3) How should the project be carried out ?

In the first phase, the first two questions are of importance. In the second phase the second question is the most important. In the third phase the last question draws the attention.

The scheme is an outline for the planning of a relatively large area, in which many disciplines are involved. In the planning of smaller or less complicated areas, phases (B) and (C) are often not separated but taken together.

Table 2. Phases in land-use planning

Successive steps in the work	The planning phases		
	Pre-project	Reconnaissance	Detailed
1. Preparation	Highly qualified experts (± 1 month) Collection of reports and data on soil and water, climate, vegetation, capital resources, land tenure, production pattern Collection of maps and aerial photographs	Qualified experts (10,000 ha/ month/expert) Collection of data, reports, maps, aerial photographs	Associate experts and experts under supervision of qualified experts 1000-4000 ha/month/expert
2. Field surveys	Exploratory 1 to 2 weeks	Reconnaissance resources survey - land attributes - socio-economics	Detailed or semi-detailed survey - land attributes - socio-economics
3. Interpretation of exploratory surveys	General	General	Detailed
4. Conclusions on evaluation (5. Reporting)	- Formulation of possible land utilization type - General suitability classification - Project formulation - planning rec. phase (terms of ref.) - or, if possible, selection of sample area and planning of detailed phase	- Land suitability classification for selected land utilization types - Selection of priority areas - Planning of detailed phase (terms of reference)	- Land suitability classification - Formulation of land improvement and management - Project implementation

PHASE A : THE PRE-PROJECT STUDY

This phase consists of an exploratory orientative study of the natural and human resources, the agricultural possibilities and other aspects relevant to the agricultural development planning. Although it covers the whole field of agricultural planning, only a relatively small group of specialists will consult many others. Fact finding is an important aspect of phase A.

In this phase a general evaluation will be made which, integrated with the socio-economic conditions, will furnish a broad land classification. In this classification the conclusions and recommendations of the various specialized studies are summarized and integrated. Alternative solutions should be indicated.

The pre-project study should serve as the main basis for confirmation, consolidation or re-formulation of the original project.

The activities of the various contributing disciplines for the next phase are planned and inter-disciplinary operations coordinated into a plan of operations. If the region under consideration is extensive and varied, major priority areas can be indicated; they will receive priority and special attention during the further phases of the project.

PHASE B : THE RECONNAISSANCE STUDY

During this phase strong emphasis is laid on the inventory of the area. The number of specialists directly involved will be greater than in phase A and generally more time will be needed in the field in order to obtain the necessary more detailed data.

Most development planning projects operate during a rather short period of time. To obtain the data for assessing the feasibility of land improvement a good deal of local research is required : soil survey, profile characterization, measurements of soil properties related to irrigation and drainage possibilities.

Phase B is concluded with the formulation of an outline of the land development plan. The conclusions reached by the various disciplines are summarized into an overall plan of recommended land-use. The integration of the plan in the national or regional economy and policy is important to ensure a synchronization between the production targets set by the development plan and the national and international market situation. The same goes for other macro-economic data such as labour and capital distribution.

This phase comprises also the planning of phase C, which may include indications of pilot areas for further studies.

PHASE C : THE DETAILED STUDY

The phases A and B deal mainly with the questions, of whether the project should be effectuated, and what is feasible. Precise information on what should be done during the project effectuation is not available.

The question "how could the development project be carried out ?" will be raised many times during phases A and B, but often only to assess its feasibility. In the phase of detailed studies the central question is : What should be done during the programme effectuation ? Detailed surveys and studies are necessary to answer this question. These surveys and studies should be carried out in pilot areas, and/or in larger areas where a more intensive use will be made of the land.

Experience shows that many projects for which development plans are made are never executed; often for political reasons. Other projects are only effectuated many years after the development plan was made. Costly surveys and costly investigations necessary for the execution of the development plan but not for its drafting can therefore better be carried out during the programme effectuation as in the case with detailed contour surveying for irrigation.

The last step in the detailed phase C consists of the completion of the master plan, taking into account all the accrued practical experience of the detailed studies together with the investment requirements of the land development project. One result is the overall land classification for recommended use, reconciling the technical possibilities with the needs for production and development, the social and economic needs and feasibilities, and the organization and institutional feasibilities for changing the production methods.

The report of phase C should be acceptable to a bank for investment purposes and therefore should fully show the economic and financial implications of the project. This not only means that the land classification will be qualitative but that the eventual benefits to be derived from the land before and after the programme effectuation should be estimated, as well as the costs involved in its development and use.

The report of phase C is the final one of the development project, but it might still be subject to changes, after re-evaluation by the agencies which provide the funds for the development project.

2.2.3. STEPS IN AGRICULTURAL LAND-USE PLANNING

Every phase of the agricultural development project proceeds along five steps : preparation, surveys and investigations, interpretation, economic land classification and reporting.

STEP 1 : PREPARATION

The activities to be developed on each phase require preparation, e.g. the appointment of staff, provision of office space, provision of transport and collection of all kinds of necessary materials. In the context of this study, attention will be paid only to the acquisition of aerial photo coverage and topographic maps. If these do not already exist or if the quality of existing photographs and/or maps is insufficient, new ones should be procured. It is imperative for successful operations to have photographs and maps available before the next step starts.

The scale of maps and aerial photographs has to be adapted to the specific phases :

- PHASE A : small scale maps and photographs (1:200,000 to 1:80,000). Although photo-interpretation is useful, there is often no time for systematic interpretation and therefore a photo-mozaic at scale around 1:100,000 is very useful;

- PHASE B : most likely maps and photographs at scale 1:80,000 to 1:40,000, depending on the area and type of reconnaissance;

- PHASE C : large scale maps and photographs at scale 1:20,000 to 1:5,000

STEP 2 : SURVEYS AND INVESTIGATIONS

A wide range of disciplines is often involved in these surveys, which may comprise the natural resources, socio-economic conditions, agricultural facilities and human resources. The following aspects are important :

- **Natural resources** : climatic conditions, soils, topography, vegetation including the possibilities for grazing and forestry, geology, available surface and groundwater (both quantity and quality), possible dam sites.

- **Socio-economic conditions** : land tenure, production pattern, size of farms and actual productivity per head and per hectare, kind of crops, quantity and quality of cultivated crops, destination of crops.

- **Agricultural services** : availability of capital and capital goods such as fertilizers and agricultural machinery, marketing centres, storehouses, cold storage and transport facilities.

- **Human resources** : demography, social and cultural pattern and conditions, technical know-how level, availability of labour and alternative labour possibilities.

In the land evaluation the surveys of socio-economic conditions, agricultural services and human resources have to be fully integrated with the natural resources surveys in orienting the land evaluation towards the recognition of suitable types of land utilization. An integration between the different natural resources surveys is also necessary. This can be obtained in two ways. The land can be surveyed as an integrated unit (e.g. land systems) or as a synthesis of separately surveyed land attributes. For reconnaissance surveys integrated land units may be more practical, whereas the surveys of the separate attributes (e.g. soil surveys, vegetation surveys, etc.) become more indicated for detailed scales.

Natural resources surveys are carried out with the help of photo-interpretation. Land conditions related to the topography and in general to the physiography of the area can be studied and delineated with the help of photographs. Photo-interpretation greatly facilitates the resources surveys of phase A and B, and might also be of help in phase C.

Photo-interpretation with some limited field check will in many cases furnish the data needed in phase A. If the same information has to be gathered by field work alone, much time is lost.

During phase B, photo-interpretation is also a usual technique. Generally more additional work will be needed than in phase A, but if the surveyor has a good understanding of photo-interpretation much time can be saved. In phase C, photo-interpretation may be of less importance, although (depending on landscape and purpose) it can often be a great value and in many cases it is essential.

The data of the natural resources survey will be interpreted for the suitability classification during step 3. During the survey, it is necessary to have already clearly in mind, what additional data besides those normally provided by the survey will be required for step 3.

STEP 3 : INTERPRETATION

In step 3 the data collected during step 2 are interpreted in terms of technical feasibilities (see step 2). The findings and conclusions in respect of various land attributes are integrated and focussed on the possible land utilization types.

The interpretation step 3 comprises :

(1) interpretation of data of natural resources survey (soil, water, socio-economics);

(2) definition of relevant land utilization types;

(3) suitability classification;

(4) management and improvement specification;

Land suitability is the fitness of a given tract of land for a defined use. Differences in the degree of suitability are determined by the relationship, actual or anticipated, between benefits and required inputs associated with the use of the tract in question.

Generally two kinds of suitability classification are considered :

- actual suitability classification;
- potential suitability classification.

The actual suitability classification relates the suitability of land units for a specific use in their present conditions, without major land improvements; suitability being assessed in terms of expected benefits in relation to required recurrent and minor capital expenditure.

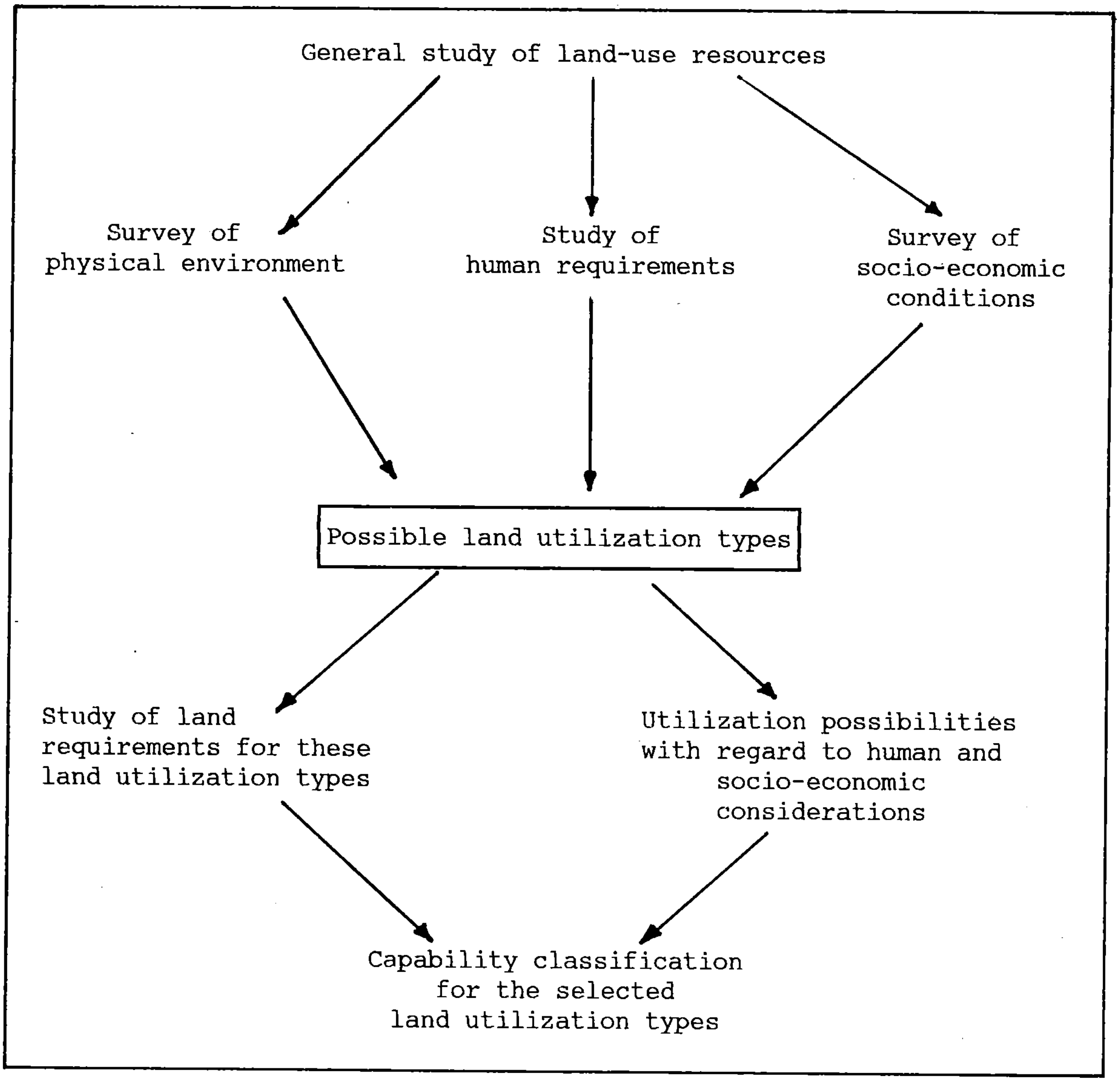
Potential suitability classification relates the suitability of land units for the use in question at some future date after major improvements have been effected where necessary.

Land suitability classification for land-use planning involves a complete survey of all natural resources (climate, soil, water, human capital, socio-economic conditions, agriculture). These surveys can be carried out for a great deal independently from the work done by the other specialists. However, at the final step of each phase in land-use planning close co-operation between the different specialists is required.

These contacts will intensify during the step of economic land-use classification, and the greater part of the responsibility will then devolve upon the specialists in the socio-economic and organizational disciplines.

Table 3 suggests a scheme of interdisciplinary research in land-use planning.

Table 3. Scheme of interdisciplinary research in land-use planning



STEP 4 : ECONOMIC LAND CLASSIFICATION

The economic land classification is a quantitative classification of land units based on analysis of costs and benefits for specific land utilization types. This has to be done, assuming an optimizing of the main production factors such as farm size, labour intensity and capital input level.

Quantitative economic land classes do not necessarily coincide fully with the qualitative technical evaluation of the physical environment. The qualitative classes do support however the determination of economic land classes by providing essential data on land management and improvement cost as well as estimates of benefits to be expected in terms of predictable yields. Economic land classification deals only with one or a few promising utilization types which are then analyzed in great detail on their socio-economic value in financial terms.

STEP 5 : REPORTING

By using the presented scheme of agricultural land use planning, two interim reports and a final report have to be made.

The interim report of phase A (the pre-project) deals mainly with the formulation of the planning project. The interim report of phase B (the reconnaissance study) will give the first outlay of the masterplan which will be finalized during phase C (the detailed study). In these reports a full integration should be achieved of all the disciplines contributing to the planning project. Overall land classifications are an essential part of these reports.

For so far the pre-project or exploratory phase is concerned it might be exaggerated to include at this stage a broad economic land classification. At this stage the land classification is often not more than a first interpretation of physical and socio-economic resources with listening of land characteristics to be evaluated in the following phase and suggestion of possible land utilization types. This in order to be able to plan in detail the second phase, often called pre-feasibility study. Such project formulation should include the "Terms of Reference" for the second phase, the budgeting of this phase and the experts to be recruited.

The second phase of pre-feasibility study is not necessarily a reconnaissance survey. In many cases semi-detailed soil maps, detailed topographic, hydrological and socio-economic data are required for the final selection of the zones to be developed. Anyhow at the end of this phase a good land classification presents the basic document for the final choice.

Phase 3 or feasibility study has to prepare the "cahier de charge" for the realization of the project and should be detailed enough to budget and supervise all reclamation works.

2.3. Land-use resources

2.3.1. MAJOR KINDS OF LAND-USE RESOURCES

Land capability classification can be done at different levels of generalization. In any case the final aim is to predict the agricultural capability of the land development units in function of the land resources.

The land development unit, according to the level of generalization, can be a single plot of land, a soil family, a soil association, a physiographic unit or even an extended natural eco-climatic zone.

The major kinds of land-use resources are :

(1) **Physical resources** : climate, vegetation, water and hydrology, landform and soil;

(2) **Human resources** : availability of farmers and their ability for farming; land tenure and social structures which may affect the land-use pattern and its possible re-allotment; and

(3) **Capital resources** : funds, as well private as national, available for recurrent and non-recurrent input.

2.3.2. PHYSICAL LAND-USE RESOURCES

2.3.2.1. Climate

The general study of the climate of a land development unit covers a range of factors of which the most important are : **rainfall, temperature** and **radiation.** The annual mean figures, as well as their distribution during the year are important.

Very important is also **evapotranspiration** computed from the climatic data.

Rainfall and temperature and their distribution over the year are the main factors for the world's differentiation in agro-climatic zones, having each a specific land-use pattern and determining the length of the growing season for cultivated plants.

The moist evergreen rainforest and the semi-deciduous forest with a permanent high rainfall pattern and high temperature are an environment of the typical tropical crops : rubber, oil palm, coffee, cocoa, and a range of food crops. Within this zone each crop may have specific climatic requirements to be considered in the detailed investigation on land utilization types.

The tropical humid savannah with 3-4 months dry season have again a specific crop pattern and so for the still dryer tropical sudano-zambesian savannah and miombo woodlands.

Steppes and deserts are specific eco-climatic environments for land-use planning because development depends for a great deal on water resources for irrigation.

Considering rainfall and water deficit, it has been pointed out that :

The potential yield of sugar-cane is 1 ton of cane per cm of water transpired (**Yates, 1978**).

In Ivory Coast, **IRHO (1976-1977)** estimates that the potential yield of oil-palm is a function of the water deficit as expressed by following relation :

$$Y = 22.3 - 0.016 X$$

Y = bunches t/ha/year
X = water deficit, mm

For steppe areas of the Mediterranean basin, **Steely et al. (1983)** elaborated the relation :

$$Yep = 2.33\ AM^{1.09}$$

Yep : potential dry matter production
AM : coefficient related to significant environmental variables

$$AM = K1 \times K2 \times K3 \times R$$

where R = rainfall, expressed in mm/year.

K1 : relative productivity index for slope as it determines the time for water to infiltrate the soil

Slope %	Relative productivity index (K1)
0 to 2	1.00
2 to 5	0.95
5 to 10	0.85
> 10	0.60

K2 : soil depth as this is primary determinant for the volume of water a soil can hold

Soil depth interval (cm)	Relative productivity index (K2)
> 100	1.00
50-100	0.90
20- 50	0.75
< 20	0.55

K3 : salinity as this determines the water extractable from a soil by plants

ECe mmhos/cm	Relative productivity index (K3)
< 8	1.00
8-16	0.72
16-24	0.48
> 24	0.24

Temperature is an important land resource. It helps to determine the length of the growing season as periods with a mean temperature of less than 6.5°C are considered to be out of growing season.

Temperatures at specific crop development stages are as well important but they are crop specific. Some examples may illustrate this kind of requirement :

- for sugar-beet the absolute minimum temperature in the initial stage should not fall below -6°C;
- for sugar-cane $\Delta T = \frac{Tmax-Tmin}{Tmean}$ is an important parameter. At maturation it should be above 0.5 for optimal conditions, while values around 0.35 are considered as marginal.

Vink (1975) mentions that solar radiation, falling on land areas, is of the order of 28,000 x 10^{12} watts per year, whereas the total depletable supply of mineral fuels is of the order of 1,400 x 10^{12} watt/year. Hydropower produces a maximum of 3 x 10^{12} watts per year (**Starr et al., 1971**). This means that 95 per cent of the total energy input of the world comes from solar radiation. Nearly half of this is directly converted into heat, 23% energizes the processes of evaporation and precipitation and only 0.02 per cent is utilized in photosynthesis (5.6 x 10^{12} watts per year).

Also important for land-use is the distribution of this radiation over the world surface, this may affect the intensity of photosynthesis. The highest potential production by photosynthesis of about 124 x 10^3 kg carbohydrates per ha is found between 10° and 20° North latitude. Agricultural production in general does not reach this high figure because of limitations imposed by other land conditions. The lowest figure given by **De Wit (1966)** is 12 x 10^3 kg carbohydrates per hectare and per year for 70° N.L. and 50° S.L. respectively. Between latitudes of 50° N.L. and 40° N.L. the highest producing land-use types of most industrialized countries are noted; these potential productions of carbohydrates are respectively 59 x 10^3 and 91 x 10^3 kg per ha.

Solar radiation is a natural resource that cannot be changed at any given point, so it will never be considered as an absolute limitation. We should, however, be informed that it influences the quantity and quality of products and the kind of crops in particular when taken together with temperature.

Information on agroclimatology in land resource surveys involves the following stages :

(1) collection of available climatic data;

(2) statistical analysis of this data, to give mean values and probabilities of variation for key variables of tempera-

ture, rainfall, etc...; and

(3) agroclimatic analysis of the relationships between climatic variables and crop requirements.

2.3.2.2. **Vegetation**

In areas under natural vegetation, or where a secondary regrowth is used for soil regeneration after a cycle of cultivation (shifting cultivation), vegetation is an important land-use resource. This resource is however in direct inter-relation with climate.

It is so important because the amount of nutrients stored in the vegetation are a direct nutrient supply for crop production after cutting and burning the vegetation. This amount of nutrients stored in the vegetation depends directly on the vegetation type (table 4).

Some natural vegetation types represent a direct economical value for land utilization. Forest may represent an utilization type for timber exploitation. Savannah and steppe are natural land utilization types for extensive grassland. Even the quantity of cattle used and their number may depend on the vegetation type. While in savannah and humid steppe cattle dominates, goats and sheep seem better adapted to the very dry steppe vegetation types.

Figure 2 illustrates the influence of rainfall on Rangeland production in the African Sahel zone.

It has further been estimated that total dry matter production of natural Rangeland in the arid part of the Sahel is as follows :

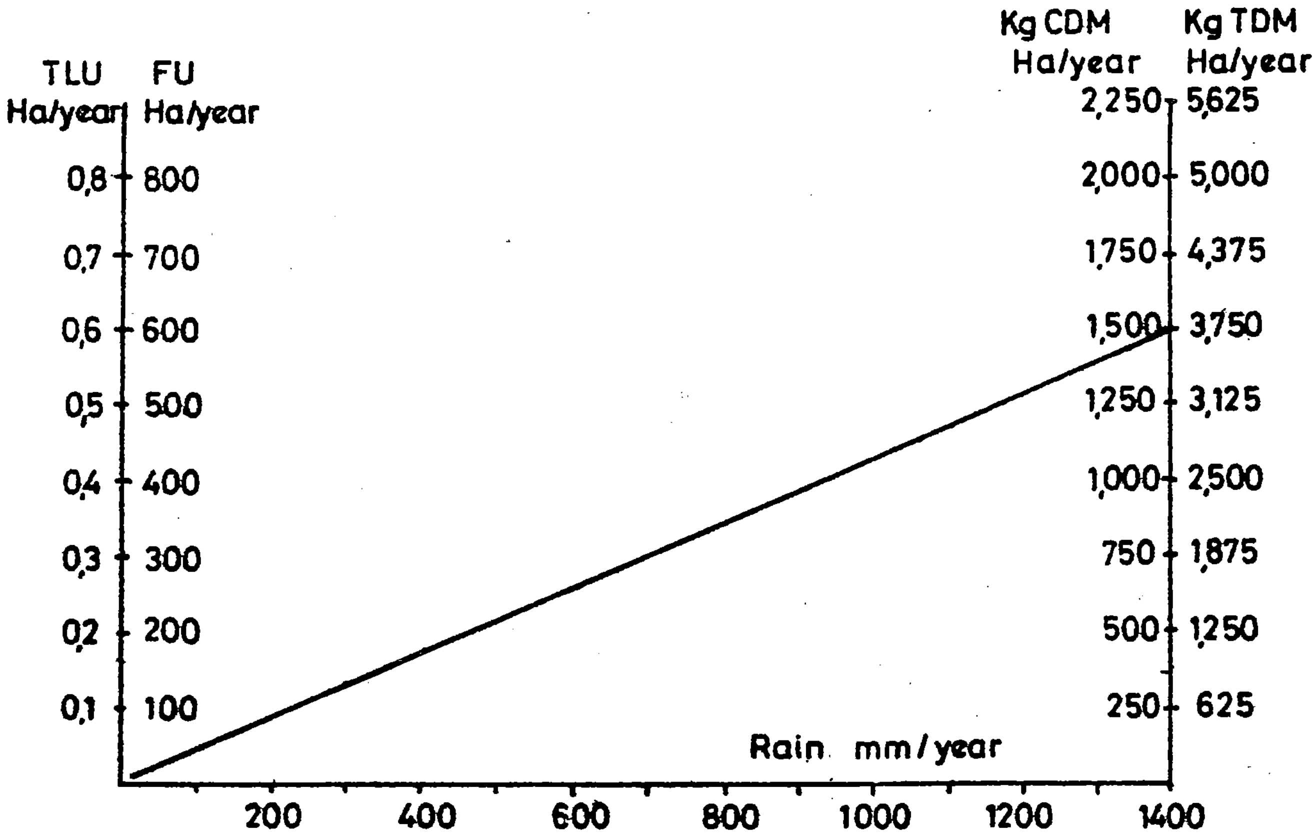


Fig. 2 *Relation between Rangeland production and annual rainfall (**Le Houerou and Hoste, 1977**).*
TLU : Tropical Livestock Units[1]
(1.5 cattle = 10 sheeps = 12 goats = 2 donkeys = 1 horse = 0.8 camel
FU : 1,650 kcal = 1 kg of barley
CDM : Consumable Dry Matter
TDM : Total Dry Matter

[1] 250 kg living weight

*Table 4. Nutrients stored in some typical vegetation types (**Nye and Greenland, 1965**)*

Vegetation type	Dry material 1,000 kg/ha	Nutrients stored, kg/ha				
		N	P	K	Ca	Mg
Moist evergreen 18 years old rainforest, Yangambi	336	559	73	405	562	
Moist semi-deciduous forest, Lower Zaire	332	1,236	123	954	2,118	325
Savannah in Southern Ghana	58	281	28	278	442	104
Miombo woodland, Copperbelt, Zambia	101	-	50	171	393	101

0- 45 mm rainfall	50-100 kg/ha/year
45- 75 mm rainfall	200 kg/ha/year
75- 90 mm rainfall	400 kg/ha/year
90-120 mm rainfall	600 kg/ha/year

The vegetation has, together with the climate, an important influence on cycling of nutrients and as such on some important soil properties which may influence the final output of a land utilization type. This is clearly illustrated in table 5.

A clear differentiation of nutrient cycling occurs already within the tropical moist forest zone where the production of dry material by the vegetation is quite uniform. In the soil however we realize that under moist evergreen rainforest the

*Table 5. Average amount of nutrients stored in soils under some typical tropical vegetation types (**Sys, 1976**)*

Vegetation type	C, tons/ha		N, tons/ha		C/N		pH		CaO, kg/ha		K_2O, kg/ha	
	0-20 (cm)	20-100 (cm)	0-20 (cm)	20-100 (cm)	0-20 (cm)	20-100 (cm)	0-20 (cm)	20-100 (cm)	0-20 (cm)	20-100 (cm)	0-20 (cm)	20-100 (cm)
Moist evergreen rainforest	24.90	39.58	2.448	4.664	10.01	8.50	4.36	4.62	634	2,607	110	318
Semi-deciduous forest	37.69	50.35	4.330	7.277	8.70	6.90	6.05	5.40	4,813	6,496	402	911
Moist Guinean savannah	33.51	66.20	2.649	6.599	12.70	10.03	4.92	4.99	834	2,879	198	281
Dry savannah	64.35	94.70	5.735	10.443	11.20	9.07	6.37	6.13	7,672	18,614	1,503	3,207

pH is very low and the amounts of CaO and K_2O are also low, C/N ratio is generally above 10. Under moist semi-deciduous rainforest, with some dry season, a lower C/N ratio in the top soil suggests a better quality of organic matter, pH is higher and greater amounts of CaO and K_2O are available.

As such this represents the best agricultural zone for development within the tropical forest area.

In Guinean savannah the amount of nutrients stored in vegetation and soils is low. These are real problem areas where the regeneration of the soil under shifting cultivation is difficult.

The dryer savannah areas, intergrading to the Sudanese type and to the fersiallitic soils, notwithstanding their low nutrient storage in the vegetation, have as a result of lower rainfall a cycling process leading to soils with a good humus content and a high amount of CaO and K_2O as well in their surface as subsurface horizons. However, for many cultivated tropical crops, climate becomes here a limiting factor. These savannah areas are however excellent grassland.

On the other hand, natural vegetation is often regarded as a hindrance for agricultural land-use. A dense tropical forest makes reclamation of land more difficult and requires a serious input for cutting down and preparing the land.

2.3.2.3. **Hydrology and water**

Hydrology is particularly important where climate becomes too dry and agriculture land-use needs an irrigation supply.

The study of water resources comprises the study of "fossil" quantities of water which have been formed in previous ecological conditions and are at great depth.

This study of hydrogeology is justified when land-use has a real shortage of irrigation water that cannot be supplied by surface water.

Hydrology is the study of surface water and water balance. Water and soil are essential for land-use; they are the stable resources on which all agricultural land-use must be based. Knowledge of soil and water conditions is indispensable for the understanding of past and present land-use as well as for prediction of future uses.

2.3.2.4. **Landform**

Landform can be considered as an indirect land resource because it will help in the choice of land utilization types influencing management, accessibility of terrain and development of infra-structural works. These may finally greatly influence the amount of non-recurrent and recurrent (maintenance of infrastructural works as terracing a.o.) inputs.

The main structures of the land are essentially defined by geological formations including tectonic action and erosion processes. They determine the major features of the relief, including altitude, which is an important ecological factor.

The management type, size and structure of farms can be greatly influenced by landform.

In the Ethiopian highlands steep slopes with Lithic Haplustolls and Lithic Ustorthents, which should normally be reserved for forest, are cultivated using a well adapted system with a low level of management. Such practices cannot be recommended but they keep people alive where a high demographic pressure could create real problems if the general principles of land-use planning should be strictly applied. Such survival practices are only possible due to adaptation of management.

It is also well known that under sub-tropical and temperate climatic conditions the exposition of a land unit has an influence on the capability for fruit trees and intensive vegetables. An orientation to the south receives more sun, more radiation and thus has a better suitability than orientations to the north.

The dissection of the landscape by a dense river system may also greatly influence the management type. As such strong dissection can prevent the installation of a plantation type of farming on suitable soils for the considered crop. This is illustrated by the fact that the very dissected landscape of the lower Zaire basin with soils suitable for coffee, oil palm and rubber is not suitable for the large plantation blocs required by the big companies, but only for the installation of small holdings by individual planters. On the other hand, the large plateaus with similar soils are widely used for industrial plantation agriculture.

Slope, an important element of landform, plays an important role when mechanization is concerned. It is generally accepted that on slopes steeper than 20 per cent mechanization becomes impossible. Cultivation needs then establishment of expensive anti-erosion works (terraces) and this complementary capital input can greatly influence the final profit. For slopes less than 20 per cent there are still important variations in productivity according to variations in slope.

2.3.2.5. **Soil**

Soil is a basic natural resource in land-use planning. The soil constitution may influence :

- the choice of crops
- the land-use pattern on marginal soils
- the management of specific soils
- the land improvement works
- the type of irrigation
- the type and quantity of fertilizers to be used

On a regional basis the yield of crops will depend for a great deal on the natural fertility of the soil.

In the humid tropics, rubber may grow on nearly all upland soils but for more exacting crops, such as cocoa and bananas, only the fertile soils will give satisfactorily yields.

When a specific crop is intended to be introduced, because of its favourable commercial situation on the world market, and the soils are marginal, the choice and adaptation of the management type may define the success or the disaster.

As such the introduction of some exacting crops (wheat, sugar-beet) in the rotation of the Flemish sandy area is only possible when a management type of mixed farming is introduced. Only such type of farming is able to produce the high amounts of organic manure necessary for a successful cultivation of these crops.

The influence of management type on suitability of marginal soils has also to be considered in the humid tropics. The Ferralsols with dark horizon (Sombriperox) on basement complex are the most common soils in the Ituri mountain area of N-E

Zaire. These soils have a low agricultural value and are marginal for Arabica coffee. In this area this crop was introduced under a management type of large plantations; however, after a few years, yields decreased in such a way that most enterprises failed. However, the same soils can successfully be used for coffee using a management type of small holdings of about 2-5 acres. In these holdings use of organic manure or application of mulching is possible and crop production is maintained at the initial level or may even increase. With this type of small holdings, a surface of 34,670 ha Arabica coffee had been planted in Rwanda-Burundi, generally on the same poor Sombriperox, with a total production of 36,325 tons in 1959. These examples illustrate how the land-use pattern and management type can determine the suitability of marginal soils.

Some good agricultural soils as Vertisols require also a specific management, according to their difficult workability, heavy machinery has to be used. Also organic soils and soils with an acid sulphate layer at a certain depth require special management.

Land improvement works such as drainage, irrigation, levelling and grading, erosion control are greatly dependent on soil constitution. On heavy textured soils with low infiltration rate open drains remain the only successful drainage practice. On more permeable soils distance and depth of tube drains should be adapted to soil texture and infiltration rate. Erosion control will depend on the amount of run-off water and here again texture and permeability play an important part.

The type of irrigation system to be used greatly depends on soil permeability and waterholding capacity both related to soil texture. When infiltration rate is higher than 12 cm/h flood irrigation is no more convenient and one has to apply sprinkler irrigation. Also the amount of irrigation water and the frequency of watering will depend on soil characteristics.

It needs further no comments that type and amount of fertilizers to be used will greatly be determined by soil conditions. On soils with a high fixation for phosphates the N/P ratio can be of the order of 1/2-3, while on normal soils a N/P ratio is around 2/1.

2.3.3. HUMAN RESOURCES

No land-use planning is possible without human resources and the ability of the farmer plays an important part in the profit of a farm.

The study of the human resources, their ability for cattle raising or arable land farming is extremely important.

Tribes involved with fishery along rivers are very difficult to reconvert to farming.

The population pressure will further help to define the land-use pattern. Shifting cultivation remains possible as long as enough land is available. It has been estimated that shifting cultivation in the Zaire basin can be supported as long as population density remains under 20 persons per km^2.

Under miombo-woodland of Zambia this critical density is estimated at 14 per km^2. In this case soil fertility, amount of cultivable soils, and rapidity of the recycling process of the fallow vegetation are important factors.

Land-use pattern and ownership of the land are also important human factors to be considered in land-use planning.

Table 6 permits to formulate some criteria suggested by **O'Hara (1979)** in order to evaluate human resources.

*Table 6. Categories of farmers by selected criteria used to assess rationality (**O'Hara, 1979**)*

Criteria	Categories of farmers			
	1	2	3	4
(1) Aspirations for change	high	high	low	none
(2) Farming practices used	modern	somewhat modern	traditional	traditional
(3) Reasons given for acting in terms of past action or future planned action	economic efficiency	some consciousness of need for change	traditional ways are best	none
(4) Justification for action	explicit	ambiguous	vague	none
(5) Knowledge of schemes and practices	field knowledge	some knowledge	vague	none
(6) Principal sources of authority or information	change agents	change agents plus neighbours	traditional	none

2.3.4. CAPITAL RESOURCES

The first necessity to realize a program of land-use planning for rural purposes is the availability of the necessary funds for the realization of the infrastructural works and the land improvement works. Besides this the capital input for recurrent practices must also be available.

Presence of roads, railway and exportation harbour are important factors to be considered.

Very suitable soils for fruit (bananas) cannot be developed for this land utilization type and are therefore an unsuitable land for this practice if no exportation harbour is present within 200-300 km.

The economic situation of a crop on the world market is also very important.

2.4. LAND UTILIZATION TYPES

The first land capability maps characterize and appraise land development units from a general point of view without mentioning the kind of use; they are defining classes as : excellent, good, moderate, poor and very poor.

This information may be very useful but, as a same soil may be suitable for a specific crop and unsuitable for another, it becomes practically impossible to proceed to a good evaluation work unless knowing for what you want to use the land. Therefore precision of the land utilization type is necessary.

A land utilization type is a specific subdivision of a major kind of land-use, serving as the subject of land evaluation and defined as precisely as possible in terms of produce and management (**FAO, 1976**).

The land utilization type should not only define the crop or crop rotation (**produce**), but in addition it has to precise how to farm these crops (**management**). This implies that the concept "Land Utilization Type" includes the kind of crop, the succession of crops in a rotation or farming system with precision of the management type.

The recognition, final choice and definition of land utilization type, are achieved through interdisciplinary resources study : physical environment and socio-economical conditions.

In many cases the soil scientist is guided in his choice through suggestions and plans of officials before the survey starts; but he may suggest other alternatives of land use according to soil conditions and human resources recognized during the survey or adapt the suggested ones better to prevailing conditions.

Land utilization types can be defined at various levels of generalization, depending on the detail of the survey and the phase of the planning procedure.

In the first exploratory phase, the experts may be phased with suggestions from government authorities who wish to introduce a specific crop. However, at this level broad differences in agricultural use should be considered : annual crops, irrigation farming, plantations, extensive grazing, forestry, etc...

At the end of the reconnaissance study a final choice has to be made with indication of the farming system, the specific crops and the kind and level of management which has to be applied. The selected farming system should be practical, that means within the ability of the majority of farmers or ranchers and their capacity to assimilate new agricultural techniques.

It may happen that a previously considered land utilization type cannot be reached, not because of limitations set forward by physical conditions, but due to socio-economic or institutional aspects (low education level of farmers, absence of services, markets, infrastructure). This incompatibility between project objectives and field facts will manifest itself during the formulation and choice of land utilization types.

Under such circumstances profound structural changes (land reform, education) should precede the implementation of the development project.

The description of land utilization types or farming systems, at any level of generalization include a quantification of :

(a) produce
(b) management type as defined by :

- farm size
- capital intensity
- labour intensity
- farm power
- technical know-how level of farmers.

The land utilization types may also be influenced by land tenure systems having an impact on farm size, outlay of farms thus influencing management.

The status of the infra-structure has also to be considered, and infra-structural improvements may be an important part of a development program.

The land utilization types have to be defined considering the produce and the factors influencing management. During this consideration following guidelines on these topics can be taken into account.

(1) **PRODUCE**

Produce consists of the crop or the crop rotation. In primitive farming under shifting cultivation the produce can be an association of crops mixed up together in one field. Example for the humid tropical Zaire basin : a mixture of upland rice, maize, cassava and banana.

At a high level of generalization, the produce can be subdivided into 4 groups :

- arable land (annual crops)
- permanent crops (fruits and tropical perennial crops)
- grassland
- forest.

At a more detailed level precision should be given. For arable land farming the crop rotation has to be precised. For permanent crops the type of crop will determine the evaluation of the land because each crop has its specific requirements.

For grassland, distinction can be made between : natural grassland, improved natural grassland, artificial grassland either for meat- or milk production.

In forestry difference can be made between timber extraction from natural forest or cultivated forest.

Irrigation farming requires specific attention for defining land utilization types : irrigated rice, annual field crops, fruits, vegetables.

(2) **MANAGEMENT**

(a) **The size of the farms** is an important factor in the elaboration of a farming system; it will further interact with capital intensity, farm power, farm labour and technical know-how of the farmer.

Certain crops have minimal surface requirements to be economically exploitable. There is also a close relationship between farm size and available farm labour which cannot often be substituted adequately by power operated machinery. Farm size is a variable which is often determined by socio-economic conditions rather than by physical conditions. It is not unusual in agricultural schemes that the farm size is established beforehand without sufficient information on the existing land conditions. Some physical conditions have to be considered. However, it will be sometimes preferable to recognize the farm size as a major variable within a certain range which is determined with greater precision during each phase of the land-use planning project and which is definitely established at an optimal level, in harmony with the other elements defining the land utilization type during the economic land classification.

Following levels of farm size are most often used for the definition of land utilization types :

- small holding (often less than 2 ha)
- medium farms
- large farms
- industrial plantations; treatments and processing of obtained yields and realized at the plantation site.

(b) **The use of capital and its availability** determine possibilities for improvement, maintenance and conservation of the land conditions. In practice, capital requirement depends on the inherent characteristics of the land conditions and the cost of modifying them in relation with the value of the desired product. Costs distinction should be made between :

- non-recurring requirements or development cost, such as land reclamation and installation of irrigation, drainage and anti-erosion structures; and

- recurring input requirements such as fertilizers, pesticides, improvement of soil structure, maintenance cost of irrigation and drainage systems.

Within each biological production process, several levels of capital input may be distinguished. For land evaluation five levels of production and development inputs are proposed :

A : **low**, can in general be born by the landowner (stone clearing, simple levelling)

B : **medium**, can be born by the landowner with credit facilities (grading, open drains)

C : **high**, government funds or long-term credit to landowner (simple land reclamation works)

D : **very high** with normal recurring costs) large
) government
E : **very high** with high recurring costs) funds are required.

High capital inputs in crop production, grazing and forestry may represent entirely different figures in terms of input per surface unit. The level of capital input should be mentioned in the comprehensive definition of a land utilization type.

For example under tropical conditions it will be important to know if the input level will be sufficiently high to improve a low plant nutrient status of the soil. In an area with steep slopes it will be relevant to know what kind of soil conservation works can be financed by the farmers. A common problem in the construction of precise input-output models for land utilization types is the generally unsatisfactory prediction of yields, compared to the more precise estimate of required recommended inputs.

(c) **Labour intensity** in biological processes is a variable influenced by the level of applied capital and technology, and by the labour requirements of the produce concerned.

Since employment opportunities are a major issue of most development policies, this factor should be taken into consideration when alternative land utilization types are formulated. Usually data are available on the government's employment policy, availability of labour and degree of unemployment in the areas surveyed. Employment considerations are an integral part of land utilization considerations in terms of total permanent and seasonal employment.

In the definition of land utilization types, one uses very often terms as : hand labour, animal power, labour intensive, labour extensive. All these concepts are directly related with the items capital intensity and farm-power.

(d) **The source of farm-power** to a great extent symbolizes the accompanying set of agricultural implements, and the level of annual capital inputs in the farm. The set of agricultural implements on its turn represents a combination of farm management practices significant for the land utilization type. The performance of each set of agricultural implements is affected differently by the agricultural land conditions.

Some examples of farm-power levels are :

- heavy mechanized with crawler tractors;
- fully mechanized with four wheel tractors;
- light mechanization with two wheel and one wheel power operated machinery, representing a modern version of handtools, frequently used in advanced labour intensive agriculture and horticulture on small plots;
- animal power which includes a much lighter type of equipment; and

- hand operated tools and manpower which includes only a small set of simple handtools.

(e) **The technical know-how level of the farmers** is an important feature for the final selection of the farming system. A major task of the multidisciplinary land-use planning team will be to propose harmonic land utilization types which suggest farming, land management and improvement practices within the ability of a majority of the farmers and ranchers concerned. It is often the relatively low technical know-how level of the local farmers what limits the possibilities for ambitious land and water development schemes to solutions of only an intermediate level of technology and efficiency, a restricted range of crops, less sophisticated farm machinery and a restricted capital input level.

No standardized and internationally accepted classification of land utilization types exists. Certain broad types of land-use widely used in world literature are : dry farming, irrigated agriculture, range farming, mixed farming, horticulture are not real land utilization types because these words are not fully defined in terms of produce and management.

Land utilization types have to be defined according to the factors discussed in this chapter : produce, farm size capital, farm power, employment, know-how.

For practical use table 7 summarizes some criteria in order to attribute a management level (input level) for the most important tropical crops.

*Table 7. Attributes of three management levels for rainfed land utilization types (**Sys and Riquier, 1980**)*

ATTRIBUTE	LOW INPUT LEVEL L.U.T.	INTERMEDIATE INPUT LEVEL L.U.T.	HIGH INPUT LEVEL L.U.T.
Produce	Single crops or crops in appropriate rotation : millet, sorghum, maize, rice, wheat, barley, sweet potato, white potato, cassava, phaseolus bean, soybean, oil-palm, groundnut, banana, cotton, sugar-cane, rubber, coffee, cocoa, tea, e.a.		
Land holdings	Small sometimes fragmented	Small sometimes fragmented	Large consolidated
Capital intensity	Low	Intermediate with credit on accessible terms	High
Market orientation	Subsistence production	Subsistence production plus commercial sale of surplus	Commercial production
Labour intensity	High, including uncosted family labour	High, including uncosted family labour	Low, family labour costed if used
Power sources	Manual labour with handtools	Manual labour with handtools and/or animal traction with improved implements	Complete mechanization including harvesting if possible
Know-how	Low	Moderate	High
Technology employed	Local cultivars, no fertilizers or chemical pests and disease control. Fallow periods. No conservation measures.	Improved cultivars as available. Sub-optimum fertilizer application. Simple extension packages including some chemical pests and disease control. No conservation measures. Some fallow period.	High yielding cultivars including hybrids. Optimum fertilizer application. Chemical pests, disease and weed control. No fallow. Conservation measures including use of crop residues.
Infra-structure requirements	Market accessibility not necessary Inadequate advisory services.	Some market accessibility necessary with access to demonstration plots and services.	Market accessibility essential. High level of advisory services and application of research findings.

2.5. Land-use requirements

2.5.1. GENERAL

Having described the land utilization types, the next step in activities related to land use is to define the requirements for their successful operation. These are known as the land-use requirements. For each land utilization type it is necessary to establish :

(1) the conditions which are best for its operation;

(2) the range of conditions which are less optimal but still acceptable;

(3) conditions which are unsatisfactory.

These land-use requirements are later matched with land characteristics or land qualities to determine the suitability of a particular land unit for a particular land utilization type.

2.5.2. LAND CHARACTERISTICS AND LAND QUALITIES

2.5.2.1. Definitions

Land characteristics and qualities are properties of the land units.

(1) **LAND CHARACTERISTICS**

Land characteristics are measurable properties of the physical environment directly related to land use. The land characteristics made available after a soil survey and therefore to be used for evaluation are :

- climate **(c)**
- topography **(t)**
- wetness **(w)**
  - drainage
  - flooding
- physical soil characteristics **(s)**
  - texture (including stoniness)
  - soil depth
  - depth and intensity of acid sulphate layer
  - calcium carbonate content
  - gypsum content
- fertility characteristics not readily to be corrected **(f)**
  - cation exchange capacity of the clay fraction as an expression of the weathering stage
  - base saturation as related to exchangeable cations
  - organic matter content
- salinity and alkalinity **(n)**
  - electrical conductivity
  - exchangeable sodium percentage

There is a clear tendency to replace the characteristic "base saturation" by sum of exchangeable basic cations (Ca + Mg + K) and pH H_2O, because these two last characteristics will give direct information necessary for the improvement of the fertility.

(2) **LAND QUALITIES**

Land qualities are measurable, calculable or estimable attributes, representing the immediate requirements of the land utilization types. They are in fact practical consequences of land characteristics.

At the highest level of generalization, **FAO (1976)** suggests three "comprehensive land qualities", each with a distinct influence on the suitability of land for a specific use. They are :

- gross productivity (yield of produce and other benefits);
- required recurrent (management) inputs; and
- non-recurrent (improvement) inputs, where relevant.

Each of these "high level comprehensive qualities" is the resultant of the interaction of less complex single land qualities of which the most important are :

(a) Internal qualities
- water availability
- oxygen availability
- availability of foothold for roots
- resistance to iron induced chlorosis
- nutrients availability
- resistance to structural degradation of top soil
- absence of salinity and alkalinity

(b) External qualities
- correct temperature regime
- resistance against erosion
- ability for lay-out of farm plan
- workability.

A more detailed list of land qualities, related to specific use, is given in the FAO framework (**FAO, 1976**) as follows :

Land qualities for physical productivity of plant growth
- moisture availability
- nutrients availability
- availability of oxygen for root growth
- availability of foothold for roots
- conditions of germination
- salinization and/or alkalinization
- soil toxicity or extreme acidity
- pests and diseases related to the land

- flooding hazards
- temperature regime (including influence of frost)
- radiation energy and photoperiod
- wind and storm as affecting plant growth
- hail and snow as affecting plant growth
- air humidity as affecting plant growth
- drying periods for ripening of crops and at harvest time.

Major land qualities specifically related to animal growth
- hardship due to climate
- endemic pests and diseases
- nutritive value of grazing land
- toxicity of grazing land
- resistance to degradation of vegetation
- resistance to soil erosion under grazing conditions
- availability of drinking water
- accessibility of the terrain.

Major land qualities related to productivity of natural product extraction
- presence of valuable tree and shrub species
- presence of medical plants and other vegetation yielding extraction products
- presence of fruits
- game productivity for meat and hides
- accessibility of the terrain.

Major land qualities related to practices in plant production, in animal production or in extractions
- possibilities for mechanization
- resistance against erosion
- freedom in the lay-out of farmplan or a development scheme including the freedom to select the shape and the size of the fields
- traficability from farm to land

- vegetation cover in terms of favourable or unfavourable effects for cropping.

2.5.2.2. **Relation between land characteristics and qualities**

The general relation between the most important land characteristics and land qualities is suggested in table 8.

The use of land qualities requires a matching exercise. They have to be determined and evaluated in accordance to their affecting land characteristics.

The rating of land qualities should therefore be done with regard to land characteristics and in many cases this will not be a simple exercise because optimal and marginal conditions are difficult to determine.

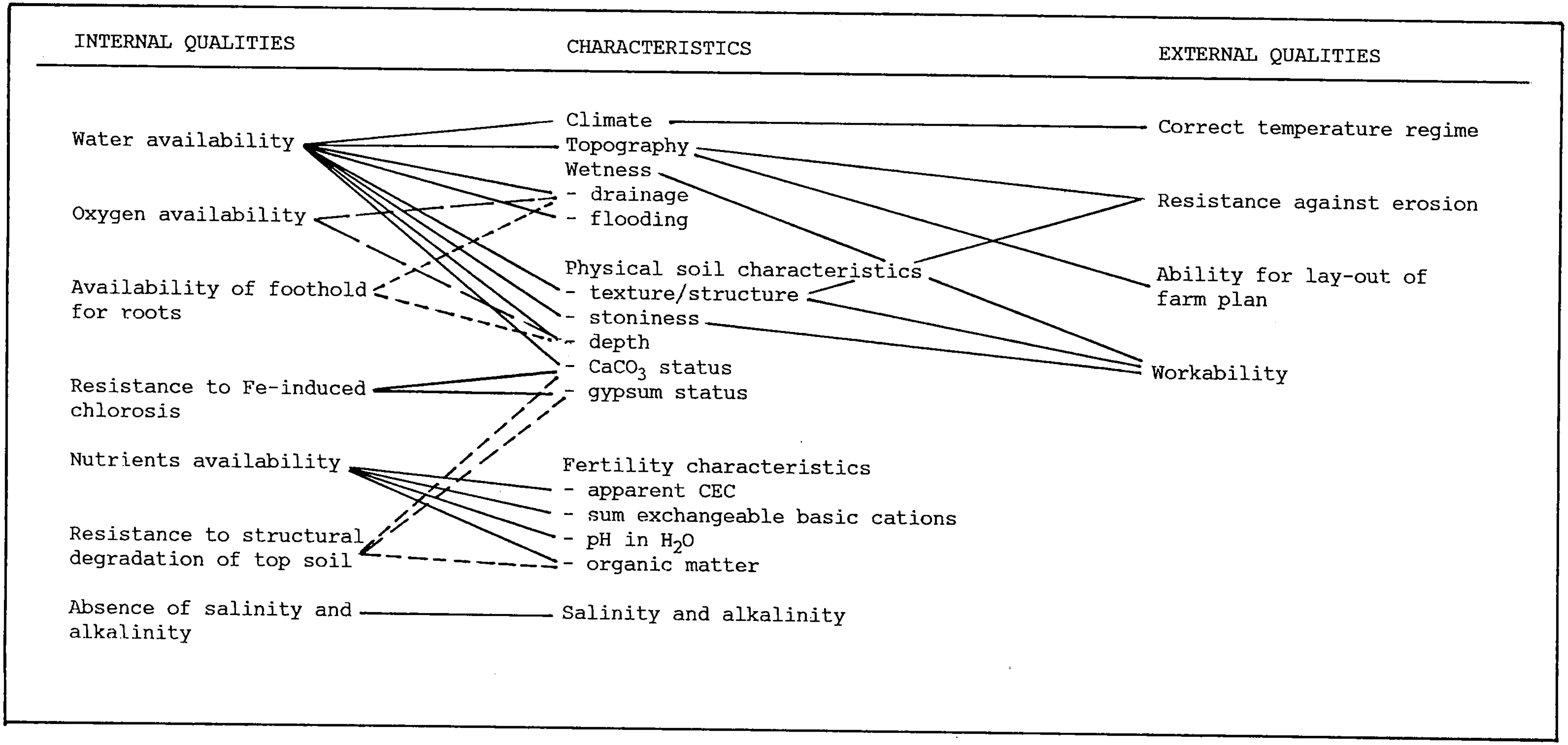
The major land quality of "available water" is related to following land characteristics :

- Climatic characteristics
  - amount of precipitation
  - evapotranspiration

- Soil characteristics
  - water retention capacity) both related
  - permeability) to texture
  - depth of the soil
  - nature of clay minerals
  - drainage (water table)

The relation between texture and available soil water is known in general terms (table 9).

Table 8. Relation between land characteristics and land qualities



The relations between texture and available water/infiltration rate given in table 9 are only guidelines and need carefulness in interpretation, particularly with regard to clay mineralogy.

Table 9. Available water and infiltration rate for the different textural classes

Textural classes	Available water (mm of water per m of soil)		Infiltration rate (cm/h)
	Ranges	Average	
1. Sand	32.5- 62.5	47.5	> 12.5
2. Loamy sand	62.5-105.0	85.0	10-12.5
3. Sandy loam	105.0-145.0	125.0	5-10
4. Loam, silt loam, silt	125.0-190.0	158.0	1- 5
5. Sandy clay loam, sandy clay	145.0-170.0	158.0	1- 3.5
6. Clay loam, silty clay loam	170.0-210.0	190.0	0.5- 1
7. Silty clay, clay < 60% 0-2µ fraction	170.0-210.0	190.0	0.1- 0.5
8. Clay > 60% 0-2µ fraction	130.0-170.0	150.0	< 0.1

Soils with allophane may have a high water retention but, because a great part of that water is retained with high tension, they may have only few available water even when the texture is clay to silty clay. As such the heavy clay soils on basalt contaminated by volcanic ash of the high Ethiopian plateaus have only an available water retention of 60 to 85 mm of water per m of soil there, where from table 9 one should read 130-170 mm. These soils have a dominance of silicate clay but include important amounts (ca. 40%) of allophane.

The infiltration rate as related to texture expressed in more general terms is given in table 10.

It is clear that the depth of the soil over an indurated horizon will not only determine the availability of foothold for roots but also the amount of water that a soil can store. This indicates an interaction between water availability and availability of foothold for roots.

For a same textural class the available water is also related to clay mineralogy.

Soil with 2:1 clays particularly montmorillonites have a higher water storage capacity than soils with pure kaolinitic

Table 10. General relation between texture and permeability

Textural class	Permeability (cm/h)	Rating
Sand, loamy coarse sand	> 12	very rapid
Coarse sandy loam, loamy fine sand	6-12	rapid
Loam, fine sandy loam, silt loam, silt, clay loam silty clay loam, sandy clay loam	0.5- 6	moderate
Sandy clay, silty clay, clay		
- non massive	0.1- 0.5	slow
- massive	< 0.1	very slow

clays and iron oxides. According to the data of **Israelson and Hanson (1969)**, clays of arid areas with dominance of 2:1 clay minerals have an average total available moisture of 18%. While the available moisture content of the highly weathered ferrallitic clays is around 5% only.

The quality of "nutrient availability" depends, for so far natural fertility is concerned, mainly on following land characteristics :

- cation exchange capacity
- sum of exchangeable basic cations
- pH-H_2O
- organic matter content

These characteristics are normally furnished with the physico-chemical characterization of the soil series.

Expressed in more chemical terms of N, P, basic cations, even trace elements, the quality "availability of nutrients" has for a long time been the main concern of soil fertility specialists. For optimal evaluation the different nutrition levels should be established for the different nutrients and for the specific land utilization types. In the present conditions this information is mostly not available and one can only refer to the physico-chemical characteristics reflecting the natural fertility.

The "availability of oxygen for plant roots" is related to soil structural conditions and to excess of water.

Lack of structural stability of the top soil may introduce a very low macro-porosity, particularly in irrigated farming, leading to conditions of poor aeration after irrigation or after a heavy rain in rainfed agriculture.

Excess water drives the air from the soil pores and leads to lack of oxygen. This can best be evaluated by determining the degree of excessive wetness.

The land quality "availability of foothold for roots" could be evaluated with regard to the characteristics soil depth and excess water (drainage). Deep well drained soils have no limitations for this quality; shallow or very poorly drained soils have severe limitations. However, this suggests an interaction between water availability and availability of foothold for roots as both are influenced by the depth of the watertable.

The conditions for germination are determined by the availability of water at the time of sowing and by the structure of the top soil. This top soil structure depends in most cases on the soil structure in relation to tillage operations and is often determined by the water content at tillage.

Salinization and alkalinization are in fact land characteristics and there is abundant literature on the influence of salinization and alkalinization of soils in relation to plant growth. The interpretation of these characteristics is one of the main concerns in judging actual and potential land-uses and possible improvements in arid and semi-arid regions.

Soil toxicity or extreme acidity are properties mainly occurring in tropical regions where Al and Mn toxicity may occur; Mn levels of more than 200 ppm are common on highly weathered soils on basic rocks. Extreme acid conditions may appear after drainage of potentially acid sulphate soils.

The other physical land qualities are related to extra soil land characteristics (climate, topography, flooding).

2.5.2.3. **Choice between land characteristics and qualities as a basis for evaluation**

It is possible to use any of the following as a basis for the assessment of land suitability (**FAO, 1983**) :

(1) land characteristics
(2) land qualities measured or estimated by means of land characteristics;
(3) a mixture of land qualities and land characteristics.

It is recommended that assessment should be based upon land qualities, although it is recognized that there will be circumstances in which the use of land characteristics may be more convenient.

Advantages of the use of land qualities are :

- land qualities are directly related to the specific requirements of land use; this enables development of simulation models to explain land/land-use relationships;

- land qualities take account of interactions between environmental factors;

- the total number of land qualities is considerably less than the number of land characteristics.

The main disadvantage is that of greater complexity, in that they require intervening stages of converting characteristics into qualities or selecting characteristics for their assessment.

The advantage of using land characteristics is that evaluation procedures are simpler and direct, permitting a direct comparison between the characteristic observed and the suitability rating. Disadvantages are the large number of characteristics, the fact that it is often not made clear what is the effect on the crop that results in a characteristic being considered favourable or unfavourable and the failure to take account of interactions.

The use of a mixture of land qualities and land characteristics will lead to important interactions between the different parameters used for evaluation. This can be done without major difficulties when the "simple limitation" method, as defined later, is used for evaluation. However when the other evaluation methods are used, it can not be recommended to use a mixture of land qualities and land characteristics without taking care for a severe selection of the used characteristics/qualities as to avoid interaction.

2.5.3. EVALUATION OF LAND CHARACTERISTICS AND LAND QUALITIES

Land characteristics and land qualities influence the suitability of land that will depend on the fact whether some of these characteristics/qualities are optimal, marginal or suitable. Therefore evaluation of characteristics and qualities, for specific land-use, is an essential stage in the overall evaluation work. This can be achieved through a relative limitation scale or by using a parametric approach.

2.5.3.1. Limitation approach

The use of land limitations is a way of expressing the land characteristics or land qualities in a relative evaluation scale.

Limitations are deviations from the optimal conditions of a land characteristic/land quality which adversely affect a kind of land-use.

If a land characteristic is optimal for plant growth it has no limitations; at the other hand, when the same characteristic is unfavourable for plant growth, it has severe limitations. The relative evaluation of land qualities (characteristics) is normally realized in several degrees of the limitation. We suggest a five level scale in the range of degree of limitations, where the "severe" level is used when the property is marginal.

The different levels in the degree of limitation are defined as follows :

- **no limitations** : the characteristic (quality) is optimal for plant growth;

- **slight limitations** : the characteristic is nearly optimal for the land utilization type and affects productivity for not more than 20% with regard to optimal yield;

- **moderate limitations** : the characteristic has moderate influence on yield decrease; however, benefit can still be made and use of the land remains profitable;

- **severe limitations** : the characteristic has such an influence on productivity of the land that the use becomes marginal for the considered land utilization type; and

- **very severe limitations** : such limitations will not only decrease the yields below the profitable level but even may totally inhibit the use of the soil for the considered land utilization type.

The limitation levels could be expressed as land classes. This means that for each characteristic or quality one can define an **S1** level (very suitable), an **S2** level (moderately suitable), an **S3** level (marginally suitable) and an **N1** level (unsuitable but susceptible for correction) and an **N2** level (unsuitable and non-susceptible for correction). In this case, no or only slight limitations define the S1 level, moderate limitations the S2 level, severe limitations the S3 level and very severe limitations the N1 and N2 levels.

A schematic relation is as follows :

Limitation levels	Class levels
0, no) 1, slight)	S1
2, moderate	S2
3, severe	S3
4, very severe	N1 and N2

The definition of the classes can be done according to two methods :

(1) SIMPLE LIMITATION METHOD

Application of the simple limitation method implies that requirement tables have to be produced for each land utilization type. Such a table (e.g. table 11) indicates for each characteristic the class level criteria.

The methodology suggests in the first place an evaluation of the climatic characteristics (rainfall, temperature, relative humidity and radiation) with as ultimate aim the determination of one class level to be introduced in the total evaluation. The class level of climate corresponds with the lowest class

Table 11. Framework for representation of the requirements for a specific land utilization type in terms of class levels

LAND CHARACTERISTICS	CLASS LEVELS				
	S1	S2	S3	N1	N2
CLIMATE (c)					
TOPOGRAPHY (t) - slope (%)					
WETNESS (w) - flooding - drainage					
PHYSICAL SOIL CHARACTERISTICS (s) - texture/structure - coarse fragments (vol. %) - soil depth (cm) - $CaCO_3$ (%) - $CaSO_4$ (%)					
FERTILITY CHARACTERISTICS (f) - apparent CEC (cmol(+)kg^{-1} clay) - sum exchangeable basic cations (Ca + Mg + K) (cmol(+)kg^{-1} soil) - pH in water - organic carbon (%)					
SALINITY AND ALKALINITY (n) - EC (dS/m) - ESP (%)					

level of only one or more climatic characteristics.

Land classes are defined according to the lowest class level of only one or more characteristics.

(2) **LIMITATION METHOD REGARDING NUMBER AND INTENSITY OF LIMITATIONS**

This method defines land classes according to the number and the intensity of limitations. Application of this method requests requirement tables whereby for each characteristic the limitation levels are defined (eg. table 12).

Table 12. Framework for representation of the requirements for a specific land utilization type in terms of limitation levels

LAND CHARACTERISTICS	LAND CLASSES AND LIMITATION LEVELS				
	S1		S2	S3	N
	0	1	2	3	4
CLIMATE (c)					
TOPOGRAPHY (t) - slope (%)					
WETNESS (w) - flooding - drainage					
PHYSICAL SOIL CHARACTERISTICS (s) - texture/structure - coarse fragments (vol. %) - soil depth (cm) - $CaCO_3$ (%) - $CaSO_4$ (%)					
FERTILITY CHARACTERISTICS (f) - apparent CEC (cmol(+)kg^{-1} clay) - sum exchangeable basic cations (Ca + Mg + K) (cmol(+)kg^{-1} soil) - pH in water - organic carbon (%)					
SALINITY AND ALKALINITY (n) - EC (dS/m) - ESP (%)					

The methodology suggests in the first place an evaluation of the climate whereby the climatic characteristics are regrouped in 4 groups :

- characteristic(s) related to radiation;
- characteristic(s) related to temperature;
- characteristic(s) related to rainfall; and
- characteristic(s) related to relative air humidity.

For each group of climatic characteristics the most severe limitation will be considered to determine the climatic suitability class as well as the corresponding limitation level to be used in the total land evaluation. Following criteria are used :

CLASS	CRITERIA	LIMITATION
S1	climate has no limitations; or	0
	climate with max. 3 slight limitations	1
S2	climate with 4 slight limitations or with max. 3 moderate limitations	2
S3	climate with 4 moderate limitations or with 1 or more severe limitations	3
N	climate with 1 or more very severe limitations	4

The land suitability classes are defined as follows :

LAND CLASSES	DEFINITIONS
S1 (very suitable)	land units with no, or only 4 slight limitations
S2 (moderately suitable)	land units with more than 4 slight limitations, and/or no more than 3 moderate limitations;
S3 (marginally suitable)	land units with more than 3 moderate limitations, and/or no more than 2 severe limitation(s);

N1 (actually unsuitable and potentially suitable)	land units with very severe limitations which can be corrected
N2 (unsuitable)	land units with very severe limitations which can not be corrected.

The evaluation is carried out by comparing the land characteristics with the limitation levels of the requirement tables.

The second method is more difficult but the approach is more accurate. According to the first method, a land unit with 1 or with 4 or even more S2 levels will be classified as S2, although it is clear that the land with 4 moderate limitations will have a lower net return as compared with the land with only 1 moderate limitation. The second method considers land with several limitations of the same level as a lower class.

2.5.3.2. **Parametric approach**

The parametric approach in the evaluation of land characteristics consists in a numeral rating of the different limitation levels of the land characteristics in a numerical scale from a maximum (normally 100) to a minimum value. If a land characteristic is optimal for the considered land utilization type the maximum rating of 100 is attributed; if the same land characteristic is unfavourable a minimal rating is applied.

The successful application of the system implies the respect of following rules :

(1) The number of land characteristics to consider has to be reduced to a strict minimum to avoid repetition of related characteristics in the formula, leading to a depression

of the land index. Therefore all land qualities expressed by one characteristic should be rated together. As such the single rating of texture should be done with regard to the capacity to retain nutrients, water availability, permeability and one should avoid to introduce separate ratings for these single qualities.

(2) An important characteristic is rated in a wide scale (100-25), a less important characteristic in a narrower scale (100-60). This introduces the concept of weighting factor. Example : studying the suitability for irrigation the very important factor of texture is rated from 100 to 25, the less important factor of calcium carbonate content from 100 to 80.

(3) The rating of 100 is applied for optimal development or maximum appearance of a characteristic. If, however, some characteristics are better than the usual optimal, the maximum rating can be chosen higher than 100. Example : if the most common organic carbon content of the top 15 cm in a specific area varies from 1 to 1.5%, the rating of 100 is applied for that carbon level. Soils with more than 1.5% O.C. are attributed a rating of more than 100 for organic matter.

(4) The depth to which the land index has to be calculated must be defined for each land utilization type. If one considers that for a specific land utilization type all horizons have a similar importance the weighted average of the profile section until the considered depth is calculated for each characteristic.
If at the other hand one considers that the importance of a horizon becomes greater when his position is nearer to the surface, a different proportional rating can be given

to the depth sections of the profile in such a way that they increase when approaching the surface. Therefore the profile can be subdivided into equal sections; to each of these sections one attributes a "depth correction index" (weighting factor) starting with a minimum value in depth and becoming gradually greater when approaching the surface section.

The depth to be considered should coincide with the normal depth of the root system in a deep soil. The weighting factors or depth correction indices suggested, are given in table 13.

Table 13. Number of sections and weighting factors for different depths

DEPTH (cm)	NUMBER OF EQUAL SECTIONS	WEIGHTING FACTORS
125-150	6	2.00-1.50-1.00-0.75-0.50-0.25
100-125	5	1.75-1.50-1.00-0.50-0.25
75-100	4	1.75-1.25-0.75-0.25
50- 75	3	1.50-1.00-0.50
25- 50	2	1.25-0.75
0- 25	1	1.00

Example : application to textural appraisal of a soil profile for a deep rooting perennial crop. Optimal depth : 150 cm.

The profile texture is as follows :

0-30 cm : sandy clay loam
30-100 cm : clay
100-150 cm : loamy sand

The textural ratings are as follows :

Sandy clay loam : 85
Clay : 100
Loamy sand : 50

The textural rating of the profile calculates as follows :

Use 6 sections of 25 cm with weighting factors : 2 - 1.5 - 1 - 0.75 - 0.50 - 0.25.

First section of 25 cm (0-25 cm) :	
25 x 2 x 85 =	4,250
Second section (25-50 cm) :	
5 x 1.5 x 85 =	637.5
20 x 1.5 x 100 =	3,000
Third section (50-75 cm) :	
25 x 1 x 100 =	2,500
Fourth section (75-100 cm) :	
25 x 0.75 x 100 =	1,875
Fifth section (100-125 cm) :	
25 x 0.5 x 50 =	625
Sixth section (125-150 cm) :	
25 x 0.25 x 50 =	312.5
Sum :	13,200.0

Textural rating profile : 13,200 : 150 = 88

The limitation scale as defined earlier can be complemented by a parametric approach leading to a combined limitation-parametric method of evaluation. The ratings to be selected for the different limitation levels are suggested in table 14.

Table 14. Limitation levels and their ratings

SYMBOL	INTENSITY OF LIMITATION	RATING
0	no	100-95
1	slight	95-85
2	moderate	85-60
3	severe	60-40
4	very severe	40- 0

Table 15 shows an example of a framework that can be used for the evaluation of land characteristics following the combined limitation-parametric approach.

The methodology suggests in the first place an evaluation of the climate, whereby the climatic characteristics are regrouped in 4 groups :

- characteristics related to radiation;
- characteristics related to temperature;
- characteristics related to rainfall; and
- characteristics related to relative air humidity.

For calculation of the climatic index the lowest characteristic rating of each group is used. This is because there is always a strong interaction between characteristics of the same group and also because they do not act together. The climatic indices are transformed to climatic ratings to be used in the total land evaluation.

Table 15. Framework for representation of the requirements for a specific land utilization type in terms of limitation levels and ratings

LAND CHARACTERISTICS	LAND CLASSES, LIMITATION LEVEL AND RATINGS					
	S1			S2	S3	N1 / N2
	0	1		2	3	4
	100	95	85	60	40	25
CLIMATE (c)						
TOPOGRAPHY (t)						
- slope (%)						
WETNESS (w)						
- flooding						
- drainage						
PHYSICAL SOIL CHARACTERISTICS (s)						
- texture/structure						
- coarse fragments (vol. %)						
- soil depth (cm)						
- $CaCO_3$ (%)						
- $CaSO_4$ (%)						
FERTILITY CHARACTERISTICS (f)						
- apparent CEC (cmol(+)kg^{-1} clay)						
- sum exchangeable basic cations (Ca + Mg + K) (cmol(+)kg^{-1} soil)						
- pH in water						
- organic carbon (%)						
SALINITY AND ALKALINITY (n)						
- EC (dS/m)						
- ESP (%)						

The climatic index, as well as the land index, are calculated from the individual ratings. The calculation of these indices can be carried out following two procedures :

(1) **STORIE METHOD**

$$I = A \times \frac{B}{100} \times \frac{C}{100} \times \ldots$$

(A, B, C ... : ratings)

(2) **SQUARE ROOT METHOD (Khiddir, 1986)**

$$I = R_{min} \times \sqrt{\frac{A}{100} \times \frac{B}{100} \times \ldots}$$

I = index

R_{min} = minimum rating

A, B, ... : other ratings besides the minimum rating

Suitability classes are arbitrary defined according to the value of the index;

SUITABILITY CLASS	LAND INDEX
S1	100-75
S2	75-50
S3	50-25
N	25- 0

When we compare the results obtained by the limitation method with the results of the parametric method, we realize that in extreme cases classes obtained with one method may differ from classes obtained by the other method.

Indeed if we consider the maximum number of characteristic ratings as related to climate, topography, drainage, flooding, combined texture - coarse fragments - depth, and 3 fertility ratings (apparent CEC, basic cations or pH and organic carbon) for the humid (sub)tropics, we reach at a number of eight. In arid areas, the fertility characteristic ratings will be replaced by $CaCO_3$, $CaSO_4$ and salinity-alkalinity ratings to reach also a maximum of eight.

The maximum land index of an S1-land unit can be considered as

100. The lowest index could be the result of the lower rating 85 of 4 slight limitations, while the other 4 characteristics could present the lowest 95-rating of the 0-level.

In such case, the lowest index of the S1-land unit, defined according to the limitation method, will be :

STORIE METHOD : Land index = $85 \times 0.85^3 \times 0.95^4 = 43$
SQUARE ROOT METHOD : Land index = $85 \times \sqrt{0.85^3 \times 0.95^4} = 60$

The upper land index of an S2-land unit with one moderate limitation, and all other characteristics optimal will be the maximum rating of the moderate limitation level, being 85. The lowest value of the S2-land unit with 3 moderate limitations rated 60, could present the other 5 characteristics with the lowest rating, 85, of the slight limitation level.

This situation will produce following land indices :

STORIE LAND INDEX = $60 \times 0.60^2 \times 0.85^5 = 10$
SQUARE ROOT LAND INDEX = $60 \times \sqrt{0.60^2 \times 0.85^5} = 24$

The upper land index of an S3-land unit presents the highest rating of the severe limitation level being 60 and all other ratings 100; the corresponding land index will be 60. If the lowest value is defined by 2 lower ratings of the severe limitation level, being 40, and all 6 other ratings as lower rating of the moderate limitation level, being 60, we obtain following indices :

STORIE LAND INDEX = $40 \times 0.40 \times 0.60^6 = 1$
SQUARE ROOT LAND INDEX = $40 \times \sqrt{0.40 \times 0.60^6} = 5$

The highest land index of a N-land unit with an upper rating of 40/25, of N1 and N2 respectively, for the severe limitation level, and all other ratings 100, will be 40 or 25, respectively for N1 and N2. The lowest values will reach the zero-level.

The relationship between the calculated land indices and the corrected land indices is presented in fig. 3.

Using these graphs, we can compute a corrected land index from each calculated parametric value. The corrected land indices permit a complete resemblance in the evaluation results from limitation and parametric methods.

2.5.4. INTERPRETATIONS OF LAND CHARACTERISTICS

The land characteristics discussed are limited to environmental properties having a direct influence on agricultural use and land-use planning. Interaction between characteristics may be important and the interpretation of soil properties has to be adapted to the local eco-climatological conditions.

2.5.4.1. Climate (c)

For a rainfed crop to be successful, its growth cycle should be comfortably contained within the growing period. In annual crops the growth cycle takes from germination to crop maturity. In perennials it is the period of new growth in the year. The growth cycle must be of such length that it allows the crop to produce sufficient vegetative growth to support concurrently (e.g. as in root and tuber crops or grain legume crops) or subsequently (e.g. as in cereal crops) the necessary yield forming activities.

When the climatic phenological requirements are met, then both temperature and radiation regimes determine crop productivity within the limits of the genetic potential of the crop variety,

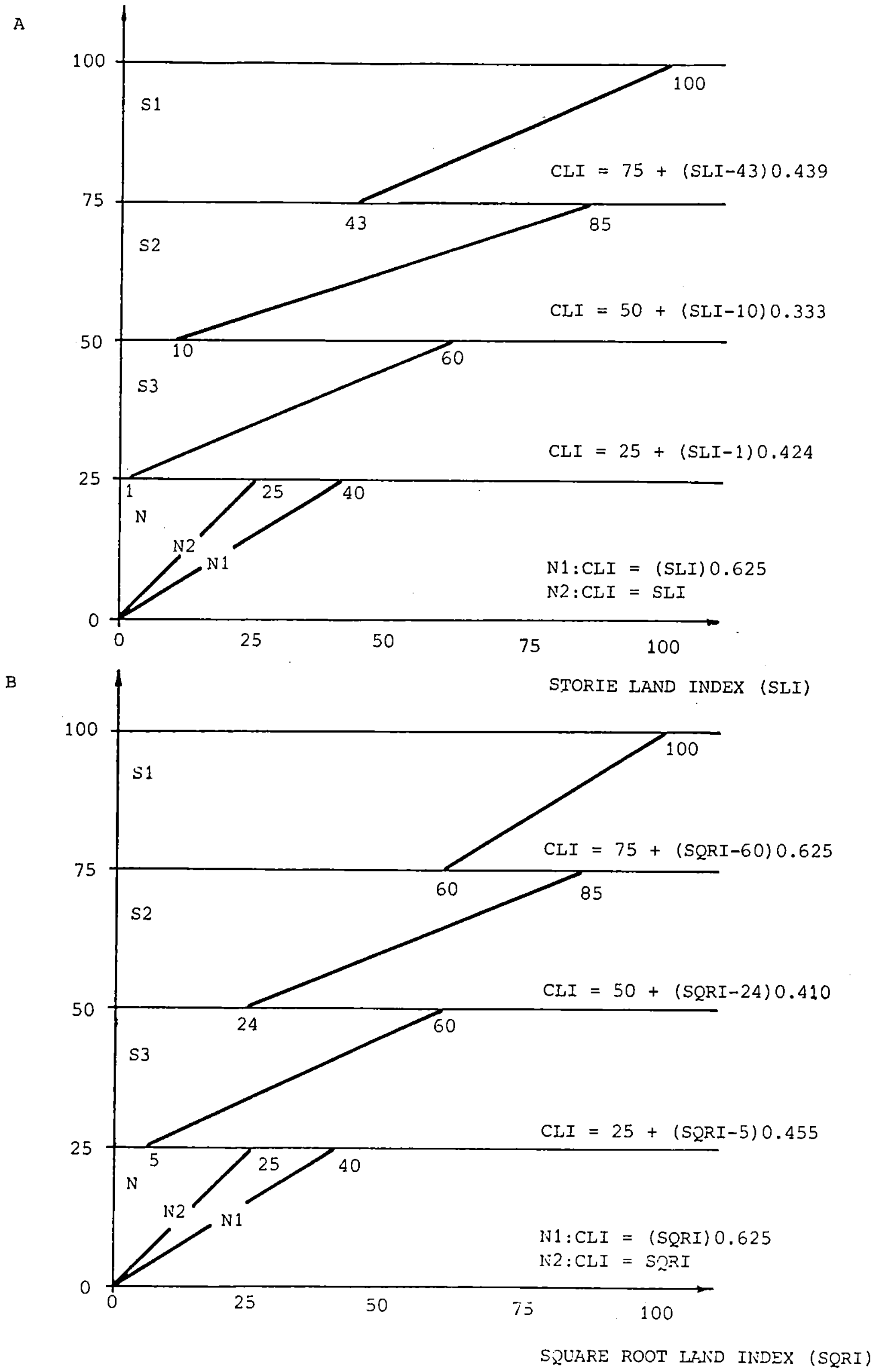


Fig. 3 *Corrected land index as related to the calculated (A) STORIE - and (B) SQUARE ROOT land indices*

cultivar or clone.

A successful crop requires an adequate water supply. If this condition is not met, water stress in the plant will adversely affect crop growth and ultimately crop yield.

Finally particular climatic conditions may be required. Such conditions may be inherent to the crop or crop variety (e.g. daylength and vernalization requirements in photoperiodic winter cereals); they may determine yield quality (e.g. low temperature enhances quality in tea; low relative air humidity is required for grain ripening in the panicle of cereals or for lint quality in cotton) or enhance the incidence of pests and/or diseases (e.g. a high relative air humidity).

In conclusion, the suitability of a climate for a given crop can best be described in terms of the climatic characteristics : minimal length of the growing period, radiation (insolation), temperature, water supply (rainfall) and particular climatic requirements.

(1) MINIMAL LENGTH OF GROWING PERIOD

The minimal length of the growing period is determined by the length of the shortest possible crop or growth cycle that can be realized under the given temperature conditions.

(2) RADIATION (INSOLATION)

Insolation determines, along with temperature, the rate of photosynthesis. The photosynthesis process provides plants with assimilates that can be used for growth. The two major pathways of photosynthesis are the C3 and C4 pathways. Crops that follow the C3 pathway have a lower rate of CO_2-exchange, a lower maximum rate of photosynthesis and reach light saturation more

rapidly than C4-species. C4 crops therefore produce more total biomass, in particular in areas with high insolation.
The radiation characteristic taken into account in the evaluation is the actual (measured) sunshine hours (n) in the crop cycle.

(3) **TEMPERATURE**

Temperature generally determines the rate of growth and development. Low temperatures may cause poor seed set and delay in flowering and maturation.
The day temperature governs the rate of photosynthesis. In C3 species, photosynthesis operates at optimum rates under conditions of low temperature : 15-20°C. Through breeding and selection some C3 species perform photosynthesis at optimum temperatures of 25-30°C. In C4 species, photosynthesis operates optimally at 30-35°C. Breeding and selection modified the optimum for some C4 crops to 20-30°C.
The mean daily temperature determines the energy to be spend for maintenance of the produced biomass.
Temperature will also determine whether a particular developmental process will begin or end (e.g. flowering) and may also determine the quality of the economical useful produce (e.g. of tea, pineapple).
The temperature characteristic taken into account in the evaluation is the average daily temperature during the crop cycle.

(4) **WATER SUPPLY (RAINFALL)**

The crop water requirements vary considerably with the crop, the crop development stages (crop coefficient or kc) and their length, and with the evaporative demand of the atmosphere (ETo).
If the water requirements are fully met, the amount of total

dry matter or yield (kg) produced per m^3 of water (water utilization efficiency) varies with the crop.
When a water deficit occurs in a part of the growth cycle, the yield response to that water deficit depends on the sensitivity of the crop to lack of water in that period (as expressed by the crop response factor, ky). In general, crops are more sensitive to water deficits during emergence, flowering and early yield formation than they are during early (vegetative) and late growth periods (ripening).
The water supply characteristic taken into account in the evaluation is the total rainfall during the crop cycle.

(5) **RELATIVE HUMIDITY**

Relative humidity can be considered as a particular climatic characteristic. At specific crop development stages a too high relative humidity may affect susceptibility to diseases. A too low relative humidity at seed formation may cause shrinkage of seeds and lower yields.

As the influence of climate on crop development is crop specific and even influenced by management, it will become impossible to suggest a standard set of climatic characteristics to be used for all land utilization types. Therefore the elaboration of climatic crop requirements will need the selection of the climatic parameters to be taken into consideration for each land utilization type.

For each of the selected parameters the optimal and marginal conditions have to be defined; they are considered respectively as "no limitation" (0-limitation level) and "severe limitation" (3-limitation level).

2.5.4.2. **Topography (t)**

SLOPE

The influence of landscape on agricultural land use is multiple. Relief is the expression of the interaction of several different phenomena and processes within the earth's crust and on its surface. Its forms and dimensions are primarily related to geological formations and to the climate, both past and present, which have either directly or indirectly acted upon these formations. Relief is further important in all methods of air-photo interpretation for the mapping of land resources.

Relief can influence the micro-climatic conditions and the hydrology.

Landform is mostly defined in terms of slope and relative elevation of plateaus, hills and mountains at one hand valleys at the other hand. As such the landform classes of the FAO guidelines for soil description have been defined as follows:

- **flat or almost flat** : slopes not steeper than 2%
- **undulating** : steepest slopes between 2 and 8%
- **rolling** : steepest slopes between 8 and 16%
- **hilly** : steepest slopes between 16 and 30%, the range of elevation being moderate
- **steeply dissected** : steepest slopes greater than 30%, range of elevation moderate
- **mountainous** : topography has a great range in elevation.

Microrelief such as gilgai on Vertisols and accumulation of eolian sand around individual shrubs in desert areas have also to be considered.

It is also surprising to know that a total annual precipitation of not more than 50 mm may provide the equivalent of 500 mm or more in depression areas in which the run-off is concentrated.

With regard to landscape and slope at least six main land utilization types can be considered. For irrigated agriculture the degrees of limitation are much more severe than for rainfed farming. Among rainfed crops one should be more severe for annual crops than for perennials, while grassland and forest have to be considered separately.

Table 16 suggests optimal and marginal conditions for these main land utilization types; they correspond respectively to limitation levels 0 and 3.

Table 16. Optimal and marginal slope conditions for some general land utilization types

Utilization type	Slope classes in %	
	Optimal	Marginal
Surface irrigation - flush - furrow	 < 0.2 < 1	 0.5 4- 6
Sprinkler irrigation	0- 2	16-25
Annual arable land farming	0- 4	16-25
Perennial crops and grassland	0- 8	25-30
Forest (exploitable)	0-16	25-30

For most gravity irrigation systems it is accepted that landscapes are capable of being graded to less than 1 per cent. Some exceptions permitting more slope are graded into contour furrows for crops and fruits as well as contour ditches for hay and pasture. For sprinkler irrigation slopes of 20-30 per cent become marginal.

2.5.4.3. **Wetness (w)**

The wetness situation of a land unit is defined by drainage and flooding.

(1) **DRAINAGE**

Drainage, sometimes together with the depth of a groundwater table, is considered in almost every system of land capability classification.

Drainage conditions of a land development unit have to be commented with regard to specific land utilization types and to texture. The suitability for upland crops decreases when drainage conditions become impeded. In addition tree crops with a deep root system are more sensitive to poorly drained conditions than annual crops with a more superficial root system. Of course, crops like paddy rice e.g. react quite different to drainage conditions, when cultivated on natural floods. Their suitability decreases when drainage conditions improve.

For irrigated agriculture, in addition to drainage, the depth of the groundwater in relation to its salinity status should be taken in consideration.

Table 17 illustrates tentative guidelines for the rating of drainage conditions for some general land utilization types.

Table 17. Guidelines for the interpretation of drainage

Utilization type	Drainage classes	
	Optimal	Marginal
Annuals (1) (2)	good imperfect	imperfect good
Perennials	good water table +1.5m	imperfect
Paddy rice under natural flood	poor and very poor	moderate
Pasture (1) (2)	moderate and good imperfect	very poor very poor
Irrigation - low to medium saline groundwater	good-water table below 2 m	imperfect
- high saline groundwater (EC > 750)	good-water table below 3 m	moderate

(1) fine and medium textured soils - (2) coarse textured soils

(2) **FLOODING**

Flooding is considered a serious limitation. Although there is a difference in flood tolerance for most crops, we suggest to define only here the general flood limitations. More precise information could be formulated when studying the capability for specific crops. For an evaluation to be used as basis for the reclamation of flood plains following classes can be suggested :

F0 - no flood limitations : the land is higher than the highest water level.

F1 - slight : the land surface is higher than the mean highest water level; however, occasional high floods may affect the land for a short period (not longer than 1-2 months).

F2 - moderate : the land surface is at about the same level of the mean highest water level so that very often (more than 5 years out of 10) the land is flooded for a period of not longer than 2-3 months.

F3 - severe : the land surface is somewhat (20-30 cm) lower than the mean highest water level, so that almost every year 20 to 30 cm floodwater occurs during a period of 2-4 months.

F4 - very severe : the land surface is much (more than 30 cm) below the mean highest water level, so that nearly every year the land is flooded for more than 2 months and in most years for more than 4 months.

For most upland crops F0 is optimal and F1 or F2 are marginal.

For paddy rice cultivation flood classes should be defined in terms of duration and depth of flooding.

The optimal duration of flooding is 110 to 160 days; marginal situations are 90-110 days and more than 180 days. The optimal depth can be considered as 10 to 30 cm.

Rice cultivation under natural floods is a common practice in S-E Asia. The parts of the flood plains used for this utilization type and their suitability will depend on depth and duration of the floods. Optimal are floods of 10 to 20 cm deep which last 3 to 4 months. Marginal situations should be defined by too less or too much water. When duration of flooding becomes less than 45 days, the situation can be considered as marginal. At the other hand, floods more than 70 cm deep will not allow cultivation of the common rice varieties, but will require the use of floating rice.

The above discussed situations are common conditions where floods occur annually under normal rainfall conditions. However some reclaimed and cultivated areas may occasionally be affected by floods in years of excessive rainfall.

The FAO agro-ecological zones project in China has suggested flood classes for specific crop groups (**Sys, 1990**) as follows :

- Flood classes for cereals except rice :

Major flood class	Description	Class name	
		Vegetative stage	Ripening stage
F0	no flooding	-	-
F1	< 5 cm water for some days (2-3)	F1v	F1r
F2	< 5 cm water for less than 1 week	F2v	F2r
F3	< 10 cm water for less than 1 week	F3v	F3r
F4	> 10 cm water for more than 1 week	F4v	F4r

Marginal situations are classes F3r and F4v.

- Flood classes for white potato and sugar beet :

Major flood class	Description	Class name	
		Early stage (before ripening	Latter stage (after ripening)
F0	no floods	-	-
F1	< 5 cm water for some days (2-3)	F1i	F1v
F2	< 5 cm water for less than 1 week	F2i	F2v
F3	< 10 cm water for less than 1 week	F3i	F3v
F4	> 10 cm water for more than 1 week	F4i	F4v

The classes F1i and F4v are considered as marginal conditions.

- Flood classes for irrigated rice (surplus to normal flooding after heavy rains) :

Major flood class	Description	Class name	
		Vegetative stage	Ripening stage
F0	no floods		
F1	< 50 cm water for some days (2-3)	F1v	F1r
F2	< 50 cm water for less than 1 week	F2v	F2r
F3	< 50 cm water for less than 1 week	F3v	F3r
F4	50-70 cm water for some days (2-3)	F4v	F4r

F5	50-70 cm water for less than 1 week	F5v	F5r
F6	50-70 cm water for more than 1 week	F6v	F6r
F7	> 70 cm water	F7v	F7r

In this range class F6 is marginal and class F7 should be considered as a situation whereby the crop is lost.

As these flood classes are related to occasional excessive rains, they will not occur every year. Therefore a choice has to be made if we should maintain them with the soil characteristics or rather consider them as climatic constraints to be evaluated with climate under the parameter "excessive rain". However, floods will not affect all land units but only specific landforms situated in lowland areas and depressions.

Another difficulty is the fact that direct information on occasional floods is most often not available in the land resources inventory and has therefore to be computed from rainfall data related to landscape.

2.5.4.4. Physical soil characteristics (s)

The land qualities, such as "moisture availability", "availability of oxygen" and "availability of foothold for root development" depend for a great deal on physical soil characteristics : texture, coarse fragments, stoniness, depth of the soil and structure; also permeability plays a role.

(1) TEXTURE AND STRUCTURE

Texture is considered as one of the most important characteristics with regard to physical soil qualities. It influences such important soil properties as soil water availability, infiltration rate, drainage, tillage conditions and capacity to retain nutrients. The effect of texture on those properties may be modified by structure, nature of the clay minerals, organic matter content, lime content.

Texture is particularly important for irrigated farming. Soils of all textural classes - with the possible exception of very coarse sand - can be successfully irrigated if the proper irrigation method is chosen. Experience has shown that if the average infiltration rate exceeds **12.5 cm/h**, gravity irrigation may not be practicable. For this reason two general land utilization types for irrigated farming are considered here : gravity irrigation and sprinkler irrigation.

For heavy textured soils it is recommended to evaluate texture with regard to structure as well for irrigated farming (permeability) as for rainfed farming (workability). For these fine textured soils structure will also regulate aeration, drainage, root penetration and water releasing capacity.

The interpretation has further to be done with regard to the utilization types; a massive clay is poorly suited for arable rainfed farming but suitable for paddy cultivation.

Lack of structure in sands and organic soils may constitute a serious limitation to crop growth as it deprives the soil of an essential property - that of anchorage especially for tree crops.

It is worthwhile to mention that texture should also be rated with regard to the length of the period at which the soil control section is below wilting point.

With regard to the utilization type one realizes that highly demanding crops (wheat, rice, barley, clover, alfalfa, sugar-cane, sugar-beet, onions, bananas) give the best yields on heavy textured soils with good structure; moderately demanding crops such as groundnuts, carrots, potatoes, salad, tomatoes, some tobaccoes and water melons do better on light textured soils. Deep-rooting perennials (rubber, coffee, cocoa, citrus, dates, grapes, figs and olives) have still other textural requirements.

Table 18 suggests optimal and marginal conditions for some general land utilization types.

In soils with heterogeneous texture, the textural class to be used for evaluation is a recalculated one using the depth weighting factors to a depth of 1 m for annual crops, up to 1.5 m depth for perennials or up to an impermeable layer. To obtain the required textural class, clay and silt content have both to be recalculated.

(2) **COARSE FRAGMENTS**

For land evaluation studies 4 distinct coarse fragment size classes could be considered :

- **fine gravels** : size between 2 mm and 2.5 cm,
- **coarse gravels** : size between 2.5 and 7.5 cm,
- **cobbles** : size between 7.5 and 25 cm,
- **stones** : size above 25 cm.

The surface coarse fragments present as gravels and cobbles at the surface and in the top 20 cm, will influence the tillage conditions as well as the capacity to retain nutrients and water. Optimal and marginal conditions are suggested in table 19.

Table 18. Optimal and marginal textural classes for some general land utilization types (*)

LAND UTILIZATION TYPE	TEXTURAL CLASSES	
	Optimal	Marginal
Surface irrigation	CL to L	LS and SiCm
Sprinkler irrigation	CL to L	cS and Cm
Paddy rice	Cm to SiCs	fS
Highly demanding annuals	C-60 to SiL	SL
Moderately demanding annuals	C-60s to L	LS
Crops with preference for coarse textured soils	L to SL	fS
Perennial crops	Co to L	LS

(*) Textural range : **Cm** : massive clay; **SiCm** : massive silty clay; **C+60,v:** fine clay, vertical structure; **C+60,s** : fine clay, blocky structure; **C-60,v:** clay, vertical structure; **C-60,s** : clay, blocky structure; **SiCs** : silty clay, blocky structure; **Co** : clay, oxisol structure; **SiCL** : silty clay loam; **CL** : clay loam; **Si** : silt; **SiL** : silt loam; **SC** : sandy clay; **L** : loam; **SCL:** sandy clay loam; **SL** : sandy loam; **LfS** : loamy fine sand; **LS** : loamy sand; **LcS** : loamy coarse sand; **fS** : fine sand; **S** : sand; **cS** : coarse sand.

Table 19. Optimal and marginal conditions for surface coarse fragments, gravel and cobbles in the upper 20 cm of the soil

SIZE CLASSES	SURFACE COARSE FRAGMENTS (vol. %)	
	Optimal	Marginal
Gravel	< 15	55
Cobbles	< 3	35

The presence of stones (size > 25 cm) at the surface will interfere with the circulation of machines and tractors. In heavy mechanized farming it may hamper the circulation of machinery. In traditional farming with oxdrawn plow and for perennial crops surface stoniness is not of such an importance.

The Soil Survey Manual suggests guidelines for the interpretation of surface stoniness as follows :

- less than **0.01** per cent (more than **30 m** apart)
  no important interference with tillage

- **0.01 to 0.1** per cent (**10 to 30 m** apart)
  stones interfere with tillage but they do not make intertilled crops impracticable

- **0.1-3** per cent (**1.5 to 10 m** apart)
  stones make tillage of intertilled crops impracticable, but the soil can be worked for hay crops or improved pasture

- **3-15** per cent (**0.8 to 1.5 m** apart)
  sufficient stones to make all use of machinery impracticable, except for very light machinery

or for hand tools. Such soils may have some use for extensive pasture or forest

- more than **15** per cent (less than **0.8 m** apart) but land is not yet paved. All use of machinery impracticable, the land may have some value for poor pasture or for forestry.

- land essentially paved with stones that occupy more than **90** per cent of the surface.

Subsoil coarse fragments content can reasonably been estimated without making distinction between gravel, cobbles and stones. However, in the tropics, where soils with stone-lines occur, it is recommended to differentiate three groups of coarse fragments : rock fragments, laterite gravel and quartz gravel. Evaluation of subsoil stoniness should also take into account the amount of coarse fragments and the depth at which the top of the gravel layer occurs.

When coarse fragments are present in the topsoil 20 cm and their content decreases with depth, then the coarse fragments content of the topsoil is used for evaluation.

When coarse fragments are present in the topsoil and their content increases with depth, or when the top of the gravel layer occurs deeper than 25 cm a recalculated gravel content using depth weighting factors can be used for evaluation.

In the case of subsurface stoniness (coarse fragments) we consider a recalculated content of < 3% as optimal, and 35 to 55 vol. % as marginal.

(3) **SOIL DEPTH**

The depth of the soil that may be exploited by plant roots is an important criterion for land evaluation. A deep well drained soil shows a root penetration until below 150 cm for most crops.

For annual crops the dense root system is usually at a depth of less than 60 cm, while most tree-crops even have a dense to moderate root system until the depth of 150 cm.

It has been considered that the optimal depth (H) represents two times the depth (h) with 60% of the root system (H = 2h).

Experience has shown that most crops will produce excellent yields with an effective root zone depth of 90 to 100 cm.

Table 20 suggests optimal and marginal depth conditions for some general land utilization types.

Table 20. Guidelines for evaluation of depth limitations

LAND UTILIZATION TYPE	DEPTH (cm)	
	Optimum	Marginal
Cereals and pasture (rain fed)	> 90	10- 20
Annual root crops (rainfed)	> 90	20- 40
Deep rooting perennials	> 150	30- 60
Irrigation farming	> 300	50-100

(4) **CALCIUM CARBONATE STATUS**

The presence of calcium carbonate affects both the physical and the chemical characteristics of a soil. High lime concentration may not severely restrict water movement but may prevent root penetration.

Carbonate nodules are less active than concentrations in diffuse form. Especially important is the calcium carbonate present in particle sizes less than 20 microns. A high calcium carbonate concentration particularly in the very fine fractions brings risks of lime-induced chlorosis for many crops. As the sensitivity of the different crops to calcium carbonate differs, we suggest to use four groups of crops for evaluation of the $CaCO_3$-level (table 21). It is also accepted that the physical characteristics of calcareous soils change when they are irrigated. Therefore lime content affects suitability for irrigation, irrigated land becomes more coherent and resistant to root penetration when $CaCO_3$ content increases.

For evaluation one can proceed as follows :

- if the mean lime content of the top soil 30 cm decreases with depth, the evaluation takes into account these upper 30 cm;
- in other cases, the recalculated lime content using the weighting factors is used.

(5) **GYPSUM STATUS**

Gypsum indirectly affects soil physical properties and therefore it is still treated with these characteristics. It improves the structure and prevents sodium saturation, therefore it favours the permeability and infiltration rate.

*Table 21. Calcium carbonate requirements (**adapted from Sys and Riquier, 1980**)*

CROPS	$CaCO_3$ (%)	
	Optimum	Marginal
<u>Tolerant crops</u>		
sorghum	0-15	50-75
wheat, barley	0-15	50-60
sugar-cane, chickpea, groundnut, millet	0-12	35-50
<u>Moderately tolerant crops</u>		
cotton	0-12	35-40
bean, soybean	0-10	28-35
maize, rice, sweet potato	0- 8	22-30
<u>Sensitive crops</u>		
potato	0- 8	20-25
citrus	0- 5	16-25
banana	0- 2	10-15
<u>Very sensitive crops</u>		
tobacco, yam, cassava	0- 1	7-10
coffee, cocoa, oilpalm	0- 1	7-10
rubber, tea	0	0- 1

A small amount of gypsum is favourable for crop growth because it serves as a relatively soluble source of calcium as plant nutrient and replaces sodium in the exchange complex and thus acts to preserve chemical and physical soil degradation.

According to practical observations it may be concluded that plant growth is strictly limited when the gypsum content of the root zone is higher than 25 to 30 per cent.

Under irrigation highly gypsiferous soils may develop dissolution depressions; for this reason those soils are not suitable for irrigation.

Table 22 gives the gypsum requirements for some representative crops. As far as plant growth is concerned the evaluation can be done as follows :

- if the mean gypsum content of the upper 30 cm decreases with depth, the evaluation takes into account the weighted average of these upper 30 cm,
- in all other cases, evaluation is done according to the weighted average gypsum content over the rooting zone of the considered land unit. The technique of attributing a higher weight to the upper horizons can hereby been used. This adapted calculated gypsum content considering the weighting factors, as suggested before, for different profile sections may be used up to the top of a gypsiferous horizon with more than 25% gypsum considered as non penetrable for roots.

2.5.4.5. **Fertility characteristics (f)**

(1) APPARENT CEC

With the exception of some soils with positive charge, the weathering stage rarely makes a soil unsuitable for cultivation; however, it will influence its suitability as it defines the presence or absence of a mineral reserve and influences the retention for nutrients and water.

Table 22. Gypsum requirements

Crops	$CaSO_4$ (%)	
	Optimum	Marginal
Tolerant crops		
sorghum, wheat, barley, sugar-cane	0-5	15-25
Moderately tolerant crops		
chickpea, groundnut, pearl millet, cotton, soybean, maize, rice, sweet potato	0-3	10-15
Sensitive crops		
white potato, citrus, rape seed, vegetables (tomato), banana	0-1	3- 5
Very sensitive crops		
tobacco, Phaseolus bean, yam, cassava, coffee, cocoa, oil palm	0-0.5	1- 3
rubber, tea	0	0- 0.2

In arid and semi-arid areas most soils are calcareous and have an appreciable reserve in weatherable minerals. Therefore these soils, at the recent stage of weathering, have no limitations with regard to weathering. Their apparent CEC is always more than 24 cmol(+)kg^{-1} clay.

In the humid and semi-humid tropics the weathering stage of the soil is expressed in the profile differentiation as well as in some specific physico-chemical characteristics related to the mineralogy of the clay fraction.

The recent stage of weathering includes soils without diagnostic subsurface horizons or having a cambic or argillic horizon with dominance of 2/1 lattice clays; what means that the CEC per kg of clay is higher than 24 cmol(+). This weathering stage includes Entisols and typic subgroups of Tropepts, Alfisols and Ultisols.

The intermediary stage of weathering includes soils with a cambic or argillic horizon, with a mixed clay mineralogy in which kaolinite is dominant but including important quantities of 2/1 clays, mostly mica but sometimes smectite. The CEC of these clays is less than 24 cmol(+)kg^{-1}. This weathering stage included Oxic subgroups of Tropepts, Alfisols and Ultisols. According to a suitability for agricultural use it could be subdivided as follows :

- low activity clay (LAC) cambic or argillic horizons with
  (1) a Munsell chroma of 4 or less, and/or
  (2) some weatherable minerals, and/or
  (3) a fine silt/clay ratio less than 0.2 on sedimentary and low grade metamorphic rocks, less than 0.15 on magmatic and high grade metamorphic rocks,
- other LAC argillic horizons with good structure and clay skins on more than 50% of ped surfaces,
- other LAC argillic horizons.

At the ultimate stage of tropical weathering the soils have an oxic horizon, without weatherable minerals and a very low activity of the clays, with apparent CEC values of less than 16 cmol(+)kg^{-1}. Some extremely weathered soils may even have a positive charge. Table 23 illustrates the influence of weathering stage on yields of some tropical crops.

Table 23. Crop yield in relation to weathering stage of parent material (Mosso, Burundi)

CROP	YIELD in kg/ha		
	Recent stage	Intermediary stage	Ultimate stage
Eleusine	-	825	624
Beans	1,702	1,021	677
Groundnuts	1,188	877	808
Cotton	1,270	976	659
Sweet potatoes	27,017	13,050	8,060

So a general evaluation of the weathering stage can reasonably be expressed by the profile development stage (entic, cambic, argillic, oxic), combined with the apparent CEC of the subsurface horizon. Following levels could be used as a guideline for evaluation; these major classes could be subdivided with regard to variations in the horizon development :

- recent : CEC, > 24 $cmol(+)kg^{-1}$ clay
- intermediary : CEC, 16-24 $cmol(+)kg^{-1}$ clay
- ultimate (-) : CEC, < 16 $cmol(+)kg^{-1}$ clay, net - charge,
- ultimate (+) : CEC, < 16 $cmol(+)kg^{-1}$ clay, net + charge.

As a guideline for interpretation we suggest in table 24 the optimal weathering stages for three groups of crops.

Table 24. Optimal weathering stages as expressed by CEC (cmol(+)kg^{-1} clay)

CROP GROUP	OPTIMAL
Exacting crops	Recent > 24
Moderately exacting crops	Recent Intermediary > 16
Non-exacting crops	Recent Intermediary Ultimate (-)

For evaluation we recommend to use the apparent CEC of the B-horizon, or at 50 cm depth for A-C profiles, or just above a lithic- or paralithic contact if present within 50 cm from the surface.

For soils where the surface horizons have been rejuvenated with volcanic ash or alluvial material, we should consider the apparent mineral CEC of the rejuvenated horizon. The correction for organic matter can be done considering that 1 per cent C communicates a CEC of 2.6 cmol(+)kg^{-1} to the soil.

(2) **SUM OF EXCHANGEABLE BASIC CATIONS (Ca + Mg + K)**

The sum of exchangeable basic cations (Ca + Mg + K) is an expression of the quantity of cations or nutrients available for plant growth. Not only the total amount of cations is important, but also the ratio between the different cations. A ratio **Ca/Mg/K** = **75/18/7** can be considered as optimal. However, for general evaluation work of taxonomic units, we have to limit ourselves to the total amount of exchangeable basic cations (Ca + Mg + K). This implies that soils with a limited leaching of basic cations will show almost always no limitation, nevertheless the cation balance is not optimal (e.g. gypsiferous soils have normally a too high Ca/Mg and Ca/K ratio). However, these imbalanced situations are going to be expressed in the evaluation system through other characteristics (e.g. gypsum content).

It is recommended to proceed to an evaluation with regard to the cation status in the rooting zone, but for practical reasons (fertilizers recommendations are given for the topsoil) we propose to use the weighted average of the sum of exchangeable Ca, Mg and K in the upper 25 cm of the soil.

(3) **SOIL ACIDITY**

Soil acidity can be mainly correlated with the sum of exchangeable cations (Ca, Mg, K and Na) and is thus related to the former characteristic. But besides this relation, soil acidity gives information about probable soil toxicities with a negative effect on crop development.

Aluminium toxicity refers to the harmful effects of a concentration of Al^{+3} ions in the exchange complex. Aluminium first enters the exchange complex below a pH of approximately 5.5, rising to some 20% Al-saturation at about pH 5.0 and 50% or more below pH 4.0. Soil acidity may be used as a diagnostic for Al-saturation.

(4) **ORGANIC CARBON**

Under natural vegetation the organic carbon content is often a good expression of the natural fertility of the soil. Therefore this characteristic is important for evaluation, particularly in highly weathered tropical soils, having no mineralogical reserve and where the organic matter constitutes the only source of nutrients.

As the organic carbon content of the soil is closely related to the agro-ecological zones, it will be necessary to work out evaluation per ecological zone or even at a regional level. Further on, it has been stated that the organic carbon of the soil is closely related to soil texture. The Kalahari sands in Zaire, under savannah, have a mean carbon content (0-20 cm) of 0,85 % for a clay content of 5-10%. The Yangambi deposits under forest have 1,25% C in their upper 20 cm for a clay content of 25-35%. Soils with 40-50% clay on shales have 3.75% C in the upper 20 cm under tropical highland savannah, 1.56% C under rainforest, 0.86% C under secondary forest and 0.65% after a cycle of shifting cultivation.

Considering the organic carbon content in the upper 15 cm one can suggest following levels for the humid tropics :

> 2,4%	:	high
1.5-2.4%	:	moderately high
0.8-1.5%	:	moderately low
< 0.8%	:	low

In semi-arid steppe areas, following levels for organic carbon (0-15 cm) could be suggested :

> 0.8%	: high
0.4-0.8%	: medium
< 0.4%	: low

Optimal organic matter levels have to be defined per agro-ecological zone or even at regional scale. We suggest to consider as optimal the organic matter content of a medium textured soil under natural vegetation and not affected by erosion. Only in few situations the organic matter content of the soil can be considered as marginal; this may happen for highly demanding crops or in areas where decline of organic matter introduces structural deterioration of the soil.

2.5.4.6. **Salinity and alkalinity (n)**

Soils in good conditions have no soluble salts and an exchange complex dominated by calcium and magnesium and only minor amounts of sodium. Therefore high salinity and alkalinity are important limitations for agricultural development.

(1) **SALINITY**

Salinity is probably one of the most common limiting factors in agricultural development of arid valleys and basins.

According to the data provided by the USDA Agricultural Handbook N° 60 (**USDA, 1954**) and the USDA Agriculture Information Bulletin N° 283 (**USDA, 1964**), the crops can be subdivided in the following three groups, with respect to their salt tolerance.

I. **Low salt tolerance** : these very sensitive crops show already a yield reduction in the conductivity levels of 2-4 dS/m.

Field crops : beans.
Vegetables : green beans, radish, celery.
Fruits : pear, apple, orange, prune, apricot, peach, strawberry, lemon, avocado.
Forage crops : white and red clover.

II. **Medium salt tolerance** : these sensitive to moderately sensitive crops show yield reductions in the conductivity levels of 4 to 8/10 dS/m.

Field crops : rye, wheat, rice, sorghum, corn, sunflower.
Vegetables : tomato, broccoli, cabbage, pepper, lettuce, potatoes, carrots, onion, peas.
Fruits : fig, olive, grape.

III. **Tolerant crops** : they support conductivity levels over 10 dS/m often up to 16 dS/m.

Field crops : barley (16 dS/m), sugar-beet (14 dS/m), cotton (14 dS/m).
Vegetables : garden-beet, asparagus, spinach (up to 12 dS/m)
Fruits : date palm.

A more detailed outline of yield reduction with regard to salinity status is given in fig. 4.

Salinity also affects the suitability for irrigation because the amount of water, necessary for leaching, will depend on the salt content of the soil.

Table 25 suggests some guidelines for the evaluation of the salinity status. It is emphasized that for the annual crops with a superficial root system we consider the weighted average

Table 25. Guidelines for the evaluation of the salinity status

LAND UTILIZATION TYPE	EC values (dS/m)	
	Optimal	Marginal
Low salt tolerance	< 3	4- 6
Medium salt tolerance	< 8	12-16
Tolerant crops	< 12	16-20
Irrigation - coarse-medium textures	< 16	20-30
- fine textured soils	< 8	16-22

of the upper 50 cm, while for perennial crops with a deep penetrating root system, the evaluation is made up to 1 m depth.

(2) **ALKALINITY**

The exchange sodium percentage (ESP) tremendously influences soil structure and permeability; this is particularly important in an irrigated system. This alkalinity factor has also direct effect on the yields.

The tolerance of the crops to sodium saturation is extremely variable. Deciduous fruits as avocado and nuts are extremely sensitive and show toxicity symptoms at ESP levels as low as 2-10%. Sensitive are beans; they show stunted growth at ESP values of 10-20%. Clover, oats and rice are moderately tolerant; adverse conditions appear at ESP's of 20-40%. Other crops as wheat, cotton, alfalfa, barley, tomatoes and beets are

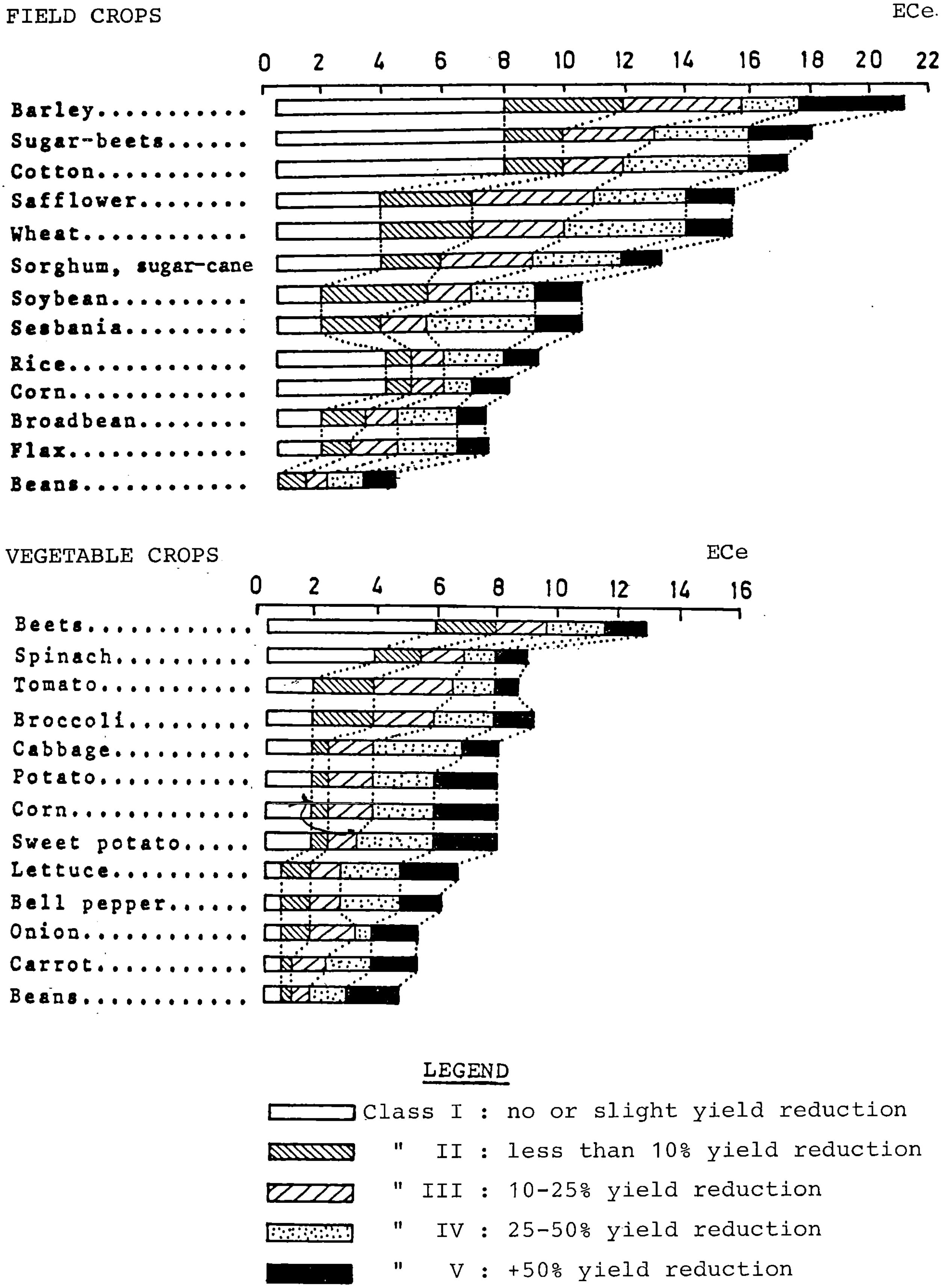


Fig. 4 *Salt tolerance of field and vegetable crops; EC in dS/m at 25°C (USDA, 1964)*

tolerant; a stunted growth is noted at ESP levels from 40-60%.

*Table 26. Influence of ESP on crop reduction (**adapted from Lunt, 1963**)*

50% CROP REDUCTION		
at ESP of 15 or less	at ESP OF 15-25	at ESP 35
maize beans chickpea avocado peach nuts citrus	sorghum pearl millet oats rice sugar cane clover groundnut lettuce	barley wheat alfalfa cotton bersim clover beets carrots tomatoes onions dates

For the evaluation of alkalinity the horizon representing the highest ESP value in the profile section 0 to 100 cm is used.

Some optimal and marginal values are suggested in table 27.

Table 27. Optimal and marginal ESP values in %.

GROUP OF CROPS OR LAND UTILIZATION TYPE	ESP values (%)	
	Optimal	Marginal
Tolerant crops	< 25	35-45
Moderately tolerant crops	< 12	20-30
Sensitive crops	< 8	10-15
Irrigation - coarse and medium textured soils	< 30	
- fine textured soils	< 15	25-35

2.5.5. INTERPRETATION OF LAND QUALITIES

2.5.5.1. Internal land qualities

Internal land qualities, or underground qualities, are mainly related to soil characteristics including soil moisture as influenced by rainfall and evapotranspiration.

(1) WATER AVAILABILITY

Water availability is an expression that refers to the amount of water available for crop growth and it could be expressed as the amount of water transpired by the crop expressed in percentage of the water that should be transpired if the soil remains at field capacity throughout the growing season.

The moisture conditions of a soil are strongly dependent on the texture (table 28). The origin of soil water is rainfall and groundwater.

Crops are affected by water availability through the effects of moisture stress on growth, and the possible death of the crop through drought.

Moisture stress occurs when soil water in the rooting zone falls substantially below field capacity. Crops vary considerably in their response to moisture stress. The moisture level at which stress effects first become apparent varies between crops. The severity of the effects of moisture stress varies according to the development stage of the crop. It may therefore be desirable to assess moisture availability during critical periods separately from that for the growing season as a whole.

Table 28. *Moisture characteristics for different textural classes (moisture contents, in vol. %)* ***(Rijtema, 1969)***

Suction (mbar or cm water) (pF) / Textural class	0	2.50	10	31	100	200	500	2,500	16,000	10^6
		0.40	1.00	1.49	2.00	2.30	2.70	3.40	4.20	6.00
Coarse sand	39.5	36.7	21.5	10.7	3.2	2.4	1.8	1.5	1.2	0.3
Medium coarse sand	36.5	35.7	33.1	27.4	9.5	6.5	5.2	3.1	1.7	0.4
Medium fine sand	35.0	33.4	32.5	30.5	15.5	8.0	6.1	4.3	2.3	0.7
Fine sand	36.4	35.6	35.2	32.8	19.6	15.0	12.9	6.5	4.2	1.2
Light loamy medium coarse sand	39.4	39.0	37.4	35.3	28.0	24.2	20.5	15.1	10.0	3.0
Loamy medium coarse sand	30.1	29.3	28.2	26.5	20.9	18.1	14.1	5.6	2.1	0.5
Loamy fine sand	43.9	43.5	39.9	30.7	17.9	14.6	11.5	8.5	6.0	0.7
Sandy loam	46.5	45.9	44.2	41.9	26.0	19.5	14.2	9.2	6.1	1.5
Loess loam	45.5	44.8	43.6	38.5	34.0	28.3	23.2	17.0	11.0	3.5
Fine sandy loam	50.4	49.9	48.8	48.2	42.3	27.3	22.4	13.2	8.7	1.7
Silt loam	50.9	50.7	49.7	48.4	46.1	33.8	27.9	13.7	9.2	2.0
Loam	50.3	49.8	48.6	48.0	42.0	29.5	24.8	16.7	9.8	2.5
Sandy clay loam	43.2	42.5	40.7	37.6	33.8	31.7	28.8	24.0	18.0	6.0
Silty clay loam	47.5	46.7	43.8	41.0	37.2	34.5	30.5	25.0	18.5	6.0
Clay loam	44.5	43.7	42.9	42.1	41.1	39.3	36.6	34.2	25.5	5.9
Light clay	45.3	45.0	43.5	40.5	36.0	34.0	31.5	27.0	21.5	7.5
Silty clay	50.7	50.0	49.2	48.2	46.3	44.7	42.2	35.2	25.7	6.5
Basin clay	54.0	53.7	53.3	52.7	51.9	49.8	47.0	40.2	32.1	11.9
Peat	86.3	85.5	83.2	81.6	76.3	70.5	64.9	35.6	26.5	9.8

Drought hazard refers to the death of the crop if soil moisture falls to wilting point for more than a certain period. The length of this period varies with the crop.

It is normally accepted that water availability is optimal when the water availability is above 80%. When water supply satisfies only 40 to 50% of the water need we may expect a marginal situation.

(2) **OXYGEN AVAILABILITY**

The evaluation of the aeration conditions of a soil depends mainly on drainage conditions and structure in the rooting zone. Structure creates pore space. Macroporosity (available oxygen) can be calculated from total porosity and water retention at field capacity (pF 2.5) expressed in volume percentage.

For sugar cane following criteria have been used for the evaluation of oxygen availability :

S1 : 0 - no limitation :
well drained and macroporosity > 25%.
1 - slight limitation :
moderately well drained and macroporosity > 20%; or well drained and macroporosity 20-25%.

S2 : 2 - moderate limitation :
imperfectly drained and macroporosity > 15%; or better drained and macroporosity 15-20%.

S3 : 3 - severe limitation :
poorly drained (aeric subgroups) and macroporosity > 10%; or better drained and macroporosity 10-15%.

N : 4 - very severe limitation :
poorly or very poorly drained and/or macroporosity < 10%.

(3) **AVAILABILITY OF FOOTHOLD FOR ROOTS**

This internal soil quality is directly related to the depth of the soil and can be evaluated according to the depth criteria.

(4) **RESISTANCE TO Fe-INDUCED CHLOROSIS AND OTHER SOIL DEFICIENCIES DUE TO LIME AND GYPSUM**

Too high Ca-levels in calcareous and/or gypsiferous soils may induce Fe-chlorosis and deficiency of some micronutrients.

For the most tolerant crops no major problems are noted with a lime content below 30% and a gypsum content of less than 10%; marginal values are 75 to 80% for lime and 25% for gypsum.

For moderately tolerant crops optimal conditions may extend to 20-25% and gypsum content of 3 to 5%, marginal values are 35-40% for lime and 10 to 15% for gypsum.

Sensitive crops should ideally have less than 10-15% lime and less than 1% gypsum.

(5) **NUTRIENTS AVAILABILITY**

Nutrients availability could be evaluated with regard to the chemical conditions in the topsoil. The supply of nutrients could be said to share with oxygen and water availability the position of one of the three most important land qualities for rainfed crop production.

In our most recent evaluations we are considering following factors :

CEC, pH, Ca, Mg, K, P, N and OC. It would be possible to regard each of the major and secondary nutrients as constituting a separate land quality (N availability, P availability, etc.). This possibility was rejected by FAO, first because of the similarity in the principles by which each is treated, and secondly because through the operation of the law of the minimum it is frequently only one or two nutrients that are limiting to the crop.

Table 29 illustrates the fertility requirements for some typical tropical crops.

(6) RESISTANCE TO STRUCTURAL DEGRADATION OF THE TOPSOIL

Physical degradation of the soil surface comprises various processes, known as slaking, sealing or crusting. High intensities of rainfall increase physical degradation hazard. Soils with high contents of silt or sand are particularly prone. The presence of organic matter or free $CaCO_3$ decreases the tendency towards degradation, whilst the presence of exchangeable sodium increases it.

Physical degradation can be measured by monitoring changes in bulk density, permeability and infiltration capacity. Surface crusting can readily be observed in the field.

Structural degradation is difficult to apply to land evaluations in the same manner as other land qualities, but at the same time it is a widespread and potentially serious hazard.

Table 29. Nutrient availability requirements of some crops

CROP	FERTILITY FACTORS (0-15 cm)	LANDCLASS AND DEGREE OF LIMITATION				
		S1		S2	S3	N
		0	1	2	3	4
Maize	pH	5.8-6.5	5.5-5.8	5.2-5.5	<5.2	-
			6.5-7.0	7.0-8.2	>8.2	
	OC	>2	1.5-2	0.7-1.5	0.5-0.7	<0.5
	CEC	>10	8-10	6-8	3-6	<3
	Ca	>6	3.8-6	2.6-3.8	1.0-3.8	<1.0
	Mg	>1.4	0.9-1.4	0.6-0.9	0.3-0.6	<0.3
	K	>0.5	0.3-0.5	0.2-0.3	0.1-0.2	<0.1
Oil palm	pH	5.5-6	4.5-5.5	3.5-4.5	<3.5	
			6.0-6.5	6.5-7.5	>7.5	
	OC	>2	1-2	<1		
	CEC	>10	8-10	6-8	<6	
	Ca	>2.6	1.5-2.6	<1.5		
	Mg	>0.6	0.4-0.6	<0.4		
	K	>0.2	0.1-0.2	<0.1		
Robusta coffee	pH	5.5-5.8	5.3-5.5	4.5-5.3	<4.5	
			5.8-6.0	6.0-6.5	>6.5	
	OC	>2	1-2	<1		
	CEC	>10	8-10	6-8	<6	
	Ca	>6	3.8-6	2.6-3.8	<2.6	
	Mg	>1.4	0.9-1.4	0.6-0.9	<0.6	
	K	>0.5	0.3-0.5	0.2-0.3	<0.2	
Rubber	pH	5.3-5.5	5.0-5.3	4.0-5.0	<4.0	
			5.5-6.0	6.0-6.5	>6.5	
	OC	>2	1-2	<1		
	CEC	>10	6-10	<6		
	Ca	2.7-3.5	<2.7	3.5-4.5	> 4.5	
	Mg	0.6-0.7	<0.6	0.7-0.9	> 0.9	
	K	>0.2	<0.2			

Empirical indices can be derived to measure the hazard of physical degradation. An example is the **Index of crusting (FAO, 1979)** at the soil surface :

$$\text{Index of crusting} = \frac{15\ Zf + 0.75\ Zc}{C + (10 \times O.M.)}$$

Where **Zf** = fine silt % (2-20 µm)
Zc = coarse silt % (20-50 µm)
C = clay %
OM = organic matter %

Such empirical indices should be checked and calibrated according to the situation where the evaluation is carried out. They may need to be modified to suit local conditions.

(7) ABSENCE OF SALINITY AND ALKALINITY

Two hazards may arise through accumulation of salts : salinity or excess of free salts, and sodicity or saturation of the exchange complex with sodium ions (also called sodium alkalinity).

Salinity affects crops through inhibiting the uptake of water by osmosis. Moderate salinity levels retard growth and reduce yields, whilst high levels kill crops and may cause areas to be barren of plants.

Sodicity has two distinct effects on crops : firstly through direct toxicity of the sodium ion and secondly by giving rise to massive or coarse columnar soil structure and low permeability. This second effect is much worse if a high exchangeable sodium percentage is combined with a low level of soluble salts.

Salinity and sodicity may be assessed using one or more of the following parameters, measured on samples from the relevant crop rooting depths :

Salinity : Electrical conductivity of the saturation extract (formerly mmho/cm, in SI units, dS/m).
Total soluble salts (ppm).
Sodicity : Exchangeable sodium percentage (ESP, %).
Sodium absorption ratio (SAR).

2.5.5.2. **External land qualities**

External land qualities are land qualities only related to environmental conditions operating at the earth surface.

(1) **CORRECT TEMPERATURE REGIME**

There are three main effects of temperature upon plant growth:
- growth ceases below a critical temperature, varying with the plant, but typically 6.5°C;
- the rate of growth varies with temperature;
- very high temperature have adverse effects.

Between the minimum temperature for growth and the optimum temperature for photosynthesis, the rate of growth rises more or less linearly with temperature; growth rate then reaches a plateau within the optimum temperature range before falling off at higher temperatures. The relationship interacts with radiation; that is, the highest potential for growth is achieved with temperature in the optimal range and high amounts of radiation.

For assessment by means of individual land characteristics, appropriate diagnostic factors are mean monthly temperatures during the growing season, day-degrees during the growing season, temperatures for the coldest and hottest months during the growing season,or similar values for soil temperatures. For mean monthly temperatures, 24-hour means are slightly preferable but averages of daily maxima and minima are more widely available and the differences are small.

For every crop, one should select the temperature factors to be considered and define at what level they are optimal, marginal and unsuitable.

(2) **RESISTANCE AGAINST EROSION**

All evaluations should take account of erosion hazard. In more humid areas, approximately above an annual rainfall of 700 mm in the tropics, it may not be necessary to consider wind erosion. The converse is not the case; water erosion hazard can be severe in the semi-arid zone.

Assessment of erosion hazard involves two aspects :

- the susceptibility of land to erosion;
- the resulting loss in productivity of the land affected.

The most satisfactory methods of erosion hazard assessment are based on predicted soil losses by modelling the determinants of climate, soil erodibility, slope and vegetation factors.

(3) **ABILITY FOR LAY-OUT OF FARM PLAN**

This quality mainly depends on land-form, surface of plateaus, intensity of slope and related topographic factors.

(4) WORKABILITY

The workability of the land depends mainly on texture, structure, drainage conditions and surface stoniness.

GENERAL CONCLUSION : we can conclude that evaluation based on land qualities is still in the initial stage of the experimental phase. It remains difficult, due to lack of experience, to set up crop requirements in terms of land qualities. Future research is needed to set up these criteria for the specific land utilization types.

3. CROP PRODUCTION

3.1. Introduction

In this chapter a synopsis is presented of selected methods and techniques that permit to anticipate potential irrigated and rainfed yields of annual crops and that enable the calculation of the crop water demand for rainfed and irrigated cropping.

Estimated yields and irrigation requirements form an important source of information to obtain a gradually more quantitative land evaluation i.e. a land evaluation in economical terms.

Although all of the calculations can be done by hand, attention was paid to structure the matter to facilitate programming. Reference is made to computer programs that are presently available.

3.2. Climatic data

3.2.1. MINIMUM CLIMATIC DATA SET

In order to be able to process climatic data according to the procedures given in the following sections, a minimum climatic data set is required. The elements of the minimum set are given in table 30, illustrated with the data of the station of Garoua that is located in the north of Cameroon.

Table 30. Required minimum climatic data set

Station name: Garoua (Cameroon)
Latitude: 9°20'N
Longitude: 13°23'E
Elevation: 244 (m above mean sea level)
Anemometer hight: 2 (m above ground surface)

Month	n	tmax	tmin	RH	U	R	RD
JAN	9.07	35.0	18.0	24.9	1.6	0	0
FEB	9.57	37.2	21.1	21.2	2.0	1	1
MAR	8.46	39.5	24.5	26.5	2.6	5	1
APR	7.89	38.5	26.0	40.9	3.0	38	2
MAY	8.16	36.0	24.5	59.0	2.9	122	4
JUN	7.60	32.1	22.1	74.2	2.7	155	10
JUL	6.18	30.5	22.0	77.5	2.6	178	8
AUG	5.47	30.0	21.7	79.1	2.5	224	15
SEP	6.46	30.7	21.5	79.1	2.1	214	10
OCT	8.83	33.5	21.7	68.4	2.2	75	2
NOV	9.60	36.0	19.7	45.1	2.1	1	1
DEC	9.62	35.3	17.7	24.9	1.8	1	1

n : mean daily sunshine hours [hr]
tmax : mean monthly maximum air temperature [°C]
tmin : mean monthly minimum air temperature [°C]
RH : mean monthly relative air humidity [%]
U : mean 24hr wind velocity [m/s]
R : total monthly rainfall [mm]
RD : number of rain days [ ]

3.2.2. INTERPOLATION OF CLIMATIC PARAMETERS

3.2.2.1. Interpolation of decade data from monthly data

Most of the published climatic data (normals) refer to monthly periods. In the calculation procedures, outlined in the following chapters, often decade data are required. Since climatic parameters, averaged over long time periods, assume the shape of smooth curves when plotted against time, an interpolation from monthly data is justified. Such interpolated decade data reflect average conditions. They can never replace observed decade data that account for the variability of the weather variables within the month.

Gommes (1983) presents an algorithm that can be used to obtain decade data from monthly data. A difference is made between climatic parameters that constitute a sum (rainfall, evapotranspiration, sunshine hours) and parameters that are arithmetic mean values (temperature, windspeed). In this section only the final equations are presented.

The normal value of a parameter in three consecutive months is represented by M1, M2 and M3. The normal value of the parameter in three consecutive decades of the second (or middle) month is represented by D1, D2 and D3. Assuming that a month takes 30 days, and a decade takes 10 days, the normal decade values for the middle month are obtained as follows :

(1) Interpolation for rainfall, evapotranspiration and alike

D1 = (5 M1 + 26 M2 - 4 M3)/81
D2 = (- M1 + 29 M2 - M3)/81
D3 = (-4 M1 + 26 M2 + 5 M3)/81

(2) Interpolation for temperature, windspeed and alike

D1 = (5 M1 + 26 M2 - 4 M3)/27
D2 = (- M1 + 29 M2 - M3)/27
D3 = (-4 M1 + 26 M2 + 5 M3)/27

EXAMPLE

Data

At Garoua, the values of monthly rainfall (R) and maximum temperature (tmax) in the months of March, April and May are as follows :

Month	R[mm]	tmax [°C]
MAR	5	39.5
APR	38	38.5
MAY	122	36.0

Determination

(1) Rainfall values

The decade values of rainfall for the middle month (April) are calculated according to the above formula. D1, D2 and D3 are replaced by R Apr1, R Apr2, R Apr3, indicating the rainfall in the first, second and third decade of the month of April. M1, M2 and M3 are replaced by the values 5, 38 and 122.

R Apr1 =[(5)(5) + (26)(38) - (4)(122)]/81 = 6.48 mm
R Apr2 =[-(5) + (29)(38) - (122)]/81 = 12.04 mm
R Apr3 =[-(4)(5) + (26)(38) + (5)(122)]/81 = 19.48 mm

Remark that the sum of the decade rainfall in April (6.48 + 12.04 + 19.48) mm is equal to the total monthly rainfall, 38 mm.

(2) Temperature values

The decade maximum temperatures of the middle month (April) are calculated according to the equations for arithmetic mean values. M1, M2 and M3 are replaced by 39.5, 38.5, and 36 respectively. D1, D2 and D3 correspond to Tx Apr1, Tx Apr2 and Tx Apr3, the maximum air temperatures for the first, second and third decade of April.

$$Tx\ Apr1 = [(5)(39.5) + (26)(38.5) - (4)(36)]/27 = 39.06°C$$
$$Tx\ Apr2 = [-(39.5) + (29)(38.5) - (36)]/27 = 38.56°C$$
$$Tx\ Apr3 = [-(4)(39.5) + (26)(38.5) + (5)(36)]/27 = 37.89°C$$

Remark that the mean value of the decade maximum air temperatures (39.06 + 38.56 + 37.89)/3°C equals 38.5°C, the monthly maximum air temperature.

3.2.2.2. **Average daytime and nighttime temperatures**

The knowledge of average daytime and nighttime temperatures is important in understanding crop behaviour in general and in the biomass calculation procedure in particular. The daytime temperature determines the rate of photosynthesis, whilst respiration takes place during both day and night. White potato, for example, is not sucessful when grown in lowland areas in the tropics (high daytime and nighttime temperatures). The crop will produce abundant foliage but no tubers, because the assimilates accumulated during the day are lost through (high) respiration overnight instead of being stored as starch. Oranges usually remain green when the nighttime temperature is higher than 14°C and when the relative air humidity is high. Cotton requires nighttime temperatures above 16°C in order to produce long fibres (**Gommes, 1983**).

A method is presented to calculate the daytime and nighttime temperatures from maximum and minimum temperatures. It is assumed that the temperature changes smoothly following a cosinus function, as illustrated in figure 5.

The following is the outcome of the method by Petricevic, cited by **Gommes** (**1983**) :

$$td = \frac{(tmax + tmin)}{2} + \frac{(tmax - tmin)}{4\pi} \frac{(11 + TS)}{(12 - TS)} \cos \alpha$$

$$tn = \frac{(tmax + tmin)}{2} - \frac{(tmax - tmin)}{4\pi} \frac{(11 + TS)}{TS} \cos \alpha$$

$$\alpha = \frac{(11 - TS)}{(11 + TS)} \pi$$

with td = average daytime temperature [°C]

tn = average nighttime temperature [°C]

tmax = daily maximum temperature [°C]

tmin = daily minimum temperature [°C]

TS = time of sunrise = (12-N/2)

π = 3.1416

Since $\cos\alpha \approx 1$, and the time of sunrise can be expressed in terms of the daylenght (N), determined as a function of the latitude and the time of the year, the above expressions for td and tn can be transformed as follows :

$$td = \frac{(tmax + tmin)}{2} + \frac{(tmax - tmin)}{4\pi} \frac{(46 - N)}{N}$$

$$tn = \frac{(tmax + tmin)}{2} - \frac{(tmax - tmin)}{4\pi} \frac{(46 - N)}{(24 - N)}$$

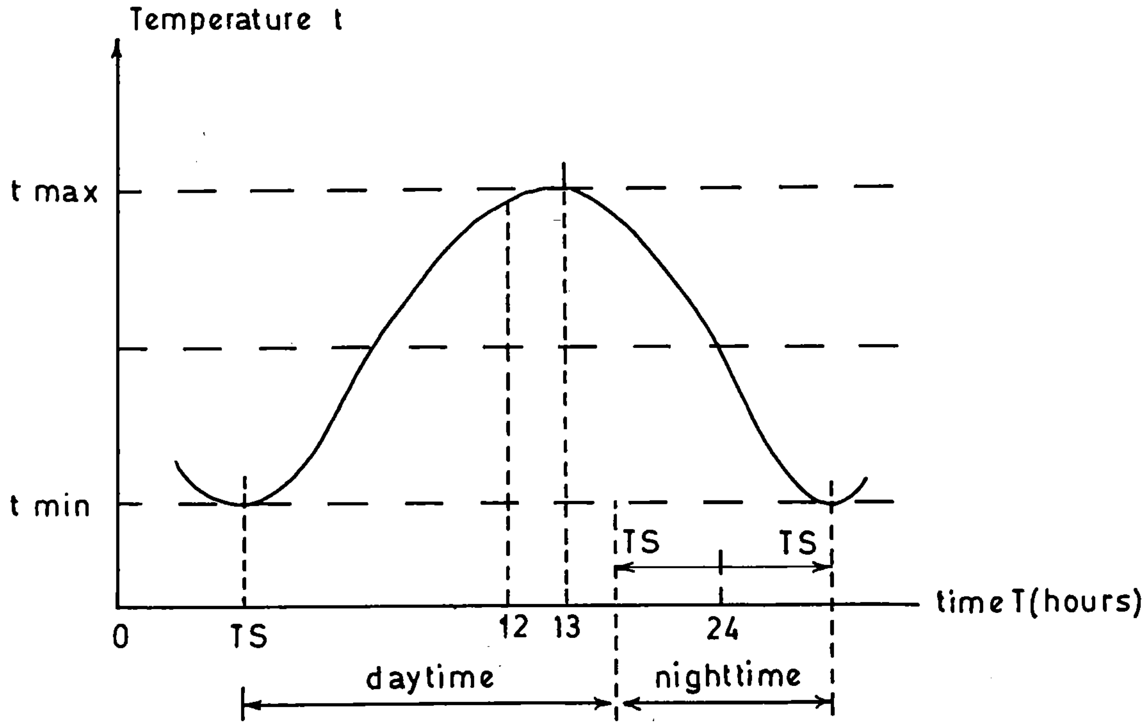


Fig. 5 *Diurnal variation of temperature according to 2 sine-waves : from minimum temperature (tmin) at the time of sunrise (TS) to maximum temperature (tmax) at time T, and from T to sunrise. The night is symmetrical around midnight (T = 0 or T = 24) and the daylength is 24 - 2 TS (**Gommes, 1983**).*

with td = average daytime temperature [°C]
tn = average nighttime temperature [°C]
tmax = daily maximum temperature [°C]
tmin = daily minimum temperature [°C]
N = daylength [hours and decimal hours], table 33
π = 3.1416

In special conditions the calculation of td and tn can be simplified to :

$$td = \frac{(tmax + tmin)}{2} + \frac{(tmax - tmin)}{\pi}$$

$$tn = \frac{(tmax + tmin)}{2} - \frac{(tmax - tmin)}{\pi}$$

In these formula equal weight has been attributed to both day and night. This means that the lenght of both day and night is set equal to 12 hours. Since this condition, throughout the year, is only valid near the equator, the use of these formula should be restricted to equatorial areas only.

EXAMPLE

Data

Station name	: Garoua (Cameroon)
Latitude	: 9° 20' N
Month	: January
tmax	: 35°C
tmin	: 18°C

Determination

The average day (td) and night (tn) temperature are calculated as follows :

N	table 33	11.63 hrs
(tmax+tmin)/2	(35+18)/2	26.5
(tmax-tmin)/4π	(35-18)/(4)(3.1416)	1.3528
(46-N)/N	(46-11.63)/11.63	2.955
(46-N)/(24-N)	(46-11.63)/(24-11.63)	2.7785
td	(26.5+(1.3528)(2.955))	30.49°C
tn	(26.5-(1.3528)(2.779))	22.74°C

The results of the simpler calculation procedure are

$(tmax-tmin)/\pi$	(35-18)/3.1416	5.41
td	(26.5+5.41)	31.91°C
tn	(26.5-5.41)	21.09°C

3.3. Irrigated crop production

3.3.1. PHOTOSYNTHETIC ADAPTABILITY OF CROPS

The photosynthesis process provides plants with assimilates that can be used for growth. The rate of photosynthesis depends on the photosynthesis pathway and its response to temperature and radiation. The two major photosynthetic pathways are the C3 pathway and the C4 pathway. Subdivisions in each of these lead to the distinction between five groups of crop species with similar assimilation pathways and similar photosynthetic ability (FAO, 1981).

3.3.1.1. Crops that follow the C3 pathway

The first produce of photosynthesis in this pathway is a 3-carbon (or C3) organic acid (3-phosphoglyceric acid). The process operates at optimum rates under conditions of low temperature (15-20°C). The rate of CO_2-exchange is relatively low at a given radiation level. The maximum rate of photosynthesis is in the range of some 15-30 mg CO_2/dm^2.hr with light saturation at 0.2- 0.6 cal/cm^2.min. Through breeding and selection, the temperature response of photosynthesis of some C3 species has been modified and is optimal at temperatures of 25-30°C. Hence, we can distinguish between :

Group I : C3 species with optimum photosynthesis at 15-20°C (wheat, white potato, phaseolus bean (temperate and tropical high altitude cultivars)).

Group II : C3 species with optimum photosynthesis at 25-30°C (phaseolus bean (tropical cvs.), soybean, rice, cotton, sweet potato).

3.3.1.2. **Crops that follow the C4 pathway**

The first products of photosynthesis are 4-carbon (or C4) organic acids (malate and asparate). The process operates at optimum rates under conditions of high temperature (30-35°C). The rate of CO_2 exchange is relatively high. The maximum rate of photosynthesis is in the range of 70-100 mg CO_2/dm^2.hr with light saturation at 1-1.4 cal/cm^2.min. Breeding and selection has modified the temperature response of photosynthesis such that in some species or cultivars the process operates optimaly at temperatures of 20-30°C. In C4 crops, equally two groups can be discerned :

Group III : C4 species with optimum photosynthesis at 30-35°C (sorghum and maize (tropical cvs.), pearl millet, sugar-cane).

Group IV : C4 species with optimum photosynthesis at 20-30°C (sorghum and maize (temperate and tropical high altitude cvs.)).

3.3.1.3. **Crops that follow the CAM-pathway**

One more group of species has evolved and adapted to operate under xerophytic conditions. These species follow a CAM pathway. CAM stands for crassulacean acid metabolism. The biochemistry of photosynthesis follows closely the one of C4 species but equally shows distinct features such as light capturing during the day-time and CO_2-assimilation during the nighttime with consequentely high water use efficiencies.

Group V : CAM species (sisal, pineapple).

3.3.1.4. **Comparison of crop groups with different adaptability**

The main differences between the first four groups of crop species are illustrated in figures 6 and 7. Figure 6 shows the relationship between the leaf photosynthesis rate (P) at optimum temperature and the photosynthetically active radiation (PAR) for the different crop groups. It shows that for a given value of PAR the photosynthesis rate increases from group I, over group II to group III and IV. Figure 6 equally demonstrates that with increasing PAR, crops of groups III and IV take more advantage of the light input than crops of groups II and I : the latter already reach light saturation (no more increase in photosynthesis rate for an increase in PAR) at respectively 0.4 and 0.2 $cal/cm^2.min$. From this it may be concluded that crops of groups III and IV have a higher production potential than crops of groups II and I, especially in areas with high insolation (and PAR).
Figure 7 illustrates the evolution of the maximum leaf photosynthesis rate (Pm) with (daytime) temperature for crop groups I to IV. This graph permits to determine the suitability of the crop groups in a given area as a function of the average daytime temperature in the crop cycle. In table 31 the suitability of the crop groups is given for daytime air temperature steps of 5°C.

Figure 7 equally permits to determine the Pm value that coincides with the average daytime temperature in the crop cycle for a crop of a chosen crop group. The knowledge of the value of Pm is required in the biomass and yield calculations.

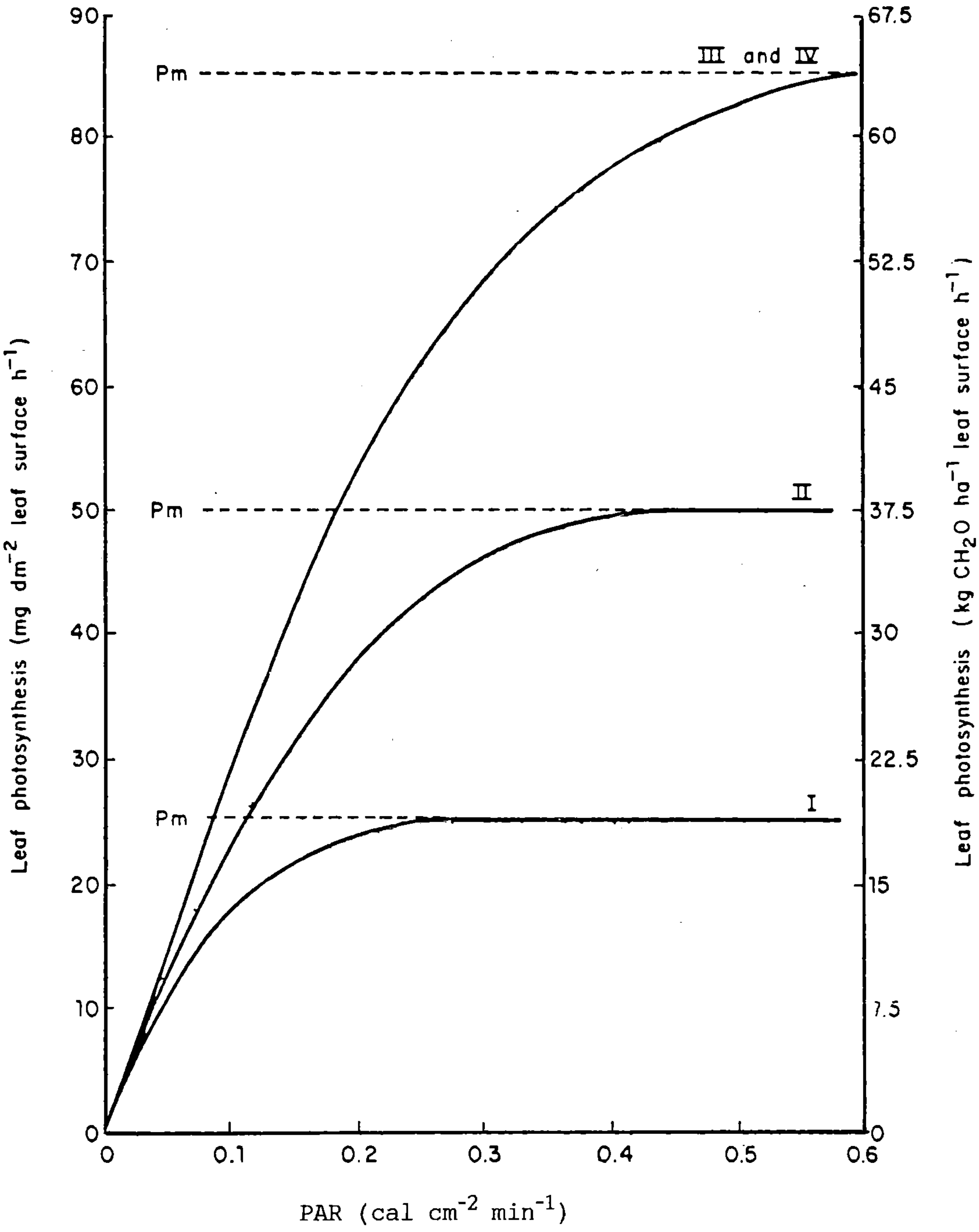


Fig. 6 *Relationship between leaf photosynthesis rate (P1) at optimum temperature and photosynthetically active radiation (PAR) for crop Groups I, II, III and IV. Pm is the maximum leaf photosynthesis rate at light saturation (**FAO, 1981**).*

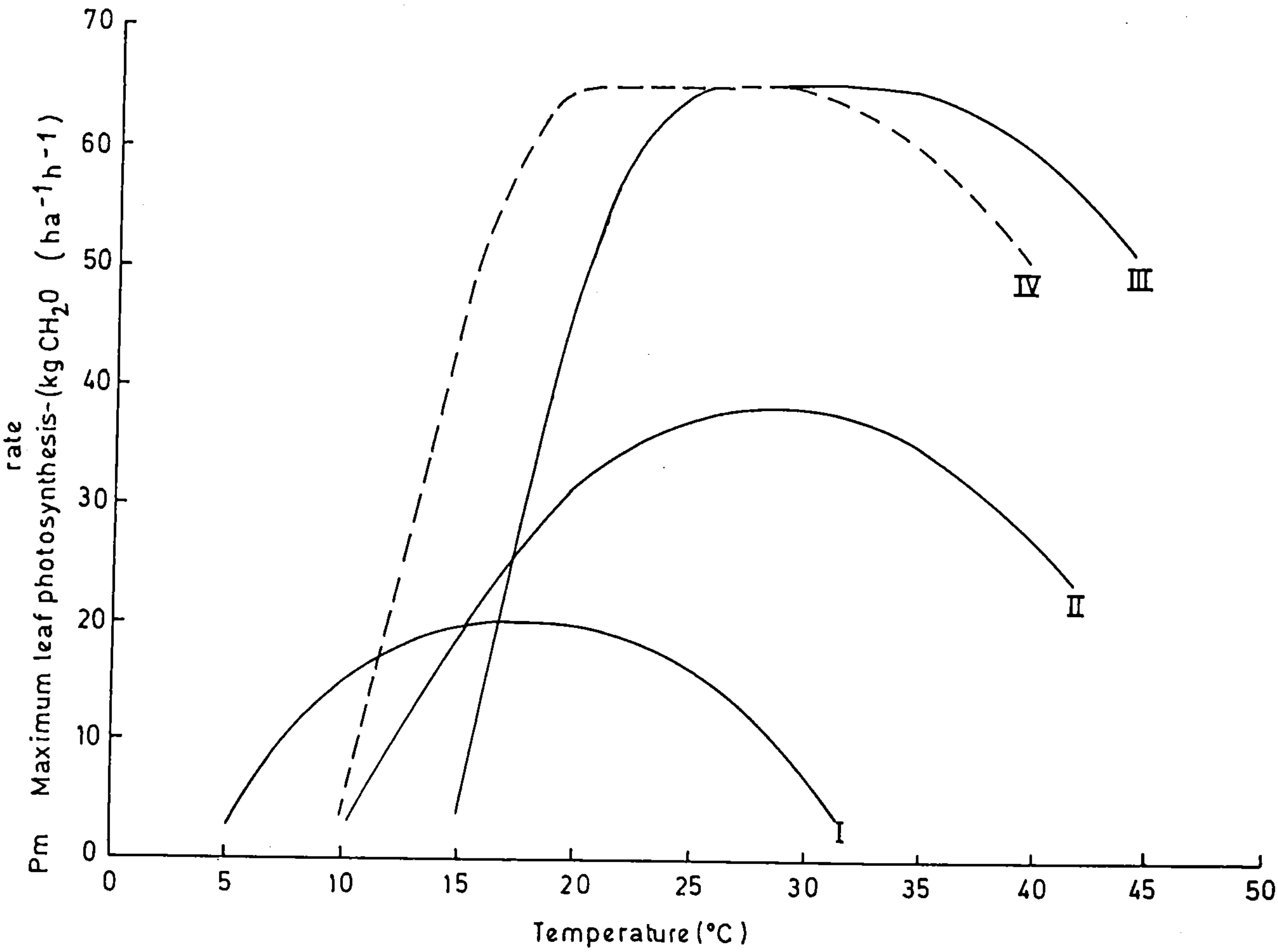


Fig. 7 *Average relationship between maximum leaf photosynthesis rate (Pm) and day-time temperature for crop groups I, II, III and IV (**FAO, 1981**).*

Table 31. Suitability of the crop groups for different daytime air temperatures (td) in the crop cycle.

td [C]	Suitability of crop groups		
	suitable	marginally suitable	unsuitable
10	-	I	II,III,IV
15	I	II	III,IV
20	I,IV	II	
25	II,III,IV	I	-
30	II,III,IV	-	I
35	III	II,IV	I

EXAMPLE

Data

Assume that the growing period in Garoua starts on May 1st, and that crop growing during 4 months (120 days) is considered.

Station name : Garoua
Latitude : 9° 20' N
Temperature data :

	May	June	July	August
tmax [°C]	36.0	32.1	30.5	30.0
tmin [°C]	24.5	22.1	22.0	21.7
tmean [°C]	30.25	27.1	26.25	25.85
td [°C]	32.7	29.2	28.0	27.6

Determination

The average daytime temperature over the 4 months of cropping is equal to (32.7+29.2+28.0+27.6)/4=29.4°C. From figure 7 the Pm value for 29.4°C and for different crop groups is determined :

Crop group	Pm [kg CH_2O/ha.hr]	Condition for photosynthesis
I	<10	unfavourable
II	37.5	optimal
III	65	optimal
IV	65	optimal

In conclusion, crops of groups II, III and IV can, in Garoua, be grown in optimal conditons with regard to temperature and photosynthesis rate. Crops of group I are excluded because the maximum leaf photosynthesis rate is too low at the temperature during the months considered for crop growing.

3.3.2. CROP GROWTH MODELS

Two crop growth models are considered in this section. The first model is the one by **de Wit (1965)**, adopted by **FAO (1979)** in the Agro-ecological Zones Project (FAO-model). The assumptions in this model permit simplifications in the calculation procedure such that biomass and yield estimations for a large number of annual crops are within reach of hand calculation. The second model by **de Wit, van Heemst and Van Keulen (1983)**, developed in Wageningen (Wageningen-model), is presented here as an alternative calculation procedure. The method is more detailed and provides a clear insight in the processes of growth and development. Both models are applicable at regional level using decade input data.

Much more crop growth models have been developed in recent years, e.g. the soybean model SOYGRO V5.41 (**Jones et al., 1988**), the CERES models for maize (**Jones and Kiniry, 1986**), for wheat and other annual crops. Many of these simulation models are crop specific. They require a more or less detailed data input (daily, pentade, weekly, decade data) depending on the scale at which they can be applied (farm level, regional scale, continental scale).

3.3.2.1. FAO-model

This model permits to estimate, from radiation and temperature data, the net biomass production and yield of a high-yielding crop variety, cultivar or clone that is optimally supplied with water and nutrients grown in the absence of pests and diseases.

(1) Net biomass production

The net biomass production is obtained from the difference between the gross biomass production and the respiration losses.

$$Bn = Bg - R$$

with Bn = net biomass production [kg CH_2O/ha]
Bg = gross biomass production [kg CH_2O/ha]
R = respiration [kg CH_2O/ha]

The above equation can equally be written in terms of the rate of the biomass production process :

$$bn = bg - r$$

with bn = net biomass production rate [kg CH_2O/ha.hr]

bg = gross biomass production rate [kg CH_2O/ha. hr]
r = respiration rate [kg CH_2O/ha.hr]

and in terms of the maximum rate of the process :

bnm = bgm - rm

with bnm = maximum net biomass production rate [kg CH_2O/ha.hr]
bgm = maximum gross biomass production rate [kg CH_2O/ha.hr]
rm = maximum respiration rate [kg CH_2O/ha.hr]

(2) **Assumptions**

A first assumption in the model is that the accumulated net biomass (Bn) follows a perfect sigmoid curve, as shown in figure 8, so that the accumulated net biomass, at the time that the net biomass production rate is maximum (bn=bnm), equals half of the total accumulated net biomass.

Bm = 0.5 Bn if bn = bnm

A second assumption states that the average net biomass production rate equals half of the maximum net biomass production rate. This relationship is shown in figure 9.

bna = 0.5 bnm

with bna = average net biomass production rate [kg CH_2O/ha.hr]
bnm = maximum net biomass production rate [kg CH_2O/ha.hr]

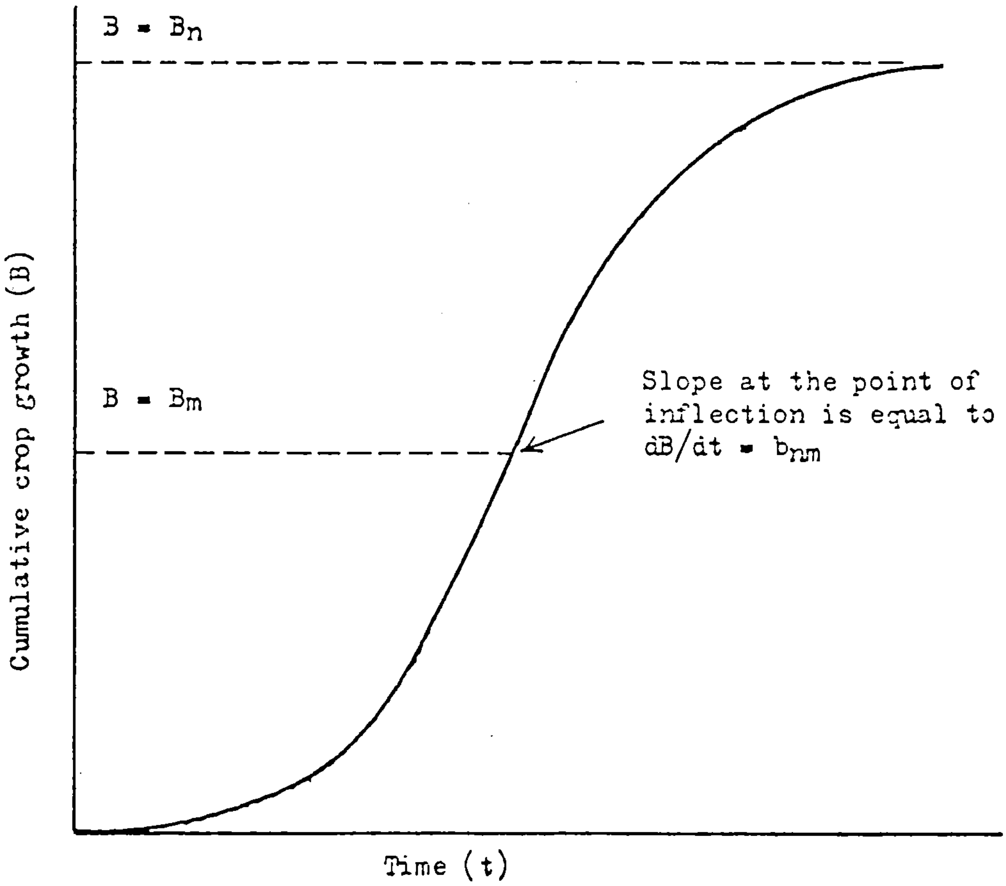


Fig. 8 *Typical cumulative crop growth curve showing the point of inflection during the period of maximum growth when the slope dB/dt is equivalent to the maximum rate of net biomass production (bnm) (**FAO, 1981**).*

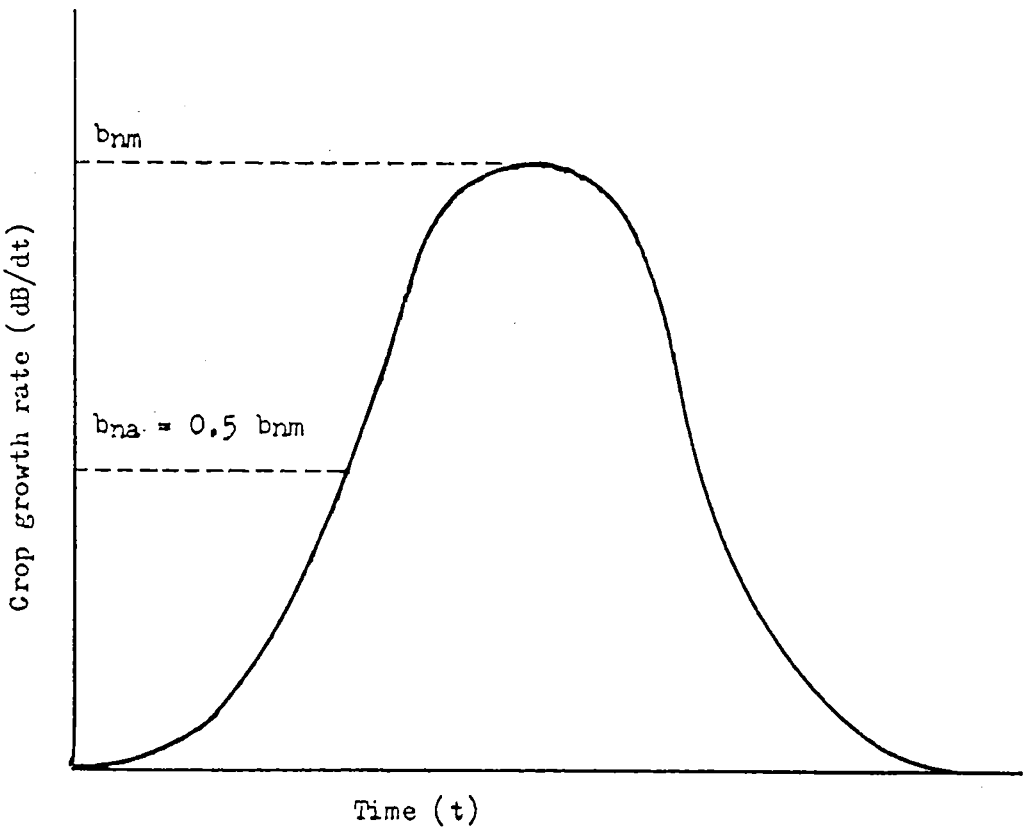


Fig. 9 *The normal shape of the curve of crop growth rate plotted against time showing average crop growth rate (bna) = 0.5 bnm (**FAO, 1981**).*

A third assumption is that the total accumulated net biomass (Bn) can be calculated from the product of the average net biomass production rate (bna) and the number of days that the crop takes to reach maturity (L).

$$Bn = bna.L$$

(3) **Respiration**

The total respiration consists of two components : growth respiration (to keep the photosynthesis process going) and maintenance respiration (to maintain the accumulated biomass in good shape). **McCree (1974)** proved that the growth respiration is proportional to the gross biomass production rate, whilst the maintenance respiration is proportional to the net biomass already accumulated. The expression for r at maximum photosynthesis rate is as follows :

$$rm = 0.28\ bgm + ct.Bm$$

where rm = maximum respiration rate [kg CH_2O/ha.hr]
bgm = maximum gross biomass production rate [kg CH_2O/ha.hr]
ct = respiration coefficient
Bm = net biomass accumulated at the time bn=bnm [kg CH_2O/ha]

The respiration coefficient depends on both the mean daily temperature (since respiration is taking place during day and nighttime) and the kind of yield component. If yield production involves the production and maintenance of sugar or starch, (non-legumes) respiration will be lower than if the more complex production and maintenance of proteins is involved (legumes).

The expression for the respiration coefficient is :

$$ct = c30(0.044 + 0.0019\ t + 0.001\ t^2)$$

where t = mean daily temperature [°C]

$c30$ = 0.0108 for non-legumes

$c30$ = 0.0283 for legumes

(4) **Total net biomass production**

The combination through substitution of the above equations leads to an expression for the total accumulated net biomass production.

The basic equation for Bm is

$$Bm = 0.5\ Bn$$

After substitution of Bn = bna.L and bna = 0.5(bnm),

$$Bm = 0.25\ bnm\ L$$

Substitution in the equation for rm :

$$rm = 0.28\ bgm + ct\ Bm$$

yields

$$rm = 0.28\ bgm + ct\ 0.25\ bnm\ L$$

Another expression for rm is

$$rm = bgm - bnm$$

Both expressions in rm give the following equation :

$$bgm - bnm = 0.28\ bgm + ct\ 0.25\ bnm\ L$$

$$(1 - 0.28)\ bgm = (1 + ct\ 0.25\ L)\ bnm$$

$$bnm = 0.72\ bgm\ /(1 + 0.25\ ct\ L)$$

Substitution of the expression for bnm in the following equation

$$Bn = 0.5\ bnm\ L$$

yields

$$Bn = 0.5\ (0.72)\ bgm\ L\ /(1 + 0.25\ ct\ L)$$

$$Bn = 0.36\ bgm\ /\ ((1/L) + 0.25\ ct)$$

This formula is valid for conditions where the leaf area index (LAI), i.e. the area of green leaves per unit area of ground surface (m^2/m^2) at the time of maximum gross biomass production is equal to 5 m^2/m^2.

According to this final equation, the total accumulated net biomass is a function of the maximum gross biomass production rate.

(5) **The maximum gross biomass production rate**

The maximum gross biomass production rate can be calculated from the following formula :

$$bgm = f.\ bo + (1-f).bc$$

where bo = maximum gross biomass production on overcast days
bc = maximum gross biomass production on clear days
f = fraction of the daytime that the sky is overcast
(1-f) = fraction of the daytime that the sky is clear

The value of f can be obtained from data of total short-wave global radiation (Rg) and of photosynthetically active radiation (PAR) on a perfectly clear day (Ac).

The amount of PAR on perfectly clear days (Ac) in cal/cm².day at different latitudes has been calculated by **de Wit (1965)** and is given in table 32. The total short-wave global radiation, Rg, is a measured value expressed in cal/cm².day.

Assuming that PAR on a totally overcast day is 0.2 Ac, and that the real PAR equals 0.5 Rg, the expression for f is as follows :

$$f = (Ac - 0.5\ Rg)/(Ac - 0.2\ Ac)$$

The value of f can equally be approximated by the following expression :

$$f = (1 - (n/N))$$

where n = actual hours of bright sunshine
N = astronomically possible hours of bright sunshine, or daylength (table 33)

Goudriaan and van Laar (1978) and **de Wit (1965)** give values for bo and bc as a function of the latitude and middle of the months in the year. These values are valid for a maximum rate of photosynthesis (or CO_2 exchange) at light saturation (Pm) of 20 kg CH_2O/ha.hr and are presented in table 32.

Table 32. *The photosynthetically active radiation on very clear days (Ac) in cal cm^{-2} day^{-1} and the daily gross photosynthesis rate of crop canopies on very clear (bc) and overcast (bo) days in kg $ha^{-1} day^{-1}$ for Pm = 20 kg CH_2O ha^{-1} H^{-1} (from* ***De Wit****)*

North Lat.		15 Jan.	15 Feb.	15 Mar.	15 Apr.	15 May	15 Jun.	15 Jul.	15 Aug.	15 Sep.	15 Oct.	15 Nov.	15 Dec.
0°	A_o	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_o	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

Table 33. Daily average month by month of the astronomically possible sunshine duration in hours and tenths

Northern Lats / Southern Lats	Jan / July	Feb / Aug	Mar / Sept	Apr / Oct	May / Nov	June / Dec	July / Jan	Aug / Feb	Sept / Mar	Oct / Apr	Nov / May	Dec / June
50°	8.5	10.1	11.8	13.8	15.4	16.3	15.9	14.5	12.7	10.8	9.1	8.1
48	8.8	10.2	11.8	13.6	15.2	16.0	15.6	14.3	12.6	10.9	9.3	8.3
46	9.1	10.4	11.9	13.5	14.9	15.7	15.4	14.2	12.6	10.9	9.5	8.7
44	9.3	10.5	11.9	13.4	14.7	15.4	15.2	14.0	12.6	11.0	9.7	8.9
42	9.4	10.6	11.9	13.4	14.6	15.2	14.9	13.9	12.6	11.1	9.8	9.1
40	9.6	10.7	11.9	13.3	14.4	15.0	14.7	13.7	12.5	11.2	10.0	9.3
35	10.1	11.0	11.9	13.1	14.0	14.5	14.3	13.5	12.4	11.3	10.3	9.8
30	10.4	11.1	12.0	12.9	13.6	14.0	13.9	13.2	12.4	11.5	10.6	10.2
25	10.7	11.3	12.0	12.7	13.3	13.7	13.5	13.0	12.3	11.6	10.9	10.6
20	11.0	11.5	12.0	12.6	13.1	13.3	13.2	12.8	12.3	11.7	11.2	10.9
15	11.3	11.6	12.0	12.5	12.8	13.0	12.9	12.6	12.2	11.8	11.4	11.2
10	11.6	11.8	12.0	12.3	12.6	12.7	12.6	12.4	12.1	11.8	11.6	11.5
5	11.8	11.9	12.0	12.2	12.3	12.4	12.3	12.3	12.1	12.0	11.9	11.8
0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0

The maximum rate of CO_2 exchange (Pm) depends on both the day temperature and the photosynthesis pathway of the crop (fig. 7). If the value of Pm shows (y) percent increase relative to the value of Pm=20 kg CH_2O/ha.hr, then an increase of (0.2 y) percent and of (0.5 y) percent in bo and bc is observed respectively. Inversely, (y) percent decrease of Pm relative to Pm=20 kg CH_2O/ha.hr leads to (2.5 y) percent and (y) percent decrease in bo and bc respectively.

If Pm differs from the standard value, then

$$y = [(Pm-20)/20]100 = (Pm-20)5$$

The formula for bgm, if Pm>20 kg CH2O/ha.hr is then

$$bgm = f.bo.(1+0.002\ y) + (1-f).bc.(1+0.005\ y)$$

The formula for bgm, if Pm<20 kg CH_2O/ha.hr is then

$$bgm = f.bo.(1-0.025\ y) + (1-f).bc.(1-0.01\ y)$$

(6) **The Leaf Area Index**

At a given Pm value, the magnitude of bgm is determined by the LAI. Assuming that the effect of variation of leaf age with depth in the crop canopy on the photosynthesis rate is negligible, **FAO (1979)** adopted a relationship between the maximum growth rate ratio and LAI from **de Wit.** This relationship is represented in figure 10. The maximum growth rate ratio is to be included as a correction factor (KLAI) in the formula for bgm to make up for LAI at the time of maximum gross biomass production rate less then 5 m^2/m^2.

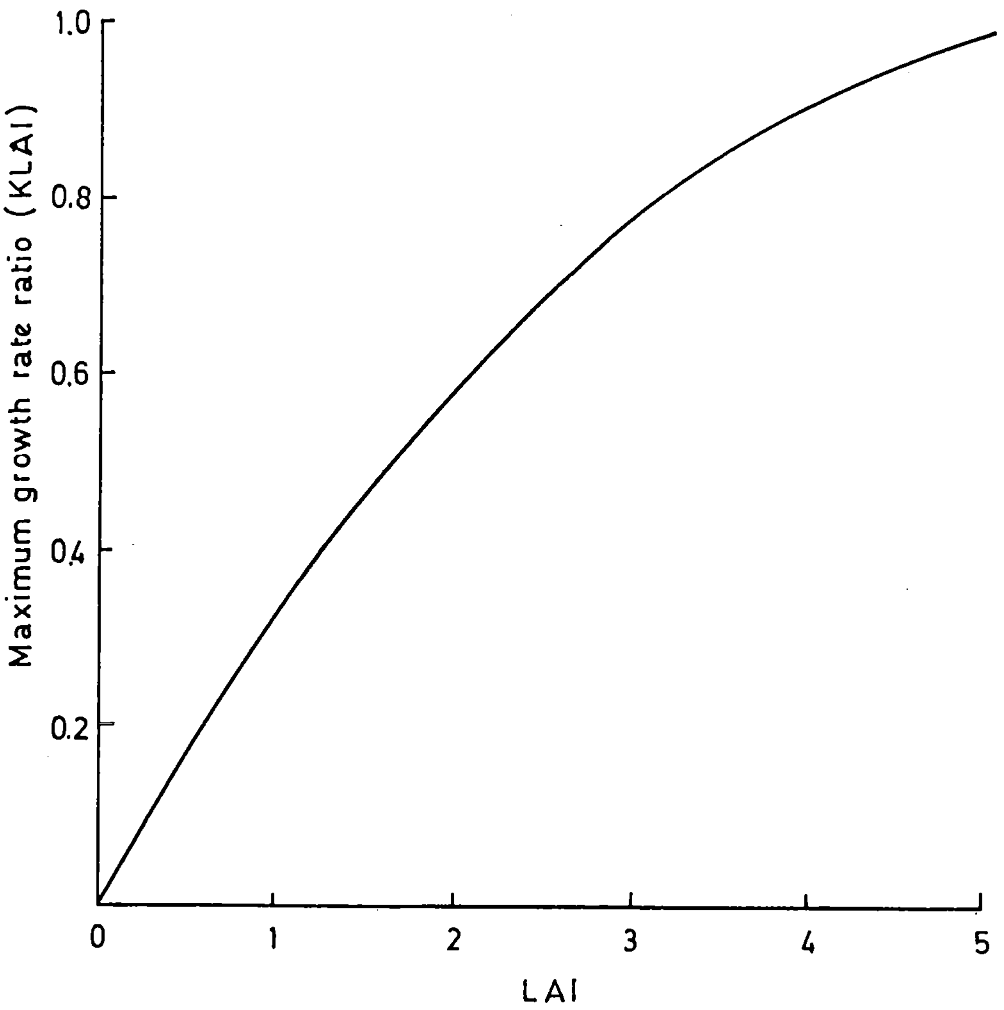


Fig. 10 *Relationship between leaf area index (LAI) and maximum growth rate as a ratio of the maximum growth rate at LAI of 5 (**FAO, 1981**).*

$$Bn = 0.36\ bgm\ KLAI/((1/L)+0.25\ ct)$$

(7) **Crop yield**

The harvest index Hi is defined as the fraction of the total net biomass of the crop that is economically useful (e.g. grain in cereals, sugar in sugar-cane or sugar-beet, lint in cotton). The value of Hi depends on the genetic potential of the crop variety or cultivar (high or low yielding), the water regime (rainfed or irrigated cropping) and cultural practices. In this model only high yielding varieties are considered. Table 34 gives harvest indices of high yielding cultivars of annual crops under rainfed conditions.

The yield of a crop can finally be written as :

$$Y = Bn \cdot Hi$$

or

$$Y = 0.36\ bgm\ KLAI\ Hi\ /\ ((1/L) + 0.25\ ct)$$

EXAMPLE

Data

1. Climatic data

Station	: Garoua
Latitude	: 9° 20' N
Elevation	: 244 m
Start of the growing period	: May 1st decade
End of the growing period	: Oct 2nd decade
Length of the growing period	: 163 days

*Table 34. Harvest index (Hi) of high yielding cultivars of field crops under rainfed conditions (1) (**FAO, 1981**)*

Crop group	Crop	Product	H_i	
			Range	Average
I	Wheat	Grain	0.35 - 0.45 3/	0.40
	White potato	Tuber 4/	0.55 - 0.65	0.60
	Phaseolus bean (temperate and tropical high altitude cultivars) 5/	Grain	0.25 - 0.35	0.30
II	Phaseolus bean (tropical cultivars) 6/	Grain	0.25 - 0.35	0.30
	Soybean	Grain	0.30 - 0.40	0.35
	Rice 7/	Grain	0.25 - 0.35 3/	0.30
	Cotton	Lint 8/	0.06 - 0.10 3/	0.07
	Sweet potato	Tuber 9/	0.50 - 0.60	0.55
	Cassava	Tuber 10/	0.50 - 0.60	0.55
III	Pearl millet	Grain	0.20 - 0.30	0.25
	Sorghum (tropical cultivars)	Grain	0.20 - 0.30 3/	0.25
	Maize (tropical cultivars)	Grain	0.30 - 0.40	0.35
	Sugarcane	Sugar 11/	0.20 - 0.30	0.25
IV	Sorghum (temperate and tropical high altitude cultivars)	Grain	0.20 - 0.30	0.25
	Maize (temperate and tropical high altitude cultivars)	Grain	0.30 - 0.40	0.35

1/ For low yielding cultivars H_i is lower and yields of such cultivars may be calculated using appropriate H_i values.

2/ Refers to bread and durum wheat.

3/ Higher H_i under controlled irrigation.

4/ Fresh tuber at 32.5 percent dry weight.

5/ Refers to P. vulgaris and P. lunatus cultivars as a group.

6/ Refers to P. vulgaris, P. lunatus, P. aureus, P. radiatus, P. mungo and P. angularis cultivars as a group.

7/ Refers to rainfed/flood water lowland paddy rice under incomplete control of water supply.

8/ Lint at ginning percentage of 35.

9/ Fresh tuber at 30 percent dry weight.

10/ Fresh tuber at 35 percent dry weight.

11/ Sugar at 10-12 percent of fresh cane.

Start of the crop cycle : May 1st
End of the crop cycle : August 20th
Length of the crop cycle : 110 days

Month	May	June	July	August	Average
tmean	30.25	27.10	26.25	25.85	27.55
tday	32.70	29.20	28.00	27.60	29.59
n	8.16	7.60	6.18	5.47	6.98
N	12.55	12.67	12.62	12.43	12.58
Ac 0°	349	337	342	357	345.27
Ac 10°	377	374	375	377	375.64
bc 0°	417	410	413	422	414.91
bc 10°	440	440	440	439	439.82
bo 0°	221	216	218	225	219.55
bo 10°	236	235	236	235	235.55
Rg	485	457	415	400	442.90

The crop cycle is extended over the months of May, June and July, and takes 20 days in the month of August. The average value over the 110 days of the crop cycle were calculated by taking the sum of the value for May, June, July and 20/30 of the value for the month of August, devided by 3 and 20/30ths or 3.67.

2. Crop data

Crop name : Maize (Zea mays L.)
Crop type (legume/non-legume) : non-legume
Days to maturity : 110 days
LAI at time of max. growth rate : 3.5 m^2/m^2
Harvest index (Hi) : 0.35

Determination

1. Calculation of the rate of gross biomass production (bgm)

Pm	fig.7		65
y	(Pm-20)5		225
bc	table 32	414.91+(439.82-414.91)9.33/10=	438.15
bo	table 32	219.55+(235.55-219.55)9.33/10=	234.48
Ac	table 32	345.27+(375.64-345.27)9.33/10=	373.61
f	(Ac-0.5Rg)/(0.8Ac)		0.51
1-f			0.49
f	(1-n/N)	(1-0.55)=	0.45
1-f	(n/N)		0.55
bgm		(0.45)(234.48)(1+0.002(225)) +(0.55)(438.15)(1+0.005(225))=	665.09

2. Calculation of the total net biomass production (Bn) and yield (Y)

c30	non-legume	0.0108
ct	c30(0.044+0.0019t+0.001t^2)	0.0092
L		110
KLAI	fig. 10	0.85
Bn	0.36(bgm)(KLAI)/((1/L)+0.25ct)	17,867
Y	Bn.Hi	6,253

The anticipated yield of a high yielding maize hydrid in Garoua is 6.3 ton grain/ha, provided all growth conditions are optimal.

3.3.2.2. **Wageningen model**

This approach was presented in the WMO course (**de Wit, van Heemst and Van Keulen, 1983**) thought at Wageningen.

(1) **Growth**

In the process of photosynthesis, CO_2 from the air is converted into carbohydrates (CH_2O) using solar energy. This is called CO_2 assimilation. The carbohydrates are used partly to build structural plant dry matter (cellulose, proteins, lignin, fats) and partly as energy source for plant processes (maintenance of ionic gradients, resynthesis of degrading structural proteins; conversion of primary photosynthesis products into structural plant material). The release of energy from sugars produced in the assimilation process is called respiration. Subtraction of the respiration from assimilation per time unit gives the growth rate. Growth is defined as the increase of weight or volume of the total plant or the various plant organs. The course of the growth rate and of the total dry weight of summer wheat in time is presented in figure 11.

In the evolution of the growth rate and of the dry weight accumulation with time three phases can be discerned :

(i) In phase 1 the growth rate increases. Most of the assimilates are invested in leaf growth, leading to an increase in leaf area and light interception. The individual plant weight increases by a constant proportion per day, thus giving exponential growth or exponential increase of the total dry weight.

(ii) In phase 2 the growth rate is constant. In this phase the crop canopy is closed and covers the soil completely. More leaf growth does not bring about more light interception.

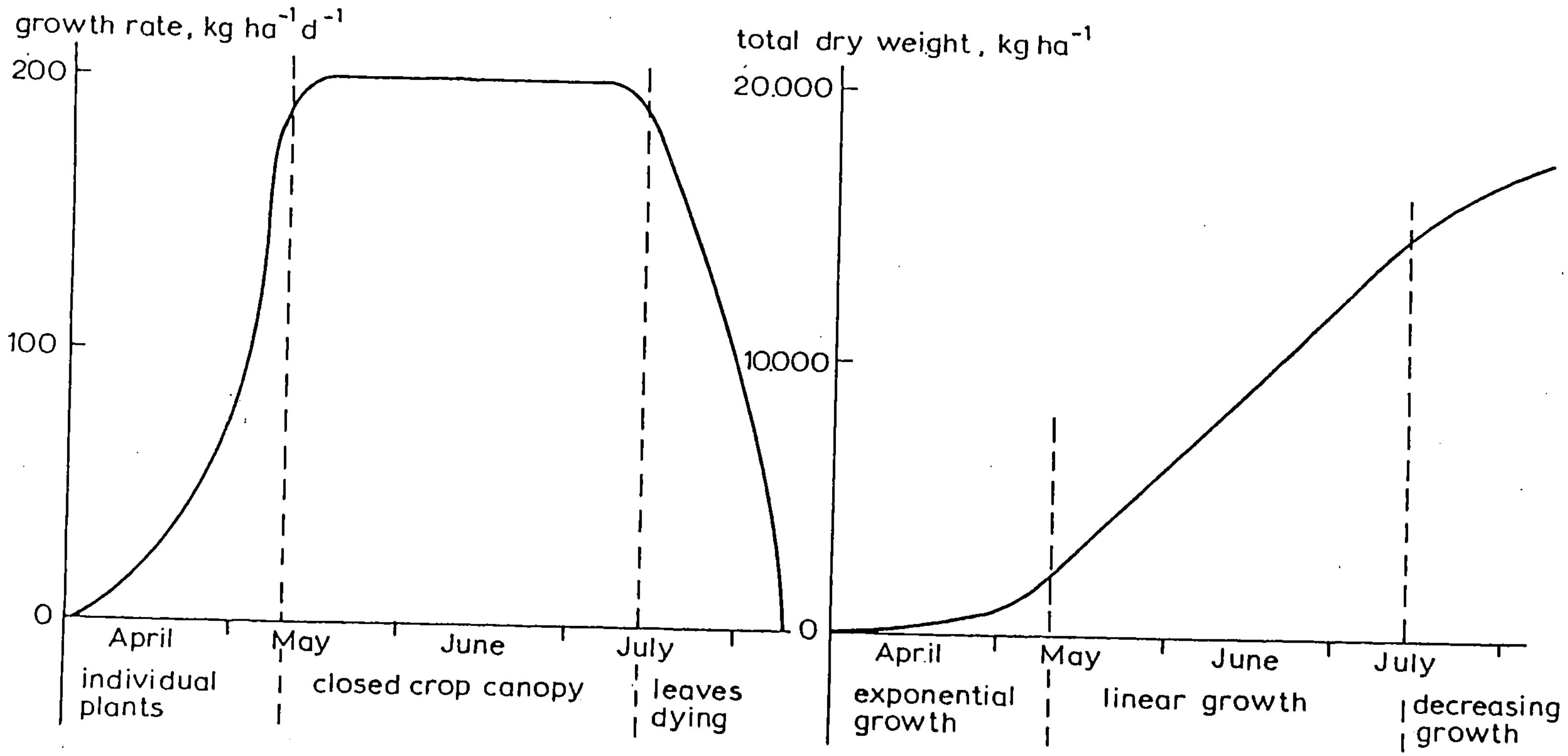


Fig. 11 *Schematized course of growth rate and total dry weight of summer wheat in time (**van Heemst, 1983**).*

Since the growth rate is constant, the total dry weight increases linearly. Most of the dry matter production is achieved in this phase. Therefore, the magnitude of the growth rate and duration of this phase will determine the total dry matter production of the crop.

(iii) In phase 3 the growth rate decreases due to leaf senescence.

(2) **Development**

Development is defined as the transition of one phenological stage to another. It is characterized by the order and rate of appearance of vegetative and reproductive plant organs. The order of appearance of the organs is practically invariable within species, but changes in the sequence may show between species.
The timing and rate of organ appearance is entirely dependent on the environmental conditions. In the sequence of phenological stages distinction is made between the time period before and after the moment that growth of the storage organs starts. In root and tuber crops this is the period before and after the start of bulking. In cereals distinction is made between the pre-anthesis phase (root, leaf and stem formation following sowing or planting) and the post-anthesis phase (flowering, seed setting and filling, crop maturation).

The environmental conditions that infuence the phenological development are temperature and daylength. It is generally accepted that a higher temperature leads to a faster crop development and a shorter total crop cycle length. The product of the average daily temperatures above a threshold temperature value and the number of days required to reach anthesis is found to be constant. This product is called the temperature sum or thermal unit, expressed in degree days. For different spp. the threshold temperature ranges between 0 and 10°C. Threshold temperatures for some species are given in table 35. Crop development can be represented on a numerical scale between the values 0 and 2 : 0 at emergence, 1 at anthesis and 2 at maturity. The development rate is then that part of the scale that is accumulated per time unit. If a crop takes 75 days from emergence to anthesis, and 25 days from anthesis to maturity, the development rate is 1/75 or 0.013 per day in the pre-anthesis stage and 1/25 or 0.04 per day in the post-anthesis stage. The development stage is defined as the sum of the daily development rates. At 50 days after emergence the development stage is (50)(0.013) or 0.66 on the scale 0 - 2.

*Table 35. Threshold values (To) used for the calculation of the temperature sum requirement (TU values) for different crop species (**van Heemst, 1983**)*

Crop	To [°C]
Maize	10
Soybean	10
Sorghum	7-10
Pea, Chickpea	4
Wheat	0- 5
Rice	0- 4

For some species or cultivars, the effect of temperature on development is modified by the day length. Some plants are day neutral or insensitive to day length. Others are long-day plants : anthesis is induced by the occurrence of short nights. In short-day plants anthesis is induced by the occurrence of long nights.

Although the processes that govern phenological development and biomass production are independent, the latter show strong interaction : if a crop shows a high rate of development, the period of linear growth will be short and consequently the vegetative biomass production will be low. A low vegetative biomass will inevitably lead to a low production of storage organs (tubers, grains, pods). On the other hand, too much biomass invested in vegetative organs may equally depress the production of storage organs as a result of high maintenance requirements.

Since the basic processes that govern dry matter partitioning are poorly understood, the subject is treated in an empirical way. It is assumed that the partitioning of assimilates over the various plant parts follows a distribution pattern that depends on the crop development or phenological stage. Such partitioning is characteristic for each crop. The partitioning pattern for rice, maize and cassava (manioc) are given in figures 12, 13 and 14 respectively.
The development and dry matter partitioning for rice, maize and cassava (manioc) is somewhat elaborated hereafter to illustrate the above theory.

The total growing cycle (emergence to maturity) of rice is normally 90 to 150 days. Early varieties are usually day-neutral, late varieties are short-day plants. The relationship between development rate and temperature is variety-specific. The treshhold temperature value is 0°C.

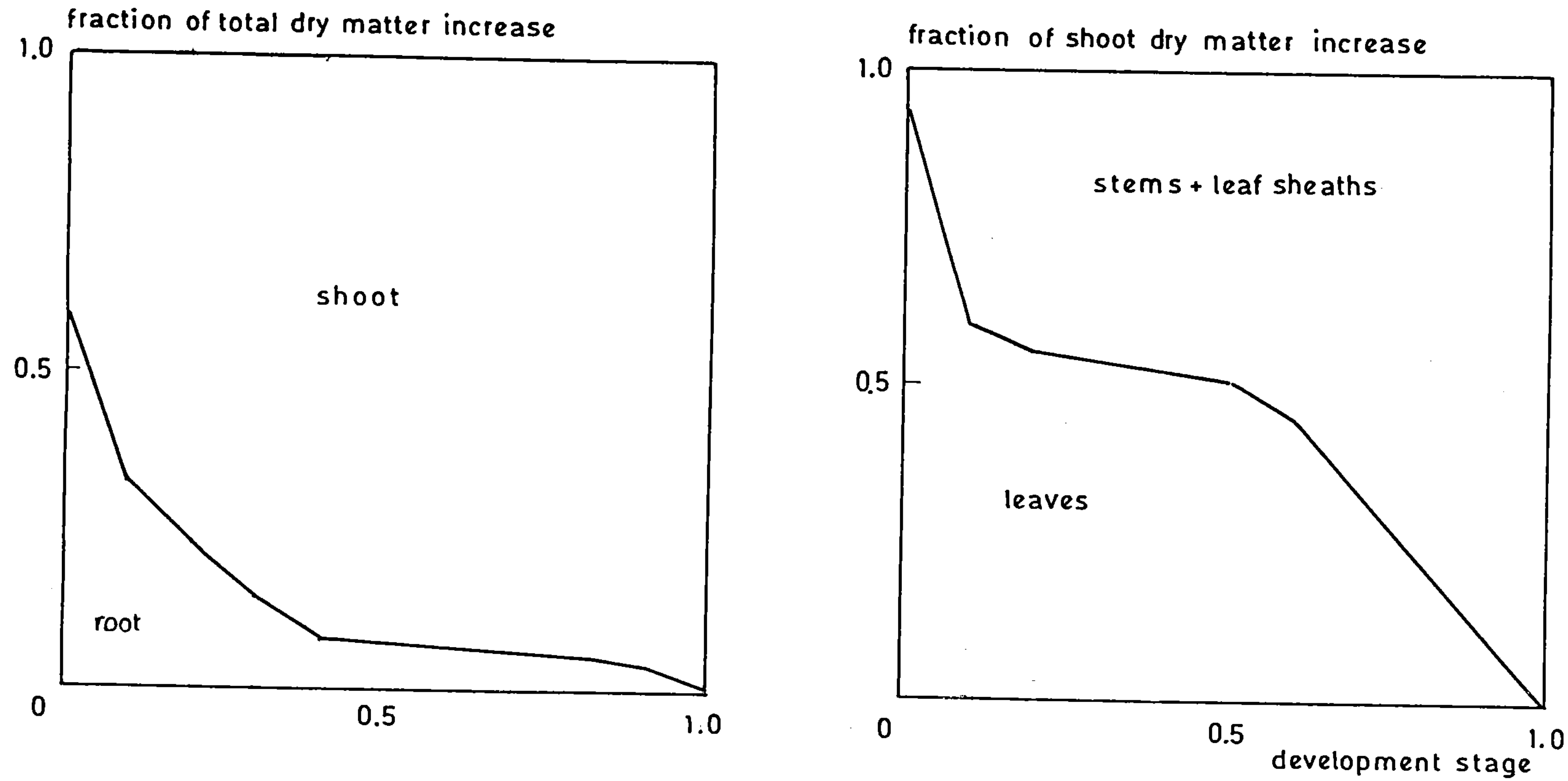


Fig. 12 *Partitioning factors for plant parts in the course of the development of rice (**van Heemst, 1983**).*

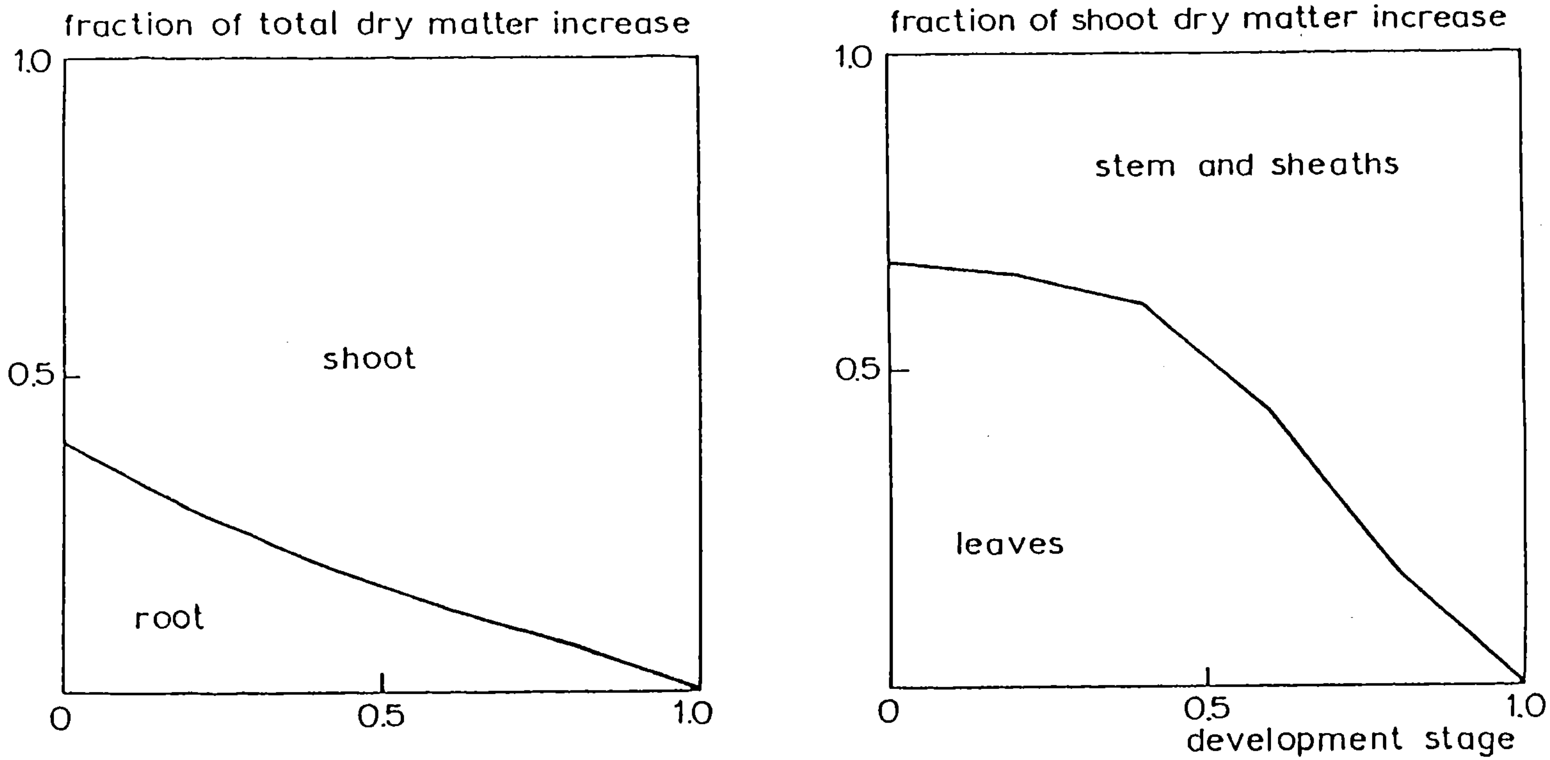


Fig. 13 *Partitioning factors for plant parts in the course of the development of maize (**van Heemst, 1983**).*

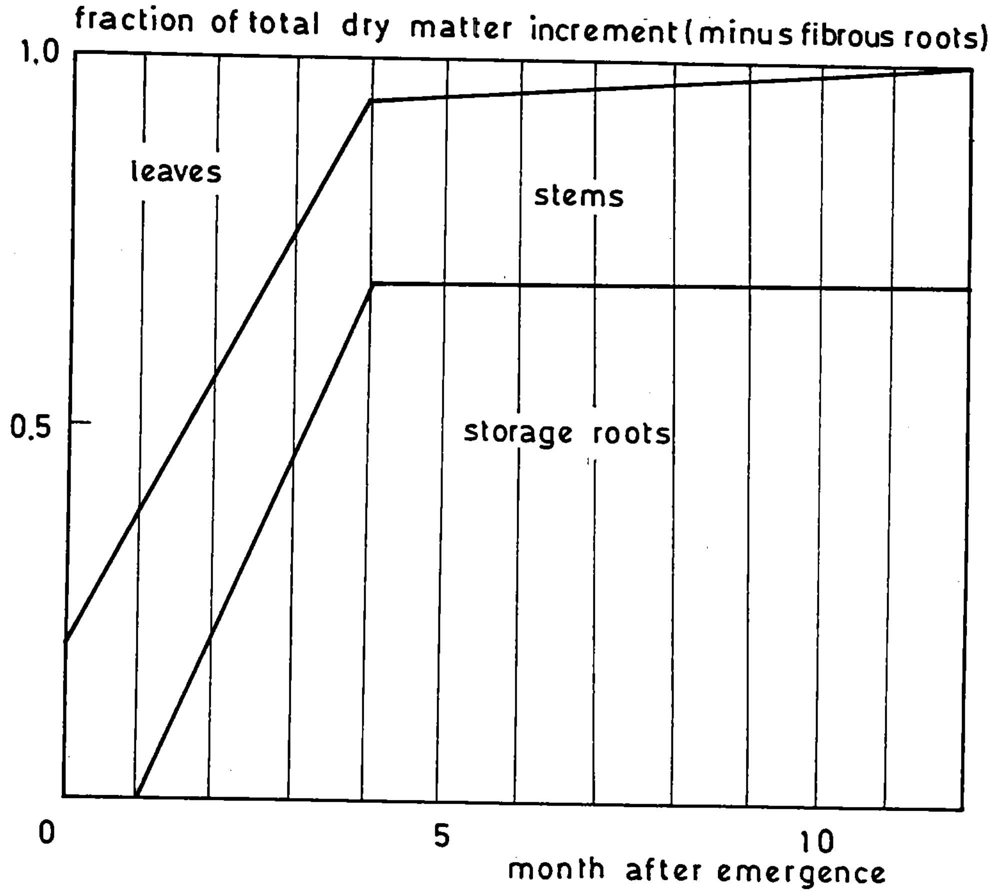


Fig. 14 *Partitioning factors for plant parts of cassava in the course of time (**van Heemst, 1983**).*

Two cultivars are considered here : a short duration cv. IR5 and a medium duration cv. B9C/Md/3/3.

The required temperature sum from transplanting to anthesis for cultivar IR5 is 2150 degree days. For variety B9c/Md/3/3 this requirement is 2700 degree days. Assuming a constant temperature of 20°C, anthesis for IR5 is reached after 2150/20 = 108 days following transplanting. The development rate is 1/108 or 0.0093/day. Variety B9c/Md/3/3 reaches anthesis after 2700/20 = 135 days. The development rate of this variety is 1/135 or 0.0074/day. The required temperature sum for the post-anthesis period is 650 degree days.

If the total dry matter increase is 200 kg/ha.day at development stage 0.5, the dry matter partitioning as shown in figure 12 is as follows : a fraction of 0.08 of the increase or 16 kg/ha.day is assigned to roots; a fraction of 0.92 of the increase or 184 kg/ha.day is attributed to the shoot. Of this portion a fraction of 0.5 or 92 kg/ha.day goes to leaf blades and 0.5 or 92 kg/ha.day goes to stems.

For maize the total growth cycle from emergence to maturity is 80 to 110 days for early varieties and 110 to 140 days for medium duration varieties, on condition that the mean daily temperatures exceed 20°C. At lower temperatures maize is usually grown as a forage crop. Maize is either a day neutral or short-day plant. The pre-anthesis period ends at silking. The time from silking to maturity is 50 to 55 days on average.

For maize varieties Ohio 401 and Pioneer 3306, **Mederski et al. (1973)** determined the temperature sum required for the pre-anthesis period as 625 and 755 degree days respectively. For the post-silking period the required temperature sum amounts to respectively 650 and 635 degree days. For the total growth cycle 1275 to 1390 degree days are required respectively.

Cassava (manioc) is a perennial crop that is propagated trough stem cuttings. Short duration cvs. are harvested after 6 to 10 months, long duration cvs. are left on the field for up to 2 years or more. The economic product is the storage root, consisting merely of starch. Under short day conditions, storage roots are initiated about 55 days after planting. Storage root initiation is delayed, and yields are lower, when the day length exceeds 10 to 12 hours.

In the development of cassava three phases may be distinguished : (i) establishment, (ii) early growth and foliage formation, (iii) simultaneaous formation of foliage and thickening of storage roots with starch accumulation. The latter phase can take up to two years.

In figure 14 the dry matter partitioning is given as a function of time after emergence, and a crop cycle of one year has been adopted. The average development rate on year basis (365 days) is 1/365 or 0.00274/day.

(3) **Crop growth simulation**

In the following, the procedure by **de Wit, van Heemst and van Keulen (1983)** is outlined. The procedure permits to calculate potential crop production and yield using radiation and temperature data as input variables.

The potential crop production is defined as the total dry matter production of a green crop that is optimally supplied with water and nutrient elements, and that grows without interference of weeds, pests or diseases. The potential yield is the potential production of economically useful plant parts.

The method takes into account the phenological development and associated partitionning of dry matter over various plant organs.

The procedure consists of iterative calculations for each time-step, beginning at a moment in time where the state of the crop can be described in quantitative terms. For most crops emergence is a suitable point in time. At that time the seedlings change of growth from reserves in the seed to growth from carbohydrates formed in the process of assimilation. For rice, the moment of transplanting is a better starting point. It is not prefered to take germination as a point of departure, since the temperature relationships that govern this process show high variability.

The state of the crop at the start of the calculations is expressed in terms of dry matter weight of the above ground plant parts (shoot) and dry matter weight of the roots. Experiments have shown that both shoot and root dry weight at emergence can be estimated as about 25% of the seed rate.

If the above ground parts consist entirely of leaf blades, the area of green leaves and LAI can be calculated using the specific leaf area. The latter is given as m^2 of green area per kg of dry matter of leaf blades.

The calculation procedure is outlined making use of the example of rice, variety IR8. The required temperature sum for anthesis for this variety is 1500 degree days. The threshold temperature value is 0°C.

At transplanting the state of the crop is described in the following quantitative terms :

WR	weight of roots	40 kg DM/ha
WLV	weight of leaves	100 kg DM/ha

TADW	total above ground dry weight	100 kg DM/ha
TDW	total dry weight	140 kg DM/ha
SLA	specific leaf area	25 m2/kg DM

From these data one can calculate :

LAI	(SLA.WLV)	
	(25)(100)/(10,000)	0.25 m2/m2

The time interval considered in these calculations is the decade (10 days). In order to obtain the state of the crop at the end of the first decade the following data and calculations are required :

(1) Climatic data

Average daily air temperature : 27.2°C
Potential daily gross CO_2 assimilation : 336 kg CH_2O/ha.day (This is the value of bgm, calculated as in the FAO-model but expressed as kg CH_2O/ha.day instead of kg CH_2O/ha.hr)

(2) Crop data

Relative maintenance respiration rate : 0.015 kg CH2O/ha.day
Conversion efficiency for vegetative material of average composition : 0.7

(3) Calculations

Development stage (DVS)

The temperature sum (TSUM) over the first time interval (10 days), taking into account the average daily air temperature (27.2°C) and the threshold temperature value (0°C) is calculated as :

$$TSUM = (10)(27.2-0)$$
$$= 272 \text{ degree days}$$

The development stage (DVS) is obtained from the temperature sum (TSUM) and the total temperature sum required for anthesis (1500 degree days) :

$$DVS = 272/1500$$
$$= 0.18$$

Gross CO_2 assimilation (GASS)

The value of the daily potential gross CO_2 assimilation is valid for closed green canopy (LAI = 5 m^2/m^2). At a LAI = 0.25 m^2/m^2 only part of the solar energy is intercepted. The fraction that is intercepted is calculated from the following formula :

$$\text{interception} = 1 - e^{-(0.8\ LAI)}$$

For a LAI of 0.25 m^2/m^2 the light interception is 0.18 .
The gross CO2 assimilation (GASS) over the time interval (10 days) is obtained from the daily potential gross CO_2 assimilation (336 kg CH_2O/ha.day) and the light interception (0.18).

$$GASS = (336)(0.18)(10)$$
$$= 605 \text{ kg } CH_2O/\text{ha.decade}$$

Maintenance respiration (MRES)

Part of the energy fixed in the assimilation process is respired by the crop to maintain the existing structures. The magnitude of the respiration losses depends on the chemical composition of the structural plant material. Both the growth and maintenance respiration are higher when the protein (nitrogen) content of the material is higher. The relative maintenance respiration rate and conversion efficiency for different types of crops are given in table 36. The maintenance respiration is calculated from the relative maintenance respiration rate (0.015 kg CH_2O/ha.day) over the time interval (10 days) and the total living dry matter (TDML = 140 kg/ha):

$$\begin{aligned} MRES &= (0.015)(10)(140) \\ &= 21 \text{ kg } CH_2O/\text{ha.decade} \end{aligned}$$

Table 36. Relative maintenance respiration rate (Rm) at 20°C [kg CH_2O/kg DM. day] and conversion efficiency (Eg) [kg DM/kg CH_2O] (DM = Dry Matter) for different crop groups (**van Heemst, 1983**)

Crop group	RM [kg CH_2O/kg DM.day]	Eg [kg DM/kg CH_2O]
Root/tuber crops	0.010	0.75
Cereals	0.015	0.70
Protein-rich seed crops	0.025	0.65
Oil-rich seed crops	0.030	0.50

Assimilation products available for weight increase (ASAG)

The amount of assimilation products that can be used to increase the crop dry weight (ASAG) is obtained from the difference between the gross assimilation (GASS) and the maintenance respiration (MRES) :

ASAG = 605 - 21
= 584 kg CH_2O/ha.decade

Dry matter increase (DMI)

Primary assimilates have to be converted into structural plant material. Since such conversion entails a loss of energy, the conversion efficiency (Ec) is less than 1. For vegetative material of average composition Ec is 0.7.

DMI = (ASAG)(Ec)
= (584)(0.7)
= 409 kg CH_2O/ha.decade

The total dry matter increase is utilized concurrently for the growth and weight increase of the various plant parts. The partitioning factors for each of the plant parts is determined by the phenological stage of the crop expressed in the development stage. The development stage in the middle of the decade is calculated as the average value at the beginning and end of the decade : (0 + 0.18)/2 = 0.09

The partitioning factors at development stage 0.09 are (fig. 12)

for roots (fr)	:	0.35
for leaves (fl)	:	0.395
for stems (fs)	:	0.255
for grain (fg)	:	0

Increase in weight of roots (IWRT)

The fraction of the dry weight increment (DMI) allocated to the roots (fr) is 0.35. Consequently the increase in weight of roots (IWRT) is :

IWRT = (DMI)(fr)
= (409)(0.35)
= 143 kg DM/ha

Weight of roots (WRT)

The total weight of roots at the end of the decade (WRT) is equal to the weight of roots at the end of the previous decade plus the root dry weight increment in the decade (IWRT).

WRT = 40 + 143
= 183 kg DM/ha

Increase in weight of leaves (IWLV)

IWLV = (409)(0.395)
= 162 kg DM/ha

Weight of leaves (WLV)

WLV = 100 + 162
= 262 kg DM/ha

Increase in weight of stems (IWST)

IWST = (409)(0.255)
= 104 kg DM/ha

Weight of stems (WST)

WST = 0 + 104
= 104 kg DM/ha

Increase in weight of grain (IWGR)

IWST = (409)(0)
= 0 kg DM/ha

Weight of grain (WGR)

WGR = 0 + 0
= 0 kg DM/ha

Total above ground dry weight (TADW)

TADW = WLV + WST + WGR
= 262 + 104 + 0
= 366 kg DM/ha

Total dry weight (TDW)

TDW = TADW + WRT
= 366 + 183
= 549 kg DM/ha

Total dry weight of living material (TDWL)

TDWL = TDW
since all dry matter is live material.

Leaf area index (LAI)

Taking into account a specific leaf area (SLA) of 25 m^2/kg DM, the weight of leaves (WLV) equal to 262 kg DM/ha and 10,000 m^2 per ha, the leaf area index is :

$$LAI = (SLA)(WLV)/10{,}000$$
$$= (25)(262)/10{,}000$$
$$= 0.66\ m^2/m^2$$

At the end of the calculations for the first decade, the same procedure is resumed for the following decades until the time that anthesis is reached. From the time of anthesis onwards, the iterative calculation procedure is identical, but the following parameters change :

Development stage (DVS)

In the post-anthesis phase, the development scale evolves from 1 at anthesis to 2 at maturation. The temperature sum required to reach maturity from the time of anthesis onwards is 800 degree days. As a result of these changes the development stage is calculated as :

$$DVS = 1 + [(TSUM - 1500)/800]$$

Maintenance respiration (MRES)

In the post-anthesis phase the nitrogen content of the vegetative material decreases. As a result of this decrease, the maintenance respiration rate lowers to 0.01 kg CH_2O/kg DM.day. The maintenance respiration is then :

$$MRES = (TDWL)(0.01)(\text{interval in days})$$

Conversion efficiency (Ec)

The conversion efficiency of primary photosynthesis products to grain structural matter is higher (0.8) than for vegetative structural matter (0.7). Since all dry matter is allocated to the grain in the post-anthesis period, the considered value to calculate the dry weight increment (DMI) is Ec = 0.8.

Weight of leaves (WLV)

Leaves have a limited life span. The process of leave senescence is accelerated after anthesis when essential substances are translocated to the developing grains. Therefore a (constant) rate of decline of the weight of active leaf blades is assumed, equal to 0.02 kg leaf blades/kg active leaf blades per day. The weight of leaves at the end of the decade is calculated as :

[WLV - (WLV)(0.02)(interval in days)]

Total dry weight of living material (TDWL)

As a result of the loss of active leave blades (calculated above), the total dry weight of living dry matter (TDWL) becomes less than the total dry weight (TDW) :

TDWL = TDW - (WLV)(0.02)(interval in days)

The results of the complete calculation procedure for rice at station Paramaribo is given in table 37.

Table 37. Calculation scheme for potential production of rice variety IR8 in Paramaribo ***(van Keulen, 1983)***

Column n° Period	1 T	2 TSUM	3 DVS	4 GASS	5 MRES	6 ASAG	7 DMI	8 FR	9 IWRT	10 WRT	11 FL	12 IWLV	13 WLV	14 FS	15 IWST	16 WST	17 FG	18 IWGR	19 WGR	20 LAI	21 TADW	22 TDW	23 TDWL
										40			100			0				0.25	100	140	140
1 Nov. 2	27.2	272	0.18	605	21	584	409	0.35	143	183	0.395	162	262	0.255	104	104	0	0	0	0.65	366	549	549
2 Nov. 3	26.3	535	0.36	1272	82	1190	833	0.165	137	320	0.445	371	633	0.39	325	429	0	0	0	1.6	1062	1382	1382
3 Dec. 1	25.8	793	0.53	160	207	1953	1367	0.075	103	423	0.48	656	1289	0.445	608	1037	0	0	0	3.2	2326	2749	2749
4 Dec. 2	26.4	1057	0.70	2604	412	2192	1534	0.07	107	530	0.40	614	1903	0.53	813	1850	0	0	0	4.75	3753	4283	4283
5 Dec. 3	26.3	1320	0.88	2950	642	2308	1616	0.07	113	643	0.265	428	2331	0.665	1076	2925	0	0	0	5.8	5256	5899	5899
6a Jan. 1-7	26.0	1502	1.0	2212	619	1593	1115	0.025	28	671	0.06	67	2398	0.225	251	3176	0.69	879	879	6.0	6453	7124	7124
6b Jan. 8-10	26.0	1580	1.10	948	214	734	587	0	0	671	0	-144	2254	0	0	3176	1.0	587	1466	5.6	7040	7711	7567
7 Jan. 2	26.0	1840	1.43	3320	757	2563	2050	0	0	671	0	-451	1803	0	0	3176	1.0	2050	3516	4.5	9090	9761	9166
8 Jan. 3	26.0	2100	1.75	3360	917	2443	1954	0	0	671	0	-361	1442	0	0	3176	1.0	1954	5470	3.6	11044	11715	10757
9 Feb. 1-8	26.0	2308	2.0	2557	860	1717	1374	0	0	671	0	-231	1211	0	0	3176	1.0	1374	6844	3.0	12418	13089	11902

3.4. Rainfed crop production

3.4.1. RAINFALL

3.4.1.1. Rainfall probability

Average rainfall data are quite unreliable for agricultural planning purposes and for irrigation planning in particular. If rainfall data follow a normal distribution, the data are spread evenly around the mean value : 50 % of the rainfall values is greater and 50 % is smaller than the average value. The degree of deviation from the mean is expressed by the variance or the standard deviation. When elaborating a planning with average rainfall data, the observed rainfall will be lower than the average rainfall in 5 years out of 10.

For planning purposes one will therefore prefer to rely on rainfall data that have a higher degree of certainty. In order to obtain such rainfall data, a statistical analysis of rainfall data over a number of years is required. The procedure to be followed is outlined hereafter.

(1) **Principle**

Annual, monthly or decade rainfall data are gathered over a period of at least 10 years. For a particular year, month or decade, the rainfall totals of all recorded years are fitted with a probability function by the method of least squares. The rainfall for a selected risk level is obtained from the theoretical distribution. In months or decades that are characterised by a sufficiently high rainfall over the years, a normal distribution is assumed. In months or decades with low or no rainfall over the years other distribution functions (e.g. the incomplete gamma law) (**Thom, 1958; Gommes, 1983**) will fit to the observed rainfall data.

(2) **Procedure**

Let N be the total number of rainfall records. The rainfall data are initially listed according to the year of observation. Subsequently the rainfall data are rearranged in ascending order, and each value is assigned a rank number (m). The lowest rank number is 1. The cumulative probability (P_i) of the rainfall with ranking number m is calculated as

$$P_i = m/(N+1) \quad [\text{fraction}]$$

A normal distribution is now fitted to the data according to the method by **Baier and Russelo (1968)**.

The following transformation is used to linearise the normal distribution :

$$Z = (x-M)/S$$

where Z = normal random variable with mean zero and variance = 1
x = sample value
M = sample mean
S = sample standard deviation

The transformation equation can equally be written as :

$$SZ = x-M$$

and

$$x = M + SZ$$

The latter equation is solved for M and S by linear regression of the dependent variable x on the independent variable Z. Sample values of 0 are discarded in the regression analysis. For each P_i, the corresponding value of Z is found from the table of values for the standard normal distribution. The value of Z can equally be calculated :

For a cumulative probability P_i, Z can be found such that

$$P_i = (1/\sqrt{2\pi}) \int_Z^{\infty} e^{-t^2/2}\, dt \qquad (0<P_i<1)$$

A solution for Z is found using a rational approximation formula (**Abramowitz and Stegun, 1970**) as follows

if $0<P_i\leq 0.5$ calculate $t = \sqrt{\ln(1/P_i^2)}$

if $0.5<P_i<1$ calculate $t = \sqrt{\ln(1/(1-P_i)^2)}$

$$Z = t - \frac{2.5155 + 0.8029t + 0.0103t^2}{1 + 1.4328t + 0.1893t^2 + 0.0013t^3}$$

if $0<P_i\leq 0.5$, change the sign of Z to -Z.

EXAMPLE

The method is illustrated with the example of decade rainfall records over 26 years (1965-1990) of an imaginary station. The data are presented in table 38. The sample distribution and fitted distribution curves are given in figure 15.

Table 38. Rainfall analysis for the first decade of January (Jan 1)

Year	Rainfall [mm]	Rainfall ascending [mm]	Rank (m)	P_i	Z
1965	50	0	1	-	-
1966	13	0	2	-	-
1967	88	0	3	-	-
1968	43	0	4	-	-
1969	15	7	5	.19	-0.90
1970	96	12	6	.22	-0.76
1971	96	13	7	.26	-0.65
1972	46	15	8	.30	-0.53
1973	26	15	9	.33	-0.43
1974	12	18	10	.37	-0.33
1975	15	21	11	.41	-0.23
1976	71	26	12	.44	-0.14
1977	7	26	13	.48	-0.05
1978	28	28	14	.52	0.05
1979	76	28	15	.56	0.14
1980	26	43	16	.59	0.23
1981	28	46	17	.63	0.33
1982	0	50	18	.67	0.43
1983	21	50	19	.70	0.53
1984	0	63	20	.74	0.65
1985	63	71	21	.78	0.76
1986	0	76	22	.81	0.90
1987	18	88	23	.85	1.04
1988	50	90	24	.89	1.22
1989	0	96	25	.93	1.45
1990	90	96	26	.96	1.79

The regression of rainfall values (x) on the random variable Z yields :

$$\text{rainfall} = 37.6154 + 31.4619\, Z$$

$n = 22$

$r^2 = 0.939$

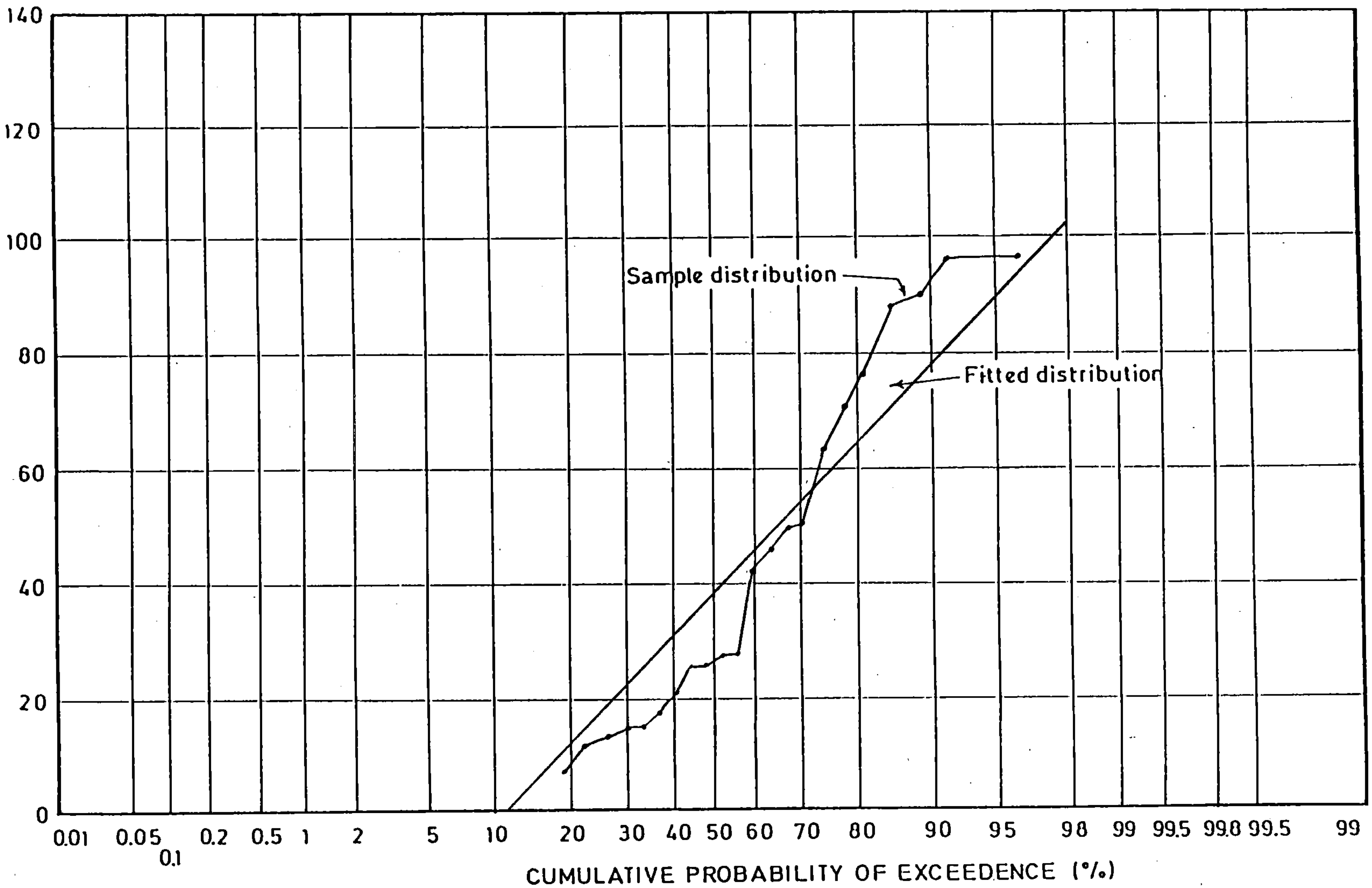


Fig. 15 Rainfall probability

The mean rainfall (M) is 37.6 mm and the standard deviation (S) is 31.5 . The rainfall for probability levels of 0.10 to 0.90 (or 10 to 90 %) in steps of 0.1 (10 %) can be calculated from the fitted distribution. The probability for the rainfall to be exceeded is equal to ($1-P_i$). Table 39 summarizes these data for the example considered.

Table 39. Cumulative probability (P_i) and probability to be exceeded ($1-P_i$) in steps of 10% and corresponding rainfall

P_i [%]	Z	Rainfall [mm]	($1-P_i$) [%]
10	-1.28	0.0	90
20	-0.84	11.1	80
30	-0.52	21.1	70
40	-0.25	29.7	60
50	0.00	37.6	50
60	0.25	45.6	40
70	0.52	54.1	30
80	0.84	64.1	20
90	1.28	77.9	10

Usually risk levels of 0.6 (60%) to 0.8 (80%) are recommended, depending on the sensitivity of the crop to inadequate water supply. In the example the amount of rainfall in the first decade of January for a risk level of 60% is 24.4 mm. This means that in 6 years out of 10 the rainfall in that decade will be **at least** 24.4 mm. The rainfall for a specified risk level is equally called **dependable rainfall** for a given probability level.

The probability for the decade being dry is obtained by reading or calculating the probability for rainfall = 0 mm. For the above data this means $Z = -37.6154/31.4619 = -1.20$;this corresponds with $P_i = 0.115$ or 11.5 % . The probability for the decade being moist is the complement $(1-P_i)$ or 88.5 % .

A complete decade rainfall analysis was carried out for the station of Dschang, Cameroon (**Ducret, 1989**). The results of this analysis is presented in table 40 and in figure 16.

3.4.1.2. **Rainfall effectiveness**

Rain water can follow a complex pathway before it becomes available for consumption by a crop. This pathway is illustrated in figure 17.

(1) **Definition**

FAO (1974) defines the effective rainfall as the portion of the rainfall that is useful, directly and/or indirectly, for crop production at the site where it falls. It therefore includes water intercepted by living or dry vegetation, water lost by evaporation from the soil surface, water lost by evapotranspiration during crop growth and water that contributes to leaching or percolation, or facilitates cultural operations (land preparation) either before or after sowing without any harm to yield and quality of the principal crops.
Consequently, ineffective rainfall is that portion that is lost by surface runoff or unnecessary deep percolation or that remains unused in the soil after harvest and not useful for the next crop.
It is emphasized that the values of effective rainfall will vary for different purposes (irrigation planning, dry farming) and for special conditions (salinity, high water table).

In a narrow sense, effective rainfall is the average, dependable or actual rainfall, corrected for losses due to surface runoff and deep percolation.

*Table 40. Probability of exceeding a decade rainfall value x (**Ducret, 1988**)*

x (mm)	JAN1	JAN2	JAN3	FEV1	FEV2	FEV3	MAR1	MAR2	MAR3	AVR1	AVR2	AVR3	MAI1	MAI2	MAI3	JUN1	JUN2	JUN3
0	.24	.34	.52	.35	.41	.62	.81	.86	1.00	1.00	.99	1.00	1.00	.99	1.00	1.00	1.00	1.00
2	.23	.31	.41	.34	.39	.56	.79	.85	1.00	1.00	.98	1.00	1.00	.98	1.00	1.00	1.00	1.00
4	.21	.27	.35	.34	.37	.50	.77	.83	1.00	1.00	.97	.99	1.00	.98	.99	1.00	1.00	1.00
6	.20	.23	.29	.33	.35	.44	.75	.82	1.00	1.00	.96	.98	1.00	.97	.98	1.00	1.00	1.00
8	.19	.19	.24	.31	.33	.40	.73	.80	.99	.99	.96	.96	1.00	.96	.97	1.00	1.00	1.00
10	.18	.13	.22	.29	.30	.36	.71	.78	.98	.97	.95	.95	1.00	.95	.95	.99	1.00	1.00
12	.16	.07	.19	.26	.28	.32	.68	.76	.96	.96	.95	.93	1.00	.93	.94	.98	1.00	1.00
15	.15	.01	.17	.21	.25	.29	.65	.74	.95	.94	.94	.91	1.00	.91	.92	.97	1.00	.99
20	.13	.00	.14	.12	.20	.23	.59	.69	.93	.89	.91	.87	1.00	.88	.88	.94	1.00	.97
25	.11	.00	.11	.06	.15	.21	.54	.64	.90	.84	.85	.82	1.00	.84	.84	.91	.96	.93
30	.09	.00	.09	.03	.11	.18	.49	.59	.86	.78	.78	.77	.96	.79	.80	.87	.92	.90
35	.08	.00	.08	.01	.08	.15	.43	.54	.79	.72	.70	.71	.86	.74	.75	.83	.88	.86
40	.07	.00	.07	.01	.06	.12	.39	.48	.72	.65	.63	.66	.76	.69	.70	.78	.84	.82
45	.06	.00	.03	.00	.04	.10	.34	.44	.64	.58	.56	.60	.66	.63	.65	.73	.79	.78
50	.05	.00	.02	.00	.03	.09	.30	.39	.57	.52	.51	.54	.58	.57	.59	.68	.73	.74
60	.03	.00	.01	.00	.01	.06	.23	.30	.45	.40	.41	.43	.44	.45	.49	.56	.62	.65
70	.02	.00	.01	.00	.01	.04	.17	.23	.35	.31	.33	.33	.33	.33	.38	.44	.51	.55
80	.02	.00	.00	.00	.00	.03	.12	.17	.27	.24	.26	.25	.24	.24	.29	.34	.40	.46
90	.00	.00	.00	.00	.00	.02	.09	.12	.21	.18	.21	.18	.18	.17	.22	.25	.31	.38
100	.00	.00	.00	.00	.00	.01	.07	.09	.16	.14	.17	.13	.13	.11	.16	.18	.23	.31
110	.00	.00	.00	.00	.00	.01	.05	.06	.13	.11	.14	.09	.10	.07	.12	.12	.17	.24
120	.00	.00	.00	.00	.00	.01	.03	.05	.10	.08	.11	.07	.07	.05	.08	.08	.12	.19
130	.00	.00	.00	.00	.00	.00	.02	.03	.08	.06	.09	.05	.05	.03	.06	.06	.08	.14
140	.00	.00	.00	.00	.00	.00	.02	.02	.06	.05	.07	.03	.04	.02	.04	.04	.06	.11
150	.00	.00	.00	.00	.00	.00	.01	.02	.05	.04	.06	.02	.03	.01	.03	.02	.04	.08
160	.00	.00	.00	.00	.00	.00	.01	.01	.04	.03	.05	.02	.02	.01	.02	.02	.03	.06
170	.00	.00	.00	.00	.00	.00	.01	.01	.03	.02	.04	.01	.01	.01	.01	.01	.02	.05
180	.00	.00	.00	.00	.00	.00	.00	.01	.02	.02	.03	.01	.01	.00	.01	.01	.01	.03
190	.00	.00	.00	.00	.00	.00	.00	.00	.02	.01	.02	.00	.01	.00	.01	.00	.01	.03
200	.00	.00	.00	.00	.00	.00	.00	.00	.01	.01	.02	.00	.01	.00	.00	.00	.01	.02
210	.00	.00	.00	.00	.00	.00	.00	.00	.01	.01	.02	.00	.00	.00	.00	.00	.00	.01
220	.00	.00	.00	.00	.00	.00	.00	.00	.00	.01	.01	.00	.00	.00	.00	.00	.00	.01
230	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.01	.00	.00	.00	.00	.00	.00	.01
240	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.01	.00	.00	.00	.00	.00	.00	.01
250	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.01	.00	.00	.00	.00	.00	.00	.00

Table 40. Cntd

x (mm)	Decades JUL1	JUL2	JUL3	AUG1	AUG2	AUG3	SEP1	SEP2	SEP3	OCT1	OCT2	OCT3	NOV1	NOV2	NOV3	DEC1	DEC2	DEC3
0	1.00	1.00	.98	.96	.97	1.00	1.00	1.00	1.00	1.00	.95	.97	.99	.60	.37	.41	.29	.35
2	1.00	.99	.97	.95	.97	1.00	1.00	1.00	1.00	1.00	.95	.96	.83	.59	.36	.37	.27	.18
4	1.00	.97	.97	.95	.97	1.00	1.00	1.00	1.00	1.00	.95	.95	.82	.57	.34	.33	.25	.12
6	1.00	.96	.97	.95	.96	1.00	1.00	1.00	1.00	1.00	.94	.94	.79	.54	.30	.28	.22	.11
8	1.00	.95	.96	.94	.96	1.00	1.00	1.00	1.00	1.00	.94	.93	.77	.50	.26	.23	.20	.10
10	1.00	.93	.96	.94	.96	1.00	1.00	1.00	1.00	1.00	.94	.92	.76	.46	.22	.21	.17	.09
12	1.00	.92	.96	.93	.96	1.00	1.00	1.00	1.00	1.00	.93	.90	.74	.41	.19	.18	.14	.08
15	1.00	.89	.95	.92	.96	1.00	1.00	1.00	1.00	1.00	.93	.88	.70	.34	.16	.15	.11	.08
20	.98	.85	.94	.91	.95	1.00	1.00	1.00	1.00	1.00	.91	.84	.60	.25	.11	.11	.06	.07
25	.96	.81	.92	.89	.95	1.00	1.00	1.00	1.00	1.00	.90	.80	.43	.18	.08	.09	.03	.07
30	.93	.76	.91	.87	.94	1.00	1.00	1.00	.99	.99	.88	.74	.33	.12	.05	.08	.01	.06
35	.89	.71	.89	.84	.93	1.00	.99	1.00	.98	.96	.86	.69	.25	.09	.04	.07	.00	.05
40	.85	.66	.86	.81	.92	.98	.99	1.00	.97	.94	.83	.62	.20	.06	.03	.06	.00	.04
45	.81	.61	.84	.78	.91	.96	.99	1.00	.95	.91	.80	.56	.16	.04	.02	.05	.00	.03
50	.76	.56	.81	.74	.89	.94	.99	.99	.94	.88	.76	.49	.13	.03	.01	.04	.00	.02
60	.65	.46	.73	.66	.83	.88	.96	.94	.89	.81	.68	.36	.09	.02	.01	.03	.00	.01
70	.54	.37	.65	.57	.75	.82	.85	.88	.84	.72	.58	.25	.07	.01	.00	.02	.00	.00
80	.42	.29	.55	.46	.64	.74	.68	.80	.77	.63	.47	.17	.03	.00	.00	.00	.00	.00
90	.32	.22	.45	.37	.48	.65	.54	.70	.69	.52	.36	.11	.02	.00	.00	.00	.00	.00
100	.23	.17	.35	.28	.35	.56	.42	.60	.59	.43	.27	.07	.01	.00	.00	.00	.00	.00
110	.16	.13	.27	.21	.26	.47	.32	.49	.49	.33	.19	.04	.00	.00	.00	.00	.00	.00
120	.11	.09	.20	.15	.19	.38	.25	.39	.39	.26	.13	.03	.00	.00	.00	.00	.00	.00
130	.08	.07	.14	.10	.14	.30	.20	.30	.30	.19	.09	.02	.00	.00	.00	.00	.00	.00
140	.05	.05	.10	.07	.10	.24	.15	.22	.23	.14	.06	.01	.00	.00	.00	.00	.00	.00
150	.03	.04	.07	.05	.07	.18	.12	.16	.17	.10	.04	.01	.00	.00	.00	.00	.00	.00
160	.02	.03	.05	.03	.05	.14	.09	.11	.12	.07	.03	.00	.00	.00	.00	.00	.00	.00
170	.02	.02	.03	.02	.04	.10	.07	.08	.08	.05	.02	.00	.00	.00	.00	.00	.00	.00
180	.01	.01	.02	.02	.03	.07	.06	.06	.06	.04	.01	.00	.00	.00	.00	.00	.00	.00
190	.01	.01	.01	.01	.02	.05	.04	.04	.04	.03	.01	.00	.00	.00	.00	.00	.00	.00
200	.00	.01	.01	.01	.02	.04	.03	.03	.03	.02	.00	.00	.00	.00	.00	.00	.00	.00
210	.00	.01	.01	.00	.01	.03	.03	.02	.02	.01	.00	.00	.00	.00	.00	.00	.00	.00
220	.00	.00	.00	.00	.01	.02	.02	.01	.01	.01	.00	.00	.00	.00	.00	.00	.00	.00
230	.00	.00	.00	.00	.01	.01	.02	.01	.01	.01	.00	.00	.00	.00	.00	.00	.00	.00
240	.00	.00	.00	.00	.00	.01	.01	.01	.01	.00	.00	.00	.00	.00	.00	.00	.00	.00
250	.00	.00	.00	.00	.00	.01	.01	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00

Example :

- the probability of receiving at least 35 mm of rain during the third decade of march (MAR3) is 0.79
- the probability of receiving at least 105 mm of rain during the 2nd decade of September is 0.54 (interpolation required)

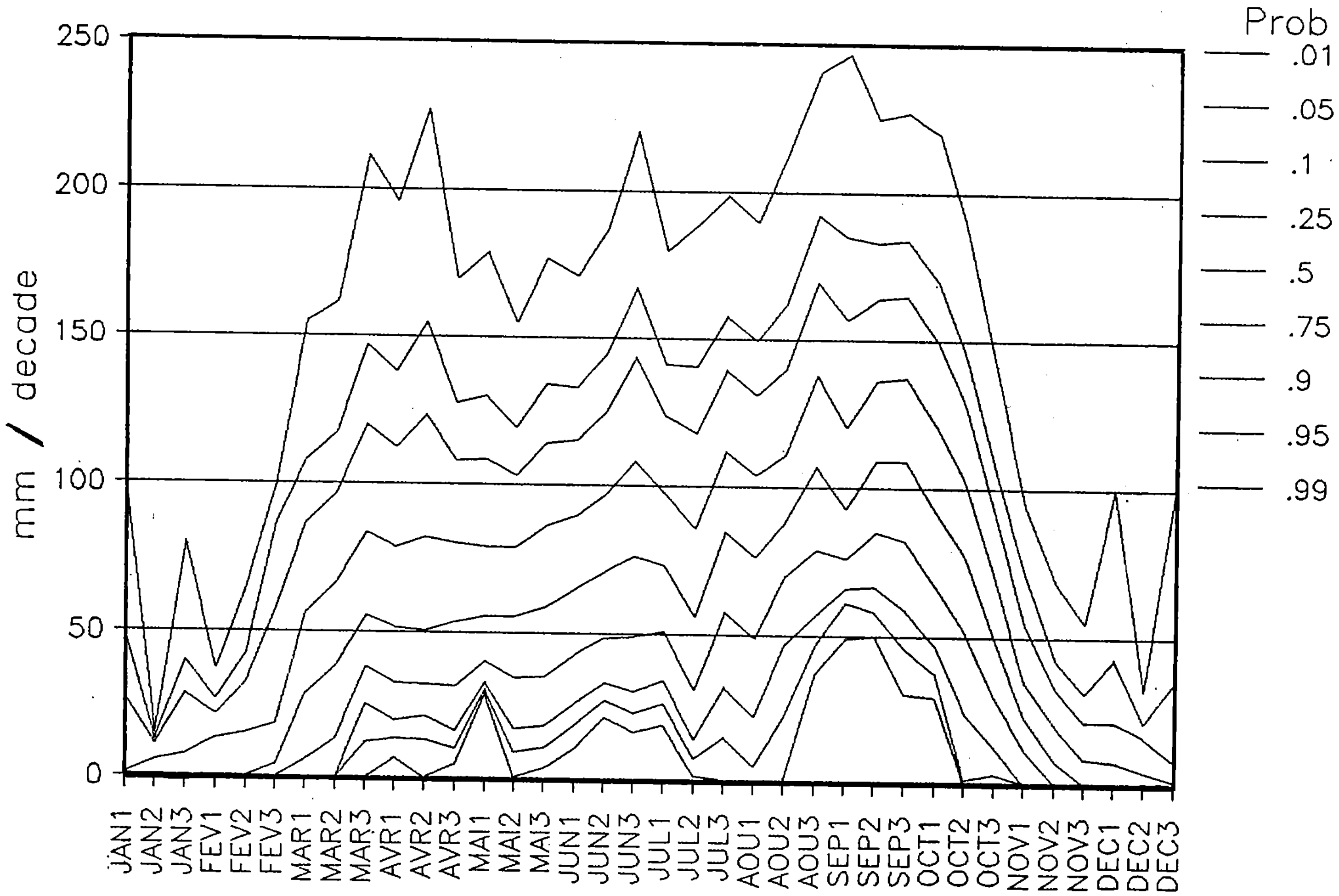


Fig. 16 *Decade rainfall values obtained for different probability levels*

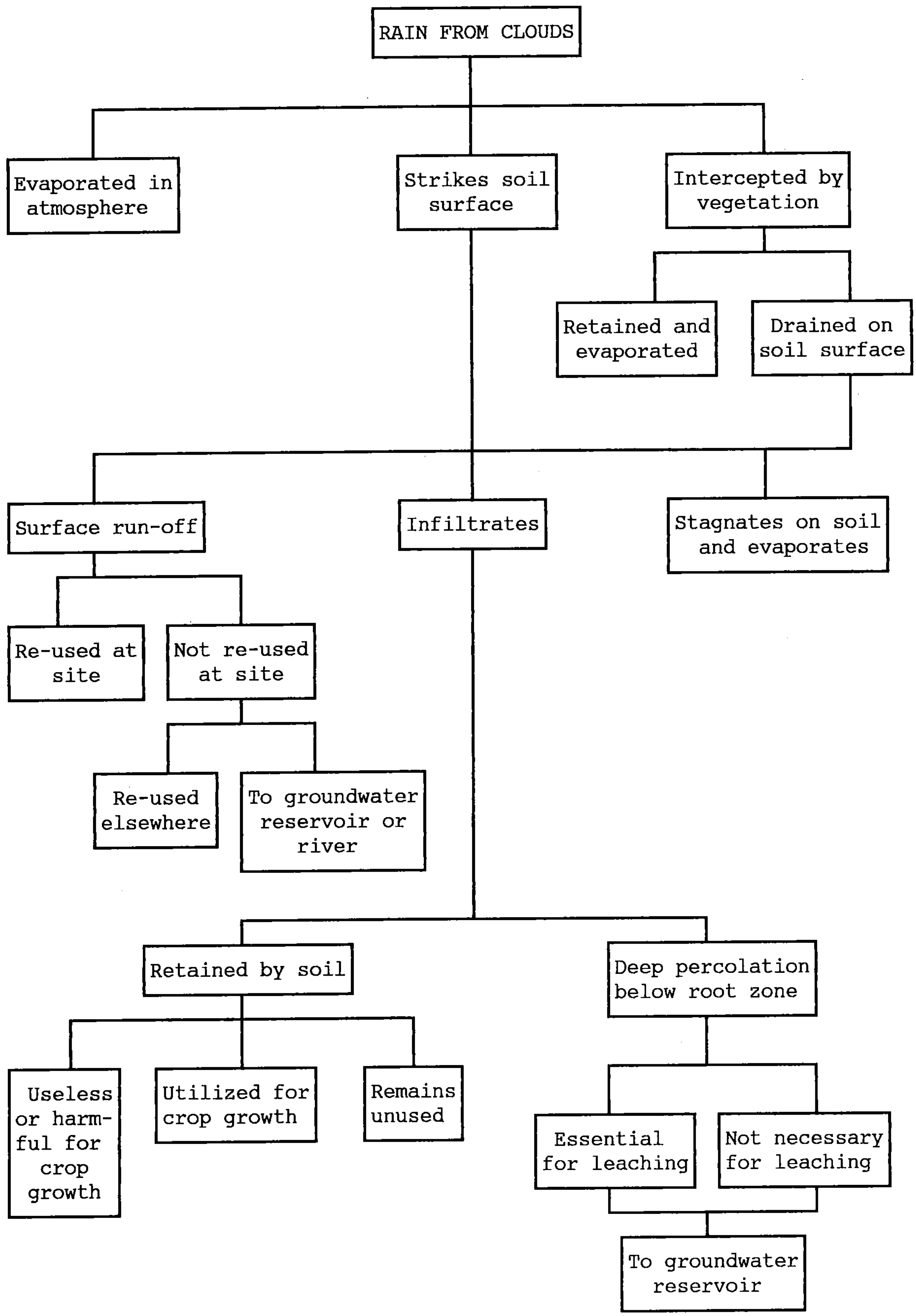


*Fig. 17 Pathway of rain water (**FAO, 1974**)*

(2) **Estimation procedures**

In assessing the effectiveness of rainfall different estimation procedures have been proposed. Values of monthly rainfall are used as input in the estimation procedures. The soil moisture storage capacity is not considered in the first three methods.

(2.1) **Fixed percentage of rainfall**

The effective monthly rainfall (P_{eff}) is calculated as a fixed percentage of the total monthly rainfall (P_{tot}) :

$$P_{eff} = a(P_{tot})$$

Usually losses amount to 10-30% of the total rainfall. The value of the coefficient a is accordingly 0.9 to 0.7 (**Smith, 1988**).

EXAMPLE

Data

Total monthly rainfall (P_{tot}) : 100 mm
Coefficient (a) : 0.80

Determination

$P_{eff} = (0.80)(100) = 80$ mm

(2.2) **FAO/AGLW formula**

Based on an analysis carried out for different climatic data, an empirical formula was developed in FAO/AGLW to determine the dependable effective rainfall i.e. the dependable rainfall at 80% probability corrected for assumed losses due to runoff and percolation (**Smith, 1988**) :

$$P_{eff} = 0.6(P_{tot})-10 \quad \text{for } P_{tot} \leq 70 \text{ mm}$$

$$P_{eff} = 0.8(P_{tot})-25 \quad \text{for } P_{tot} > 70 \text{ mm}$$

EXAMPLE

Data

Dependable monthly rainfall at 80% prob. (P_{tot}) : 50 mm

Determination

P_{eff} = (0.6)(50)-10 = 20 mm

(2.3) **USBR method**

The United States Bureau of Reclamation recommends the following formula to calculate the effective rainfall (**Smith, 1988**) :

$$P_{eff} = P_{tot}[(125-0.2(P_{tot}))/125] \quad \text{for } P_{tot} \leq 250 \text{ mm}$$
$$P_{eff} = 125+0.1(P_{tot}) \quad \text{for } P_{tot} > 250 \text{ mm}$$

EXAMPLE

Data

Monthly rainfall (P_{tot}) : 100 mm

Determination

P_{eff} = 100((125-20)/125) = 84 mm

In the two latter methods, heavier losses due to runoff and deep percolation in periods of excessive rainfall are taken care of by separate formula for high total rainfall (more than 70 mm and 250 mm respectively).

(2.4) **USDA Soil Conservation Service method**

The United States Department of Agriculture, Soil Conservation Service, has developed a procedure for estimating effective rainfall using 50 years of precipitation records at 22 experimental stations, representing different climatic and soil conditions (**FAO, 1974**).

Effective rainfall (P_{eff}) is computed from monthly total rainfall (P_{tot}) and monthly consumptive use (ETc).

$$P_{eff}=P_{tot}^2[(0.025/ETc)-0.001]+P_{tot}(0.6+0.0016\ ETc)$$

The obtained value is valid for an available soil moisture storage capacity in the root zone of 75 mm. For other values of available soil moisture storage capacity a correction is required. The correction factors are given in table 41.

The monthly effective rainfall (P_{eff}) cannot exceed the rate of consumptive use (ETc).

EXAMPLE

Data

A crop with a rooting depth of 0.50 m;
Soil moisture content at field capacity : 150 mm/m
Soil moisture content at wilting point : 50 mm/m
Fraction of the water holding capacity that is available : 2/3 or 67%

*Table 41. Multiplication factors to relate monthly effective rainfall to net depth of irrigation application (d), in mm (**FAO, 1974**)*

d [mm]	factor	d [mm]	factor	d [mm]	factor
10.00	0.620	31.25	0.818	70.00	0.990
12.50	0.650	32.50	0.826	75.00	1.000
15.00	0.676	35.00	0.842	80.00	1.004
17.50	0.703	37.50	0.860	85.00	1.008
18.75	0.720	40.00	0.876	90.00	1.012
20.00	0.728	45.00	0.905	95.00	1.016
22.50	0.749	50.00	0.930	100.00	1.020
25.00	0.770	55.00	0.947	125.00	1.040
27.50	0.790	60.00	0.963	150.00	1.060
30.00	0.808	65.00	0.977	175.00	1.070

P_{tot} = 90 mm
ETc = 70 mm

Determination

Total soil moisture storage capacity : 150-50 = 100 mm/m
Available soil moisture storage capacity in the root zone (d):
d = (150-50)(0.67)(0.5) = 33.5 mm
Correction factor for d= 33.5 mm is 0.832 (table 41)

P_{eff} = 0.832(-5.21+64.08) = (0.832)(58.87) = 49 mm

3.4.2. REFERENCE EVAPOTRANSPIRATION

3.4.2.1. Definition

The reference evapotranspiration is the potential evapotranspiration from a grass reference surface. The reference surface can equally be alfalfa or a water surface, but these cases are not considered here.

If the reference surface is a grass, ETo stands for the maximum evapotranspiration of an extensive green grass cover of uniform height (8 to 15 cm), completely shading the ground, actively growing, and experiencing no shortage of water.

Four methods of ETo calculation are discussed in this section. The first method is the one by **Blaney and Criddle (1950)** modified by **Doorenbos and Kassam (1977)**. This method is useful if limited climatic data are available : only mean monthly temperature data are requested in the procedure. All other methods are based on the **Penman (1948)** formula. The second and third method were developed by **Frère and Popov (1979)** and by **Doorenbos and Pruitt (1977)** respectively. The fourth and most recent method is the Penman-Monteith approach (**Smith, 1991**). The latter methods yield more accurate estimations of the reference evapotranspiration but require a larger climatic data set : mean monthly data of maximum temperature, minimum tempera-ture, sunshine hours, relative humidity and wind velocity.

3.4.2.2. Units

The climatic variables entered into the calculation procedures of the first three methods should have units according to the c.g.s. convention as requested in the formula. If the data have different units a transformation is required. Some of these transformations are given below.

1) Latitude
units : degrees and minutes

2) Altitude/Elevation
units : meter
transformation :
if the elevation is given in feet, multiply by 0.3048 to obtain m

3) Temperature
units : °C
transformation :
if temperature is expressed in degrees Fahrenheit then convert as $°C = 5/9(°F+40) - 40$

4) Bright sunshine
units : hours and decimal hours
transformation :
if time of bright sunshine is given in hours and minutes then convert as hours + (minutes/60)
if visual cloud observation is given in tenths (0 to 10) then multiply by 0.8 to obtain okta's
if cloudiness is given in okta's one finds the value of n/N using : $n/N = [1-(cloud/8)] + [0.025\ (5-cloud)] + 0.075$

5) Radiation
units : $J/cm^2.day$
transformation :
if radiation is given in $cal/cm^2.day$ (langley/day), multiply by 4.1855 to obtain $J/cm^2.day$
if radiation is given in $W/m^2.day$, multiply by 8.64 to obtain $J/cm^2.day$

if radiation is given in J/cm^2.day, multiply by 0.0709 to obtain equivalent evaporation in mm/day

6) Relative humidity
units : percent
transformation :

if actual vapour pressure is given in mm Hg, multiply by 1.33 to obtain mbar
if actual vapour pressure (eact) is given in mbar, and saturation vapour pressure (esat) calculated from the mean air temperature,relative humidity is obtained from
RH = (eact/esat) 100

7) Wind velocity
units : m/s
transformation :

to obtain wind velocity in m/s multiply by
0.2778 if data are in km/hr
0.3048 if data are in ft/s
0.4470 if data are in mile/hr
0.5144 if data are in nautical mile/hr (knot)
to obtain wind velocity in km/day multiply by
86.4 if data are in m/s

Wind velocity data, not collected at 2 m above ground level can be converted using the following equation :

$$U2 = Uz \log (200/2)/\log (100\ z/2)$$

where U2 = wind run at 2 m above ground level
Uz = wind run at z m above ground level

In both the calculation procedures of **Frère and Popov** (1979) and **Doorenbos and Pruitt** (1977), a preliminary knowledge on the climatic type is required. In the original procedure of **Frère**

and Popov (**1979**) reference is made to a map of climatic zones by **Trewartha** (**1957**). Since the zones on the map only have an indicative value they can be identified using the climatic classification of **Köppen and Geiger** (**1928**).

Köppen and Geiger (**1928**) differentiate between 5 major climatic types :

A climates : humid tropical climates
B climates : dry (steppe and desert) climates
C climates : warm-temperate rainy climates
D climates : subarctic climates
E climates : polar climates

In order to classify a climate, the following input data are needed :

the mean temperature of the coldest month (tc in °C)
the mean temperature of the warmest month (tw in °C)
the mean annual temperature (ta in °C)
the total annual rainfall (r in mm/year)
the rainfall distribution

A first differentiation is based on the values of tc and tw :

tw<10	and	tc<0	:	E
tw≥10	and	tc<-3	:	D,B
	and	-3<tc<18	:	C,B
	and	tc≥18	:	A,B

A second differentiation uses the values of ta, r and rainfall distribution :

equal rain :	r>20(ta+7)	:	A,C,D
	r<20(ta+7)	:	B

summer rain :	$r>20(ta+14)$:	A,C,D
	$r<20(ta+14)$:	B
winter rain :	$r>20(ta)$:	A,C,D
	$r<20(ta)$:	B

The climate of the area considered belongs to the climatic type that occurs in the outcome of the two successive differentiation steps.

3.4.2.3. ETo according to Blaney and Criddle

The reference evapotranspiration ETo [mm/day] according to the method of **Blaney and Criddle (1950)**, modified by **Doorenbos and Pruitt (1977)**, is obtained from the following expression :

$$ETo = c \cdot f$$

where $f = [\ p\ (0.46\ t + 8)\ ]$

with f = consumptive use factor
t = mean monthly temperature (°C)
p = mean daily percentage of total annual daytime hours
c = adjustment factor which depends on estimates of the minimum relative humidity (RHmin in %), actual bright sunshine hours over astronomically possible sunshine hours (n/N) and daytime wind velocity (Uday in m/s) at 2 m above ground level.

The value of p can be retrieved from table 42. The value of f is calculated from the formula using p and t as input data. The

*Table 42. Mean Daily Percentage (p) of Annual Daytime Hours for Different Latitudes (**Doorenbos and Pruitt, 1977**)*

Latitude North / South[1]	JAN / JULY	FEB / AUG	MAR / SEPT	APR / OCT	MAY / NOV	JUNE / DEC	JULY / JAN	AUG / FEB	SEPT / MAR	OCT / APR	NOV / MAY	DEC / JUNE
60°	.15	.20	.26	.32	.38	.41	.40	.34	.28	.22	.17	.13
58°	.16	.21	.26	.32	.37	.40	.39	.34	.28	.23	.18	.15
56°	.17	.21	.26	.32	.36	.39	.38	.33	.28	.23	.18	.16
54°	.18	.22	.26	.31	.36	.38	.37	.33	.28	.23	.19	.17
52°	.19	.22	.27	.31	.35	.37	.36	.33	.28	.24	.20	.17
50°	.19	.23	.27	.31	.34	.36	.35	.32	.28	.24	.20	.18
48°	.20	.23	.27	.31	.34	.36	.35	.32	.28	.24	.21	.19
46°	.20	.23	.27	.30	.34	.35	.34	.32	.28	.24	.21	.20
44°	.21	.24	.27	.30	.33	.35	.34	.31	.28	.25	.22	.20
42°	.21	.24	.27	.30	.33	.34	.33	.31	.28	.25	.22	.21
40°	.22	.24	.27	.30	.32	.34	.33	.31	.28	.25	.22	.21
35°	.23	.25	.27	.29	.31	.32	.32	.30	.28	.25	.23	.22
30°	.24	.25	.27	.29	.31	.32	.31	.30	.28	.26	.24	.23
25°	.24	.26	.27	.29	.30	.31	.31	.29	.28	.26	.25	.24
20°	.25	.26	.27	.28	.29	.30	.30	.29	.28	.26	.25	.25
15°	.26	.26	.27	.28	.29	.29	.29	.28	.28	.27	.26	.25
10°	.26	.27	.27	.28	.28	.29	.29	.28	.28	.27	.26	.26
5°	.27	.27	.27	.28	.28	.28	.28	.28	.28	.27	.27	.27
0°	.27	.27	.27	.27	.27	.27	.27	.27	.27	.27	.27	.27

(1) Southern latitudes : apply 6 month difference as shown

value of ETo is estimated graphically from figure 18 where ETo is represented on the Y-axis and f is represented on the X-axis. Relationschips are given for 3 levels of RHmin, 3 levels of n/N and 3 levels of daytime wind run (Uday).

Note that air humidity refers here to minimum daytime humidity and that wind run refers to daytime wind velocity. If estimates of 24 hour mean wind velocity are available, these have to be converted to daytime wind velocity. Generally Uday/Unight ≈ 2, and 24 hour wind data should be multiplied by 1.33 to obtain Uday. For areas with either predominantly night or daytime wind, the following correction factor can be used :

Uday/Unight	1.0	1.5	2.0	2.5	3.0	3.5	4.0
correction	1.0	1.2	1.33	1.43	1.5	1.56	1.6

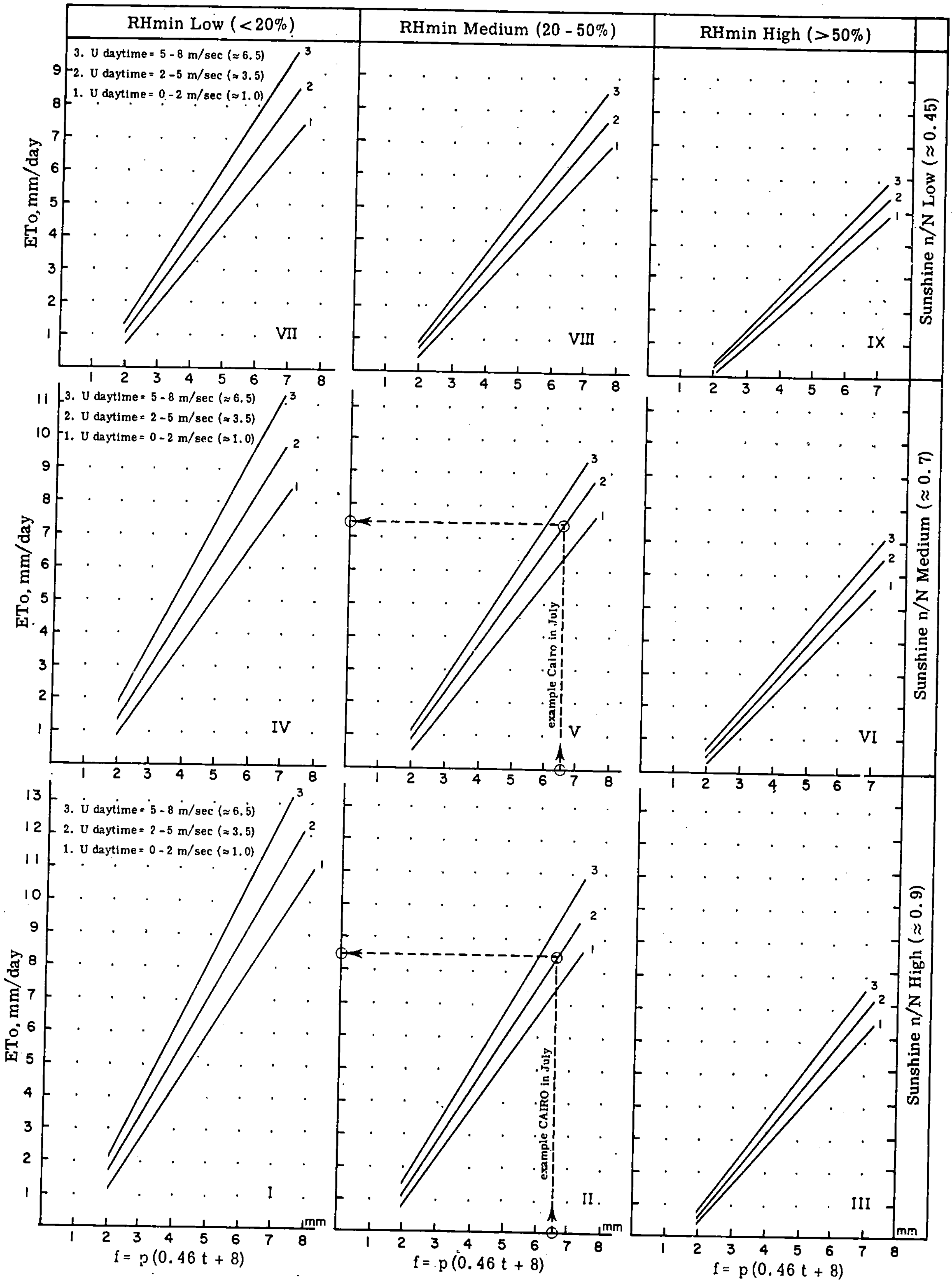


*Fig. 18 Prediction of ETo from Blaney-Criddle f factor for different conditions of minimum relative humidity, sunshine duration and day time wind (**Doorenbos and Pruitt, 1977**).*

Although this method is interesting as only few input data are required, and although the method has validity when locally-calibrated correction factors are used, in a recent expert consultation (**Smith, 1991**) it was not proposed to recommend this method further. It was felt that a possibly more satisfactory temperature method could be developed by using maximum and minimum temperatures.

EXAMPLE

Data

Country	:	Cameroon	
Station	:	Garoua	
Latitude	:	9° 20'N	
Month	:	June	
t mean	:	27.10 °C	
RHmin estimate	:	45 %	[Medium]
n/N estimate	:	0.6	[Medium]
Uday estimate	:	3.6 m/s	[Medium]

Determination

p	table 42	.29
t	data	27.10
f	calc p(0.46t+8)	5.94
RH min	[Medium]	
n/N	[Medium]	
Uday	[Medium]	

Block/line V/2 **ETo = 6.6 mm/day**

3.4.2.4. Modified Penman ETo according to Frère and Popov

Frere and Popov (1979) proposed a calculation method that represents the experience acquired by the FAO over the period 1969-1979.

The formula for calculating ETo (mm/day) is given by :

$$\mathbf{ETo} = \frac{(Rn.C + A)}{C + 1}$$

The calculation involves :

The estimation of a net radiation term : Rn
The determination of an aerodynamic term : A
The determination of a correction term : C
the latter takes into account the ratio of the atmospheric pressure at sea level and the atmospheric pressure at the altitude of the location, and the slope of the saturated vapour pressure curve devided by the psychrometric constant.

(1) **Net radiation term (Rn)**

The net radiation term is obtained from the difference between the net incoming shortwave radiation Rns and the net outgoing long wave radiation Rnl.

$$Rn = Rns - Rnl$$

(1.1) **The incoming shortwave radiation (Rns)**

The total or global radiation received at the earth surface (Rs) is proportional to the number of hours of bright sunshine received during the day (n).

$$Rs \approx n$$

The extraterrestrial radiation (Ra), received at the edge of the atmosphere, is a function of the latitude and the period in the year.
The daylength, and thus the astronomically possible number of sunshine hours (N) equally varies with the latitude and time in the year. Since bright sunshine duration usually is represented by the ratio of actual sunshine hours over astronomically possible sunshine hours (n/N), it is reasonable to accept the following relationship :

$$Rs/Ra \approx n/N$$

Since this relationship was found to be linear, it was writen as

$$Rs/Ra = a + b\ (n/N)$$

or

$$Rs = Ra\ (a + b\ (n/N))$$

This is the Angström formula. Remark that, if n=0 (no bright sunshine), Rns = Ra.a. This means that on a complete could-covered day with no bright sunshine, the global radiation transmitted and received at the earth surface equals the fraction "a" of the extraterrestrial radiation Ra. The fraction "b" of the extraterrestrial radiation is absorbed by clouds.

The values of a and b depend on the climatic zone.If use is made of the climatic classification defined by Köppen and Geiger (1928), the following is valid :

a = 0.29 b = 0.42 for A climates (humid tropical)
a = 0.25 b = 0.45 for B climates (dry tropical)
a = 0.18 b = 0.55 for C,D or E climates (temperate and cold)

Most of the earth's phenomena do not absorb all of the received global radiation, but partially reflect it. The reflection or albedo in the case of an open water surface is 5 % .In the case of a vegetative cover the albedo amounts to about 25 % .
The net incoming shortwave radiation then becomes :

$$Rns = (1 - 0.25)\ Ra\ (a + b\ (n/N))$$

or

$$Rns = 0.75\ Ra\ (a + b\ (n/N))$$

The value of Ra is obtained from table 43. The value of N can be retrieved from table 33. The values of a and b are given above for the climatic zone of interest. The value of n is given for the climatic station.

(1.2) **Outgoing longwave radiation (Rnl)**

The outgoing longwave (infrared) radiation depends on the black body radiation calculated according to the Stefan-Boltzmann law (equivalent mm evaporable water per day), the presence of water vapour (vapour pressure in mbar) and the degree of cloudiness. The latter two elements act as absorbers of the emitted longwave radiation.

$$Rnl = \sigma T^4\ (0.56 - 0.079\sqrt{eact})(0.1 + 0.9(n/N))$$

*Table 43. Extra-terrestrial Radiation (Ra) expressed in equivalent evaporation in mm/day (**Doorenbos and Kassam, 1979**)*

Northern Hemisphere													Southern Hemisphere											
Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Lat	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
6.4	8.6	11.4	14.3	16.4	17.3	16.7	15.2	12.5	9.6	7.0	5.7	40°	17.9	15.7	12.5	9.2	6.6	5.3	5.9	7.9	11.0	14.2	16.9	18.3
6.9	9.0	11.8	14.5	16.4	17.2	16.7	15.3	12.8	10.0	7.5	6.1	38	17.9	15.8	12.8	9.6	7.1	5.8	6.3	8.3	11.4	14.4	17.0	18.3
7.4	9.4	12.1	14.7	16.4	17.2	16.7	15.4	13.1	10.6	8.0	6.6	36	17.9	16.0	13.2	10.1	7.5	6.3	6.8	8.8	11.7	14.6	17.0	18.2
7.9	9.8	12.4	14.8	16.5	17.1	16.8	15.5	13.4	10.8	8.5	7.2	34	17.8	16.1	13.5	10.5	8.0	6.8	7.2	9.2	12.0	14.9	17.1	18.2
8.3	10.2	12.8	15.0	16.5	17.0	16.8	15.6	13.6	11.2	9.0	7.8	32	17.8	16.2	13.8	10.9	8.5	7.3	7.7	9.6	12.4	15.1	17.2	18.1
8.8	10.7	13.1	15.2	16.5	17.0	16.8	15.7	13.9	11.6	9.5	8.3	30	17.8	16.4	14.0	11.3	8.9	7.8	8.1	10.1	12.7	15.3	17.3	18.1
9.3	11.1	13.4	15.3	16.5	16.8	16.7	15.7	14.1	12.0	9.9	8.8	28	17.7	16.4	14.3	11.6	9.3	8.2	8.6	10.4	13.0	15.4	17.2	17.9
9.8	11.5	13.7	15.3	16.4	16.7	16.6	15.7	14.3	12.3	10.3	9.3	26	17.6	16.4	14.4	12.0	9.7	8.7	9.1	10.9	13.2	15.5	17.2	17.8
10.2	11.9	13.9	15.4	16.4	16.6	16.5	15.8	14.5	12.6	10.7	9.7	24	17.5	16.5	14.6	12.3	10.2	9.1	9.5	11.2	13.4	15.6	17.1	17.7
10.7	12.3	14.2	15.5	16.3	16.4	16.4	15.8	14.6	13.0	11.1	10.2	22	17.4	16.5	14.8	12.6	10.6	9.6	10.0	11.6	13.7	15.7	17.0	17.5
11.2	12.7	14.4	15.6	16.3	16.4	16.3	15.9	14.8	13.3	11.6	10.7	20	17.3	16.5	15.0	13.0	11.0	10.0	10.4	12.0	13.9	15.8	17.0	17.4
11.6	13.0	14.6	15.6	16.1	16.1	16.1	15.8	14.9	13.6	12.0	11.1	18	17.1	16.5	15.1	13.2	11.4	10.4	10.8	12.3	14.1	15.8	16.8	17.1
12.0	13.3	14.7	15.6	16.0	15.9	15.9	15.7	15.0	13.9	12.4	11.6	16	16.9	16.4	15.2	13.5	11.7	10.8	11.2	12.6	14.3	15.8	16.7	16.8
12.4	13.6	14.9	15.7	15.8	15.7	15.7	15.7	15.1	14.1	12.8	12.0	14	16.7	16.4	15.3	13.7	12.1	11.2	11.6	12.9	14.5	15.8	16.5	16.6
12.8	13.9	15.1	15.7	15.7	15.5	15.5	15.6	15.2	14.4	13.3	12.5	12	16.6	16.3	15.4	14.0	12.5	11.6	12.0	13.2	14.7	15.8	16.4	16.5
13.2	14.2	15.3	15.7	15.5	15.3	15.3	15.5	15.3	14.7	13.6	12.9	10	16.4	16.3	15.5	14.2	12.8	12.0	12.4	13.5	14.8	15.9	16.2	16.2
13.6	14.5	15.3	15.6	15.3	15.0	15.1	15.4	15.3	14.8	13.9	13.3	8	16.1	16.1	15.5	14.4	13.1	12.4	12.7	13.7	14.9	15.8	16.0	16.0
13.9	14.8	15.4	15.4	15.1	14.7	14.9	15.2	15.3	15.0	14.2	13.7	6	15.8	16.0	15.6	14.7	13.4	12.8	13.1	14.0	15.0	15.7	15.8	15.7
14.3	15.0	15.5	15.5	14.9	14.4	14.6	15.1	15.3	15.1	14.5	14.1	4	15.5	15.8	15.6	14.9	13.8	13.2	13.4	14.3	15.1	15.6	15.5	15.4
14.7	15.3	15.6	15.3	14.6	14.2	14.3	14.9	15.3	15.3	14.8	14.4	2	15.3	15.7	15.7	15.1	14.1	13.5	13.7	14.5	15.2	15.5	15.3	15.1
15.0	15.5	15.7	15.3	14.4	13.9	14.1	14.8	15.3	15.4	15.1	14.8	0	15.0	15.5	15.7	15.3	14.4	13.9	14.1	14.8	15.3	15.4	15.1	14.8

with σ = 1.9838 10^{-9} mm/day. K^4
(Stefan-Boltzmann radiation constant)
T = absolute mean temperature (°K =°C + 273.15)
eact = mean actual vapour pressure [mbar]
n = actual sunshine hours
N = astronomically possible sunshine hours

The value of the mean actual vapour pressure (eact) is obtained from the expression for the saturated vapour pressure (esat) based on the mean air temperature (t) and from the value of the mean relative air humidity (RH), as follows :

$$esat = 6.1078\ e^{[17.27\ t/(t\ +\ 237.3)]} \qquad [mbar]$$

$$eact = esat\ (RH/100) \qquad [mbar]$$

(2) **Aerodynamic term**

This term is related to the vapour pressure deficit (esat - eact) and to the daily wind velocity measured at 2 m above the ground.

$$A = 0.26\ (esat\ -\ eact)\ (1\ +\ cu.U)$$

where esat = saturated vapour pressure [mbar]
eact = mean actual vapour pressure [mbar]
cu = correction term
U = daily wind velocity [m/s]

The correction term cu makes up for advection contributions to the evapotranspiration in arid areas (which show large differences between minimum and maximum air temperatures).
The values for cu are as follows, considering that t equals the mean air temperature and δt is the difference between maximum

and minimum air temperature :

cu = 0.54
if t ≤ 5 °C or δt ≤ 12 °C

$cu = 0.54 + (0.35/(1 + 50\ e^{0.9(9.5-\delta t)}))$.
if δt > 12 °C and δt < 16 °C

cu = 0.89
If δt ≥ 16 °C

(3) **Correction term (C)**

The correction term is given by

$$C = (esat/T)\ ((9792/T) - 5.95)\ (10^{(E/67.40721\ T)})$$

with esat = saturated vapour pressure [mbar]
T = mean absolute temperature [°K = °C + 273.15]
E = elevation of the site [m]

EXAMPLE

Data

Country	:	Cameroon
Station	:	Garoua
Latitude	:	9°20'N
Altitude	:	244 m

Month	:	June	
n	:	7.60	[hours.decimal hours]
tmax	:	32.10	[°C]
tmin	:	22.10	[°C]
RH	:	74.20	[%]

U	:	2.70	[m/s]
tw	:	32.25	[°C]
tc	:	25.85	[°C]
ta	:	28.12	[°C]
r	:	1014.00	[mm]

rain distribution : summer rain

Determination

(1) Climatic type

step 1	tc≥10 C	25.85>10
	tw≥18 C	32.35>18

climatic type A or B

step 2	calc 20(t+7)	702.4
	check r>20(t+7)	1014>702.4

climatic type A,C or D

Conclusion : climatic type A (humid tropical)

(2) Net radiation term

(2.1) Net incoming shortwave radiation

Ra	table 43		15.20
N	table 33		12.67
n	data		7.60
a	clim.type A		0.29
b	clim.type A		0.42
Rns	calc	0.75Ra(a+b(n/N))	6.18

(2.2) Net outgoing longwave radiation

T	calc	(t+273.15)	300.25
esat	calc	(6.108 $e^{(17.27\ t/t+237.3)}$	35.86
eact	calc	(RH/100)(esat)	26.61
σT4	calc	1.9838 $10^{-9}T^4$	16.12
	calc	(0.56-0.079 $\sqrt{eact}$)	0.15
	calc	(0.1+0.9n/N)	0.64
Rls	calc		1.55

(2.3) Net radiation term

Rn	calc	(Rns - Rnl)	4.63

(3) Aerodynamic term

t	data		27.10
δt	calc	tmax-tmin	10.00
cu	check	δt<12	0.54
U	data		2.70
eact	calc		26.61
esat	calc		35.86
A	calc	(0.26)(esat-eact)(1+cu.U)	5.91

(4) Correction term

term1	calc	esat/T	0.119
term2	calc	(9792/T)-5.95	26.663
term3	calc	$10^{(E/67.40721\ T)}$	1.028
C	calc	(term1.term2.term3)	3.26

(5) Evapotranspiration

ETo	calc	(A+Rn.C)/(C+1)	4.93 mm/day

3.4.2.5. Modified Penman ETo according to Doorenbos and Pruitt

The modified Penman method as described by **Doorenbos and Pruitt (1977)** yields good results with minimum possible errors of ± 10 % under high evaporative conditions and up to ± 20 % under low evaporative conditions.

The reference evapotranspiration ETo (mm/day) is calculated as

$$\mathbf{ETo = c\ [\ W\ Rn + (1-W)\ f(u)\ (esat-eact)\ ]}$$

where

- W : temperature related weighting factor (dimensionless) [ ]
- Rn : net radiation in equivalent evaporation [mm/day]
- f(u) : wind-related function [mm/mbar.day]
- esat : saturation vapour pressure at mean air temperature [mbar]
- eact : mean actual vapour pressure [mbar]
- c : adjustment factor related to maximum humidity, solar radiation, the ratio of day-time to night-time winds and wind velocity.

(1) **Temperature term (W)**

δ, the rate of change of the saturation vapour pressure with temperature [mbar/°C], is calculated as

$$\delta = 2(0.00738\ t + 0.8072)^7 - 0.00116$$

with t = mean air temperature [°C]

The psychrometric constant τ [mbar/°C] is given by

$\tau = 1.61452\ P/L$

with 1.61452 [J/°C.gram]

P = barometric pressure of the air [mbar]

L = latent heat of vaporization [J/gram]

The value for P and L are obtained from

$P = 1013 - 0.1093\ E$

$L = 4.1855\ (595 - 0.51\ t)$

with E = elevation above sea level [m]

t = mean air temperature [°C]

The term W is ultimately calculated as

$W = (\delta/\delta+\tau)$ [ ]

(2) **Net radiation term (Rn)**

The net radiation is obtained from the difference between the net incoming shortwave radiation Rns and the net outgoing longwave radiation Rnl, both expressed in mm/day.

$Rn = Rns - Rnl$

(2.1) **Incoming shortwave radiation (Rns)**

Rns is given by the following expression :

$Rns = (1-\alpha)\ Rs$

where α = albedo (fraction of the incoming solar radiation

that is reflected by the surface)
α=0.25 for most crops and α=0.05 for water
Rs = the incoming solar radiation [mm/day]

The value of Rs is calculated from the Angstrom formula :

$$Rs = Ra\,(a + b\,(n/N))$$

where n = actual sunshine hours
N = maximum possible sunshine hours
Ra = the extra-terrestrial radiation [mm/day]

Both the values of N and Ra are depending on latitude and the time of the year. The values of the coefficients a and b differ with major climatic areas. If use is made of the climatic classification of **Koppen and Geiger (1928)**, the following is valid :

a = 0.29	b = 0.42	for A climates (humid tropical)
a = 0.25	b = 0.45	for B climates (dry tropical)
a = 0.18	b = 0.55	for C,D or E climates (temperate and cold)

(2.2) **The net outgoing longwave radiation (Rnl)**

The term Rnl is calculated by the Stefan-Boltzmann law, adapted for the presence of water vapour and cloudiness which absorb the emitted longwave radiation.

$$Rnl = \varepsilon\,(\sigma T^4)\,(0.34 - 0.044\sqrt{eact})\,(0.1 + (1-0.1)\,n/N)$$

with ε = the emissivity constant ($\approx$ 1)
σ = the Stefan-Boltzmann radiation constant, equal to 1.9838 10^{-9} [mm/day. K^4]
T = absolute mean temperature [°K = °C + 273]

eact = mean actual vapour pressure of the air [mbar]

(3) **The wind function f(u)**

The wind function is of the form

$$f(u) = 0.27 + 0.0030\ U2$$

where U2 = the daily wind speed at 2 m above the ground [km/day]

0.27 and 0.0030 are coefficients for a grass reference surface

The above equation is valid for moderate day-time wind and a ratio of day-time wind to night-time wind equal to 2. If these conditions are different, corrections are made in the adjustment term of the ETo formula.

(4) **Vapour pressure deficit term (esat - eact)**

The values of the saturation vapour pressure esat and of the actual vapour pressure eact are given by the following formula:

$$esat = 6.1078\ e^{(17.27\ t/(t + 237.3))}$$

$$eact = esat\ (RH/100)$$

with t = mean air temperature [°C]

RH = relative air humidity [%]

(5) **The adjustment term (C)**

The adjustment term is required if the conditions for which the Penman formula was derived are not met. The values of C are obtained from table 44 as a function of four variables :

*Table 44. Adjustment factor c as a function of the maximum relative humidity (RHmax), incoming solar radiation (Rs), day time wind speed (Uday) and the day/night wind ratio (**Doorenbos and Pruitt, 1977**).*

	RHmax = 30%				RHmax = 60%				RHmax = 90%			
Rs mm/day	3	6	9	12	3	6	9	12	3	6	9	12
Uday m/sec	Uday/Unight = 4.0											
0	.86	.90	1.00	1.00	.96	.98	1.05	1.05	1.02	1.06	1.10	1.10
3	.79	.84	.92	.97	.92	1.00	1.11	1.19	.99	1.10	1.27	1.32
6	.68	.77	.87	.93	.85	.96	1.11	1.19	.94	1.10	1.26	1.33
9	.55	.65	.78	.90	.76	.88	1.02	1.14	.88	1.01	1.16	1.27
	Uday/Unight = 3.0											
0	.86	.90	1.00	1.00	.96	.98	1.05	1.05	1.02	1.06	1.10	1.10
3	.76	.81	.88	.94	.87	.96	1.06	1.12	.94	1.04	1.18	1.28
6	.61	.68	.81	.88	.77	.88	1.02	1.10	.86	1.01	1.15	1.22
9	.46	.56	.72	.82	.67	.79	.88	1.05	.78	.92	1.06	1.18
	Uday/Unight = 2.0											
0	.86	.90	1.00	1.00	.96	.98	1.05	1.05	1.02	1.06	1.10	1.10
3	.69	.76	.85	.92	.83	.91	.99	1.05	.89	.98	1.10	1.14
6	.53	.61	.74	.84	.70	.80	.94	1.02	.79	.92	1.05	1.12
9	.37	.48	.65	.76	.59	.70	.84	.95	.71	.81	.96	1.06
	Uday/Unight = 1.0											
0	.86	.90	1.00	1.00	.96	.98	1.05	1.05	1.02	1.06	1.10	1.10
3	.64	.71	.82	.89	.78	.86	.94	.99	.85	.92	1.01	1.05
6	.43	.53	.68	.79	.62	.70	.84	.93	.72	.82	.95	1.00
9	.27	.41	.59	.70	.50	.60	.75	.87	.62	.72	.87	.96

- maximum relative air humidity (RHmax)
- incoming solar radiation (Rs)
- ratio of day-time windspeed over night-time windspeed (Uday/Unight)
- day-time windspeed (Uday)

EXAMPLE

Data

Country	:	Cameroon
Station	:	Garoua
Latitude	:	9°20'N
Month	:	June
n	:	7.60 [hrs.decimal hrs]
tmax	:	32.10 [°C]
tmin	:	22.10 [°C]
RH	:	74.20 [%]
U2	:	2.70 [m/s]
Uday/Unight	:	2.00
tw	:	32.25 [°C]
tc	:	25.85 [°C]
ta	:	28.12 [°C]
r	:	1014.00 [mm]

rain distribution : summer rain

Determination

(1) Temperature term

t	calc	(tmax-tmin)/2	27.10
δ	calc	$2(0.00738t+0.8072)^7-0.00116$	2.10
E	data		244.00
P	calc	1013-0.1093E	986.33
L	calc	4.1855(595-0.51t)	2432.52
τ	calc	1.61452(P/L)	0.65
W	calc	(δ/δ+τ)	0.76

(2) Net Radiation term

(2.1) Incoming shortwave radiation

Ra	table 43		15.20
n	data		7.60
N	table 33		12.67
a	clim.type		0.29
b	clim.type		0.42
Rns	calc	0.75Ra(a+b(n/N))	6.18

(2.2) Outgoing longwave radiation

T	calc	(273.15+t)	300.25
$\sigma T4$	calc		16.12
esat	calc	$(6.108\ e^{(17.27t/t+237.3)})$	35.86
eact	calc	(RH/100)esat	26.61
n	data		7.60
N	data		12.67
Rnl			1.15

(2.3) Net radiation

Rn	calc	(Rns-Rnl)	5.03

(3) Wind function

U2	data	233.3
f(u)	calc	0.97

(4) Vapour pressure deficit term

esat	calc	35.86

eact	calc	26.61
(esat-eact)	calc	9.25

(5) Adjustment term

c	table 44	1.00

(6) ETo

ETo calc	c[W Rn + (1-W) f(u) (esat-eact)]	5.98 mm/day

3.4.2.6. Comparison of the modified Penman ETo methods

The methods of **Frere and Popov (1979)** and of **Doorenbos and Pruitt (1977)** have been developed from the original Penman formula. They differ mainly in their interpretation of the wind term.

Between values obtained from both methods the following significant linear relationship is observed :

ETODP = -1.32399 + 1.48401 ETOFP

ETOFP = 0.976941 + 0.65642 ETODP

with r = 0.987 (correlation coefficient)
n = 107 (number of observations)
ETODP = ETo (Doorenbos and Pruitt)
ETOFP = ETo (Frere and Popov)

3.4.2.7. The Penman-Monteith approach

Recent comparative studies carried out under the auspices of the ASCE and the European Commission have shown the very convincing performance under varying climatic conditions of the method based on the Penman-Monteith approach. The expert consultation on procedures for revision of FAO guidelines for prediction of crop water requirements (**Smith, 1991**) therefore recommends this approach as the best-performing combination equation. The calculation of the parameters to be used in the estimation of the reference evapotranspiration and the estimation procedure s.s. are given in detail hereafter.

The definition of the reference evapotranspiration in the Penman-Monteith approach is slightly modified. The reference evapotranspiration ETo is now defined as the rate of evapotranspiration of a hypothetic crop with fixed crop height (12 cm), canopy resistance (69) and albedo (0.23) which would closely resemble evapotranspiration from an extensive surface of green grass cover of uniform height, actively growing, completely shading the ground and not short of water.

The Penman-Monteith approach has equally other features that will enable to calculate the crop evapotranspiration (ETc) at once, rather than using the two-step procedure : calculation of ETo and a crop coefficient kc separately to obtain ETc.

(1) Parameters used in the ETo equation

(1.1) Conversion of units

In line with the international standards SI units are used for all parameters. These units replace the c.g.s. convention used previously.

	c.g.s. convention	SI system
Pressure	1 mbar	0.1 kPa
Radiation	1 cal/cm².day	0.041868 MJ/m².day
	1 mm/day	2.45 MJ/m².day
	23.884 cal/cm².day	1 MJ/m².day
	0.408 mm/day	1 MJ/m².day

(1.2) **Latent heat of vaporization (λ)**

$$\lambda = 2.501 - (0.002361\ t)$$

where λ = latent heat of vaporization [MJ/kg]
t = air temperature [°C]

Reference : **Harrison (1963)**

As the value of the latent heat varies only slightly over normal temperature ranges, a single value for lambda may be taken. For t = 20°C, λ = 2.45

(1.3) **Saturation vapour pressure (e_a)**

$$e_a = 0.6108 \exp(17.27\ t/(t+237.3))$$

where e_a = Saturation vapour pressure [kPa]
t = Temperature [°C]

Reference : **Tetens (1930)**

(1.4) **Actual vapour pressure**

at early morning :

$$e_{d(tmin)} = e_{a(tmin)}\ RH_{max}/100$$

where $e_{d(tmin)}$ = Actual vapour pressure at tmin [kPa]
$e_{a(tmin)}$ = Saturation vapour pressure at tmin [kPa]
$RH_{(max)}$ = Maximum daily relative humidity [%]
tmin = Minimum daily air temperature [°C]

at noon :

$$e_{d(tmax)} = e_{a(tmax)}\ RH_{min}/100$$

where $e_{d(tmax)}$ = Actual vapour pressure at tmax [kPa]
$e_{a(tmax)}$ = Saturation vapour pressure at tmax [kPa]
RH_{min} = Minimum daily relative humidity [%]
tmax = Maximum daily air temperature [°C]

The average vapour pressure is calculated as :

$$e_d = (e_{d(tmin)} + e_{d(tmax)})/2$$

If no RH_{min} and RH_{max} information is available, the actual vapour pressure may be estimated as follows :

$$e_d \approx e_{a(mean)}\ RH_{mean}/100$$

where e_d = Actual vapour pressure [kPa]
$e_{a(mean)}$ = Mean saturation vapour pressure [kPa]
RH_{mean} = Mean relative air humidity [%]

(1.5) **Slope of the vapour pressure curve (δ)**

$$\delta = 4098\ e_a/(t+237.3)^2$$

where δ = Slope of the vapour pressure curve [kPa/°C]
t = air temperature [°C]
e_a = Saturation vapour pressure [kPa]

Reference : **Tetens (1930); Murray (1967)**

(1.6) **Atmospheric pressure (P)**

$$P = P_o \, [(T_o - \alpha(z-z_o))/T_o]^{g/\alpha R}$$

where P = Atm pressure at elevation z [kPa]
P_o = Atm pressure at reference level [kPa]
z = elevation [m]
z_o = elevation at reference level [m]
g = gravitational acceleration (=9.8) [m/s²]
R = specific gas constant (=287) [J/kg.°K]
T_o = Air temperature at elevation z_o (=273.16+t)[°K]
α = constant lapse rate saturated air (=0.0065) [°K/m]

When assuming P_o = 101.3 kPa (z_o = 0)
T_o = 293 K (t=20°C)

$$P = 101.3[(293-0.0065\, z)/293]^{5.256}$$

(1.7) **Psychrometric constant (τ)**

$$\tau = 0.0016286\, P/\lambda$$

where τ = Psychrometric constant [kPa/°C]
P = Atm pressure [kPa]
λ = Latent heat [MJ/kg]

Reference : **Brunt (1952)**

(1.8) **Modified psychrometric constant (τ^*)**

$$\tau^* = \tau(1+(r_c/r_a))$$

where τ^* = Modified pscychrometric constant [kPa/°C]

τ = Psychrometric constant [kPa/°C]
r_c = Crop canopy resistance [s/m]
r_a = Aerodynamic resistance [s/m]

Reference : **Monteith (1965)**

The resistance factors in the above equation are defined as follows :

$$r_c = R_l/(0.5\ LAI) = 200/LAI$$

where r_c = Crop canopy resistance [s/m]
R_l = average daily stomata resistance of a single leaf(≈100) [s/m]
LAI = Leaf area index [ ]

Reference : **Allen et al. (1986)**

For the reference crop (grass) with a crop height (h_c) of 0.12 m, the LAI is calculated as LAI = 24 h_c = 2.88 m^2/m^2. The canopy resistance then becomes :

$$r_c = 200/2.88 = 69\ s/m$$

The aerodynamic resistance r_a is defined as follows :

$$r_a = \ln[(z_w-d)/z_{ow}].\ln[(z_h-d)/z_{oh}]/k^2U_z$$

where r_a = Aerodynamic resistance [s/m]
d = zero plane displacement of wind profile [m], equal to 2/3 h_c (h_c = crop height [m])
z_w = height of the wind velocity measurement [m]
z_{ow} = roughness parameter = 0.123 h_c
z_h = height of the humidity and temperature measurement [m]

z_{oh} = roughness parameter = 0.0123 h_c
k = Von Karman constant (=0.41) []
U_z = Wind velocity at height z_w[m/s]

For wind speed, temperature and humidity readings at 2.00 m, and for a reference crop (grass) with a canopy height of 0.12 m, the expression for τ^* becomes :

$$\tau^* = \tau\ (1+0.33\ U_2)$$

(1.9) **Wind velocity (U_2)**

Wind velocity data obtained from instruments that are placed at elevations different from the standard height of 2 m have to be adjusted using the following equation :

$$U_2 = U_z\ [\ln((2-d)/z_o)/\ \ln((z-d)/z_o)]$$

where U_z = Wind velocity at height z [m/s]
U_2 = Wind velocity at 2 m height [m/s]
z = Height of the wind velocity measurement [m]
d = zero plane displacement of wind profile (=0.08) [m]
z_o = roughness parameter for momentum (=0.01476) [m]

When substituting the values for d and z_o, the formula becomes

$$U_2 = 4.868\ U_z/\ln(67.75\ z - 5.42)$$

Reference : **Allen et al. (1989)**

(1.10) **Day wind**

Wind speed measurements normally concern daily averages of 24 hours. The following relationship can be used to determine the day time wind velocity :

$$U_d = 2U\ (U_d/U_n)/(1+(U_d/U_n))$$

where U = 24 hour average wind velocity [m/s]
Ud = Wind velocity during day time (07.00-19.00 hrs) [m/s]
Un = Wind velocity during night time (19.00-07.00 hrs) [m/s]

For average conditions $U_d/U_n = 2$ and $U_d = 1.33\ U$

(2) **Combination formula**

The combination equation, based on the Penman-Monteith approach, that enables the estimation of the reference evapotranspiration is written as

$$ETo = ET_{aero} + ET_{rad}$$

where ETo = Reference crop evapotranspiration [mm/d]
ET_{aero} = Aerodynamic term [mm/d]
ET_{rad} = Radiation term [mm/d]

(2.1) **ET_{aero}**

$$ET_{aero} = [\tau/(\delta+\tau^*)]\ [900/(t+275)]\ (e_a-e_d)\ U_2$$

with ET_{aero} = Aerodynamic term [mm/d]
τ = Psychrometric constant [kPa/°C]
τ^* = Modified psychrometric constant [kPa/°C]
δ = Slope of the vapour pressure curve [kPa/°C]
t = Air temperature [°C]
(e_a-e_d) = Vapour pressure deficit [kPa]
U_2 = Wind velocity at 2 m height [m/s]

(2.2) **ET_{rad}**

$$ET_{rad} = (\delta/(\delta+\tau^{*}))\ (R_n-G)\ (1/\lambda)$$

where ET_{rad} = Radiation term [mm/d]
R_n = Net radiation [MJ/m².d]
G = Soil heat flux [MJ/m².d]
λ = Latent heat of evaporation [MJ/kg]

(2.2.1) **R_n**

The net radiation is determined from the difference between incoming and outgoing radiation :

$$R_n = R_{ns} - R_b$$

where R_n = Net radiation [MJ/m².d]
R_{ns} = Net incoming short wave radiation [MJ/m².d]
R_b = Net outgoing long wave radiation [MJ/m².d]

(2.2.1.1) **Net incoming shortwave radiation (R_{ns})**

This is the radiation received effectively by the crop canopy, taking into account losses due to reflection :

$$R_{ns} = (1-\alpha)R_s$$

where R_{ns} = Net incoming shortwave radiation [MJ/m².d]
α = Albedo or canopy reflection coefficient (=0.23 for grass)
R_s = Incoming solar radiation [MJ/m².d]

R_s can be measured with various types of radiometers. In most cases however, the incoming shortwave radiation will be estimated from measured sunshine hours according to the following relationship :

$$R_s = (a + b\ (n/N))R_a$$

where a = fraction of the extra terrestrial radiation (Ra) received on overcast days (≈0.25 for an average climate)

b = 0.5 for an average climate

a+b = fraction of the extra terrestrial radiation (Ra) received on clear days (≈0.75 for average climate)

n = bright sunshine hours per day [hr]

N = total daylength [hr]

R_a = Extra terrestrial radiation [MJ/m².d]

Using the values, recommended for an average climate and for grass as a reference crop, the formula for R_{ns} is reduced to :

$$R_{ns} = 0.77\ R_a\ (0.25 + 0.50\ (n/N))$$

(2.2.1.2) **Net long wave radiation (R_b)**

$$R_b = [0.9(n/N)+0.1](0.34-0.14\sqrt{e_d})\ \sigma\ (Tmax^4+Tmin^4)/2$$

where R_b = Net long wave radiation [MJ/m².d]

ε' = $(0.34-0.14\sqrt{e_d})$ = net emissivity, obtained as : emissivity by the atmosphere minus the emissivity by vegetation and soil

e_d = Vapour pressure at dew point [kPa]

σ = Stefan Boltzmann constant ($4.903\ 10^{-9}$) [MJ/m².K⁴.d]

Tmax = Maximum air temperature [°K]

Tmin = Minimum air temperature [°K]

In order to calculate the saturation vapour pressure at dew point, the minimum temperature can be considered as the dew point temperature.

The net emissivity ε' can equally be estimated from average temperature data according to the following equation :

$$\varepsilon' = -0.02+0.261\ e^{-0.000777\ t^2}$$

where t = mean daily air temperature [°C]

(2.2.2) **Soil heat flux (G)**

Some energy flux may occur through heat storage in the soil. To estimate the soil heat flux the following equation is used:

$$G = c_s.d(t_n-t_{n-1})/\Delta t$$

where G = Soil heat flux [MJ/m²d]

t_n = Air temperature in period n [°C]

t_{n-1} = Air temperature in period (n-1) [°C]

Δt = Length of period n [d]

c_s = Soil heat capacity (≈2.1 for average moist soil) [MJ/m^3°C]

d = Estimated effective soil depth [m]

Reference : **van Wijk and de Vries (1963)**

For daily temperature fluctuations, an effective soil depth of 0.18 m is used. For monthly temperature fluctuations the adopted effective soil depth is 2.0 m.

Since the magnitude of the daily soil heat flux over 10-30 day periods is relatively small, it normally can be neglected, and thus G = 0.

EXAMPLE

Data

Station	:	Garoua
Latitude	:	9°20'N
n	:	7.6 [hrs.decimal hrs]
tmax	:	32.1 [°C]
tmin	:	22.1 [°C]
tmean	:	27.1 [°C]
RH	:	74.2 [%]
U2	:	2.7 [m/s]

Determination

(1) Parameters

λ		2.45
e_a	tmean	3.59
e_d	RH	2.66
δ	tmean	0.21
P	z=244m	98.45
τ		0.065
τ^*	U2	0.123

(2) Aerodynamic term

$\tau/(\delta+\tau^*)$	0.195
900/(t+275)	2.98
(e_a-e_d)	0.93
U2	2.7
ETaero	1.46

(3) Radiation term

$\delta/(\delta+\tau^*)$	0.63
$1/\lambda$	0.41

(3.1) Net radiation (Rn)

(3.1.1) Net incoming radiation (Rns)

n	data	7.6
N	table 33	12.67
n/N	calc	0.60
Ra	table 43 (15.2 mm/day*2.45)	37.24
Rns	calc	15.77

(3.1.2) Net outgoing radiation (Rb)

(0.9(n/N)+0.1)	0.64
e_d	2.66
$(0.34-0.14\sqrt{e_d})$	0.12
ε'	0.128
$\sigma(Tmax^4+Tmin^4)/2$	39.92
Rb	3.26

(3.1.3) Net radiation

Rn=Rns-Rb	15.77-3.26	12.51

(3.1.4) ETrad

ETrad	G=0	3.22

(4) Reference evapotranspiration (ETo)

ETaero+ETrad	1.46+3.22	**ETo = 4.68 mm/day**

3.4.3. THE GROWING PERIOD

3.4.3.1. Definition

The growing period can be defined as the period of the year in which agricultural production is possible as a result of adequate moisture availabibity and absence of temperature limitations.

Since moisture availability and temperature sufficiency are not consistently related, the growing period can be considered as the combined outcome of a moisture-limited growing period and a temperature-limited growing period.

In tropical and subtropical areas, where moisture adequacy is an important constraint to crop production, the growing period concept has proved to be very usefull. In temperate areas and in tropical highlands where temperature can often be a limiting factor to crop production, the concept appeared to be less usefull since crops have very different temperature requirements and tolerances.

3.4.3.2. The original concept

Cocheme and Franquin (1967) presented the first well-published example of the use of a growing period. They used the Penman open-water evaporation (Eo) and rainfall as input data in their model. The growing period was subdivided in distinct subsequent phases that are described below. Figure 19 illustrates the original concept of the growing period and its subdivisions.

1) The preparatory period : precedes the beginning of the growing period. It is the period with low but sufficient rainfall to moisten the soil for tillage operations before

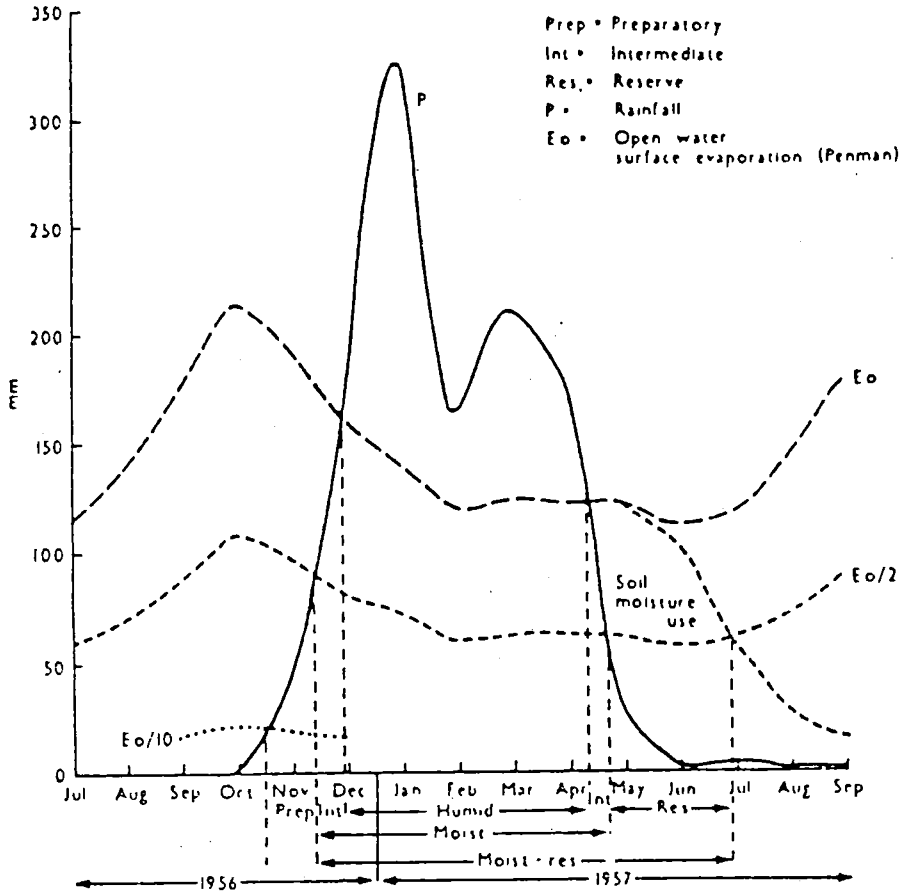


Fig. 19 *Songea : waterbalance diagram. An example of the original growing period concept (from* ***Jackson, 1977****).*

planting or sowing. In the model it is the time with rainfall between Eo/10 and Eo/2.

2) The first intermediate period : is the period in which both the rainfall and the crop water requirements gradually increase. There is no substantial build-up of soil moisture. In the model it is the time with rainfall between Eo/2 and Eo.

3) The humid period : is the time that rainfall is maximum and exceeds the evaporative demand of the atmosphere. The excess rainfall over Eo is used to build up soil moisture reserves. In the model it is the time that rainfall > Eo.

4) The second intermediate period : is the period in which the lower but still substantial water demands of the crop are met by the decreasing amounts of rainfall and by the stored soil moisture. In the model this period is the time that rainfall is between Eo and Eo/2.

5) The reserve period : is the time that the crop thrives mainly on stored soil moisture. In the model it is the period with rainfall smaller than Eo/2, determined by the time needed to exhaust the available soil moisture reserve in order to keep the crop evaporation above Eo/2. It is assumed that the soil moisture storage in the root zone is limited to 300 mm and that up to half the amount in storage at the end of any month can be used in the following month.

3.4.3.3. **The FAO growing period concept**

The original concept was modified by FAO and was adopted for an assessment of the agro-ecological zones at a continental scale.

The FAO defines the growing period as a continuous period in the year during which the precipitation is greater than half the potential evapotranspiration, calculated by Penman's method, plus a number of days required to evaporate an assumed 100 mm of soil water, stored at the end of the rains (**Kowal, 1978**). Figure 20 illustrates the FAO definition of a (normal) growing period.

Some of the names of the subperiods of the original growing period concept have been changed :

1) The first intermediate period has been named beginning of the growing period. This is the time that rainfall is between ETo/2 and ETo.

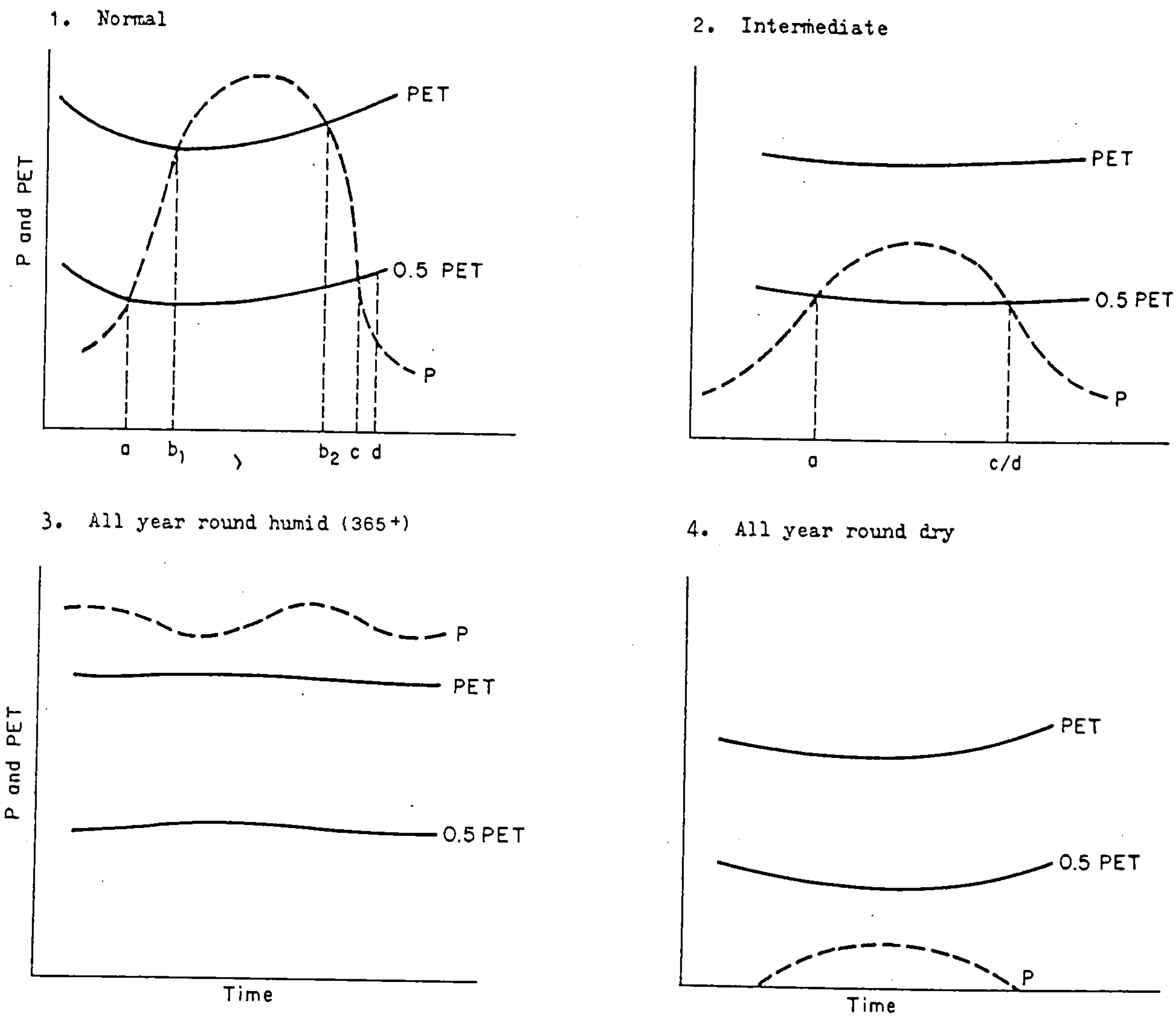
2) The humid period, period with rainfall greater than ETo, remained humid period.

3) The second intermediate period, characterised by rainfall between ETo and ETo/2, is called end of the rains and the rainy season.

4) The reserve period or time of soil moisture utilisation is named end of the growing period.

The main contribution by FAO was its proposal to differentiate between different types of growing periods that express the quality of the growing period. The different types of growing periods are presented graphically in figure 20.

1) The **normal growing period** is the one that corresponds with the working definition and exhibits a humid period.



a - Beginning of rains and growing period
b_1 and b_2 - Start and end of humid period respectively
c - End of rains and rainy season
d - End of growing period with storage
P - Precipitation
PET - Potential evapotranspiration

Fig. 20 *Examples of four types of growing period (**FAO, 1979**).*

2) The **intermediate growing period** shows no humid period. Consequently this type of growing period is associated with some moisture stress, depressed crop growth and yield, since no soil moisture reserve can be build up.

3) The **all-year-round humid period** shows a rainfall that exceeds ETo during the whole year. The high humidity associated with such permanent growing period will inflict on the suitability of certain crops owing to an increased risk of pests and diseases and to the absence of a dry period during maturation and after harvest.

4) The **all-year-round dry period** shows no period in the year with rainfall higher than ETo. There is no growing period sensu stricto and rainfed cropping is excluded.

The pragmatic definition of the growing period also takes into account temperature limitations. A usual approach is to incorporate a temperature threshold value into the waterbalance and to subtract the period with temperatures below the threshold value from the water availability period.

3.4.3.4. Determination of the start and the end of the growing period and of the humid period

The usual start of the growing period and the likely end of the rains can be determined graphically or can be calculated using a linear or parabolic interpolation technique based on rainfall and evapotranspiration data. The same applies to the start and end of the humid period. The end of the growing period is determined by the number of days that are required to consume 100 mm of water since the likely end of rains.

(1) **Graphic determination**

The monthly or decade values of rainfall, ETo and ETo/2 are presented on a time axis for the middle of each month or decade. The start of the growing period and the end of the rains coincide with the time at which the lines of rainfall and ETo/2 intersect. The start and the end of the humid period coincide with the time at which the lines representing the evolution of rainfall and ETo intersect. A graphic determination is shown in figure 21.

(2) **Determination using a linear interpolation**

(2.1) **Monthly data input**

Consider two successive months. Let R1 and R2 be the rainfall, and E1 and E2 the reference evapotranspiration in the first and second month respectively. If R1<E1/2 and R2>E2/2, at the start of the growing period, or R1>E1/2 and R2<E2/2, at the end of rains, we can represent rainfall and evapotranspiration as linear functions of time (t in days) :

$$R = a + bt = R1 + ((R2 - R1)/30)t$$

$$E/2 = c + dt = E1/2 + ((E2/2 - E1/2)/30)t$$

The linear functions are shown in figure 22. When both lines intersect, R = E/2 or

$$R1 + ((R2 - R1)/30)t = E1/2 + ((E2/2 - E1/2)/30)t$$

This equation can be rewritten to find a solution for t

$$t = \text{integer}\left[\frac{(R1 - E1/2)30}{(R1-R2+E2/2-E1/2)}\right]$$

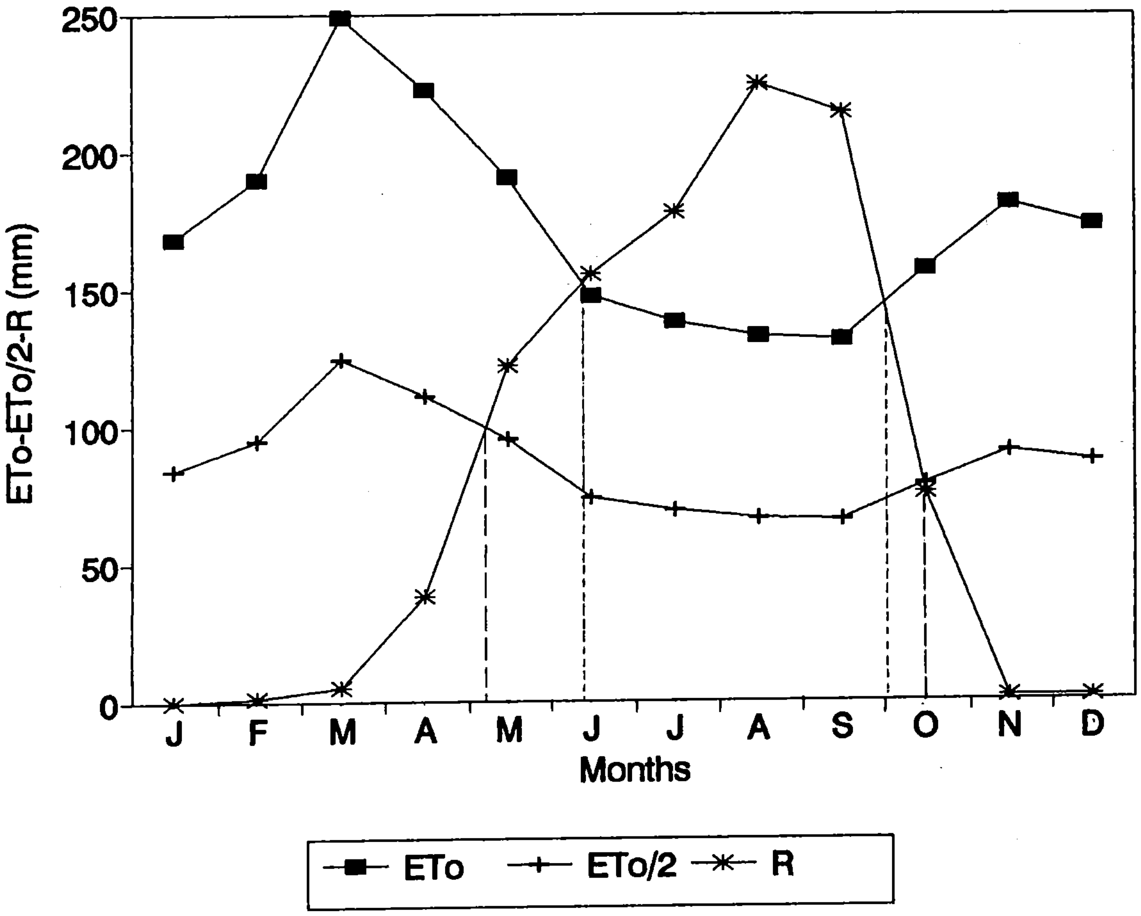


Fig. 21 *Graphic determination of the growing period : evolution of the monthly values of ETo, ETo/2 and R during the year in Garoua*

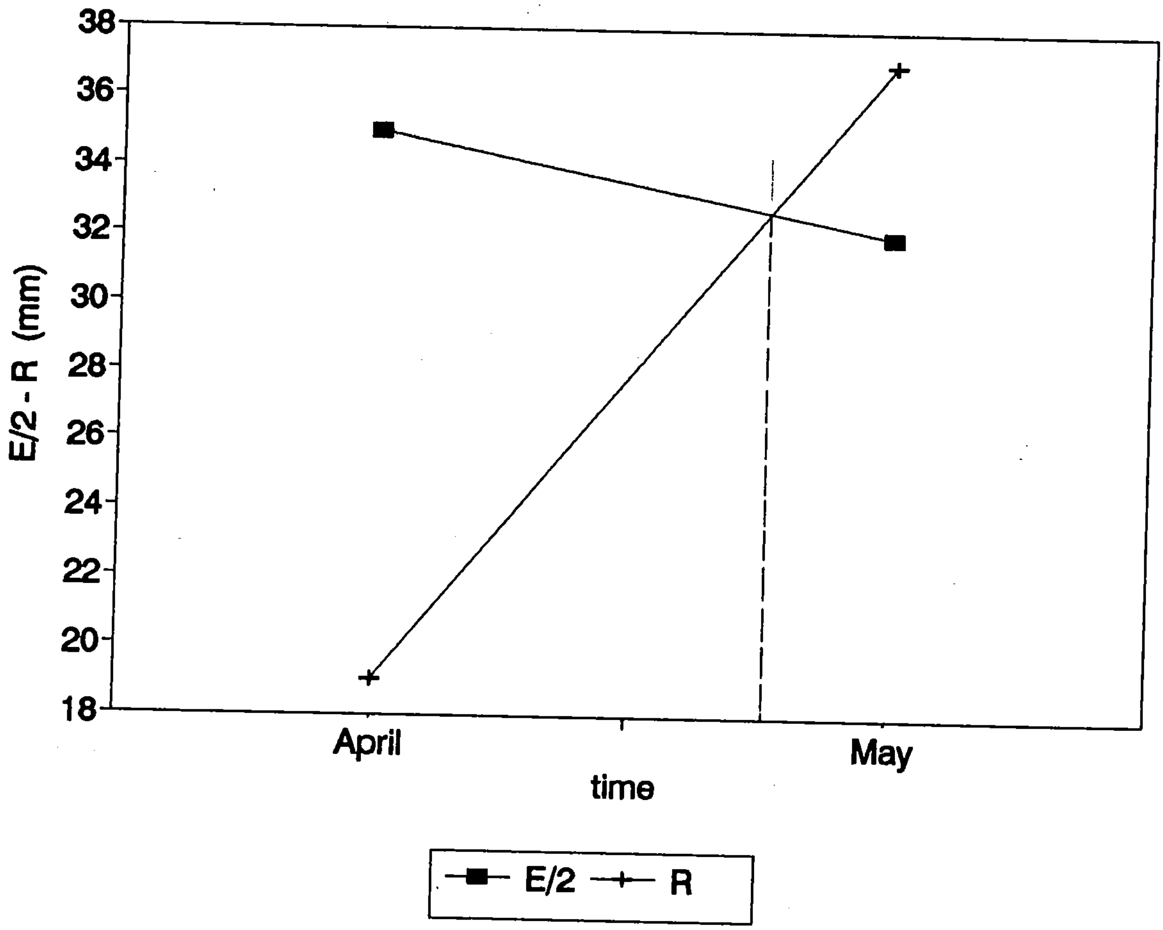


Fig. 22 *Evolution of the rainfall (R) and half the reference evapotranspiration (E/2) as a linear function of time. At the time of intersection, R = E/2).*

with t = time in days starting from the middle of the first month.

Similarly an equation can be set up to determine the beginning and end of the humid period. Select two succesive months that correspond to $R1<E1$ and $R2>E2$, at the start of the humid period, or $R1>E1$ and $R2<E2$, at the end of the humid period. The start or end of the humid period, in days following the middle of the first month is given by :

$$t = \text{integer}\left[\frac{(R1 - E1)30}{(R1-R2+E2-E1)}\right]$$

(2.2) **Decade data input**

Let P1 and P2 be the rainfall, and E1 and E2 the reference evapotranspiration in two successive decades. If $P1<E1/2$ and $P2>E2/2$ or $P1>E1/2$ and $P2<E/2$, the time of intersection that corresponds to the beginning of the growing period or end of the rains is found using the following equation :

$$t = \text{integer}\left[\frac{(P1 - E1/2)10}{(P1-P2+E2/2-E1/2)}\right]$$

with t = the time in days starting from the middle of the first decade

If for the two successive decades $P1<E1$ and $P2>E2$, or $P1>E1$ and $P2<E2$, then the time t, in days, following the middle of the first decade that corresponds to the start or end of the humid period is calculated using :

$$t = \text{integer}\left[\frac{(P1 - E1)10}{(P1-P2+E2-E1)}\right]$$

EXAMPLE

Data

Station : Garoua

Month :		April	May	Decade :	Apr3	May1
R	[mm]	38	122			
P	[mm]				19.5	33.9
E	[mm]	217	179		68.9	63.7
E/2	[mm]	108.5	89.5		34.5	31.9

Determination

Using monthly values, the start of the growing period can be obtained with these data (since R1<E1/2 and R2>E1/2). The outcome of the calculation is

$$t = int[30(38-108.5)/(38-122+89.5-108.5)] = 20 \text{ days}$$

The start of the growing period is

April 15th + 20 days = May 5th.

Using decade values the result of the calculation is

$$t = int[10(19.5-34.5)/(19.5-33.9+31.9-34.5)] = 8 \text{ days}$$

The start of the growing period is then

April 25th + 8 days = May 3rd.

(3) **Determination using a parabolic interpolation**

Gommes (**1983**) presents a method proposed by **Franquin** (**1973, 1976**) that was used by FAO in the Agro-ecological zones project (**FAO, 1979**).

Let R1, R2 and R3 be the normal monthly rainfall of three consecutive months. E1, E2 and E3 are the normal monthly reference evapotranspiration values. It is assumed that the average daily rainfall (R1/30, R2/30, R3/30) and reference evapotranspiration (E1/30, E2/30, E3/30) correspond to the middle (15th day) of the month.

For both rainfall and evapotranspiration a parabola can be defined that passes through three points. For rainfall the parabola is determined by (15, R1/30), (45, R2/30) and (75, R3/30). For evapotranspiration the curve is determined by (15, E1/30), (45, E2/30) and (75, E3/30). These parabolas are represented in figure 23.

Gommes (**1983**) shows that these parabolas can be calculated as a function of time (t in days) :

$$R = a + bt + ct^2$$

with $a = (15\ R1 - 10\ R2 + 3\ R3)/240$

$b = (-2\ R1 + 3\ R2 - R3)/900$

$c = (R1 - 2\ R2 + R3)/54000$

and

$$E = \alpha + \beta t + \tau t^2$$

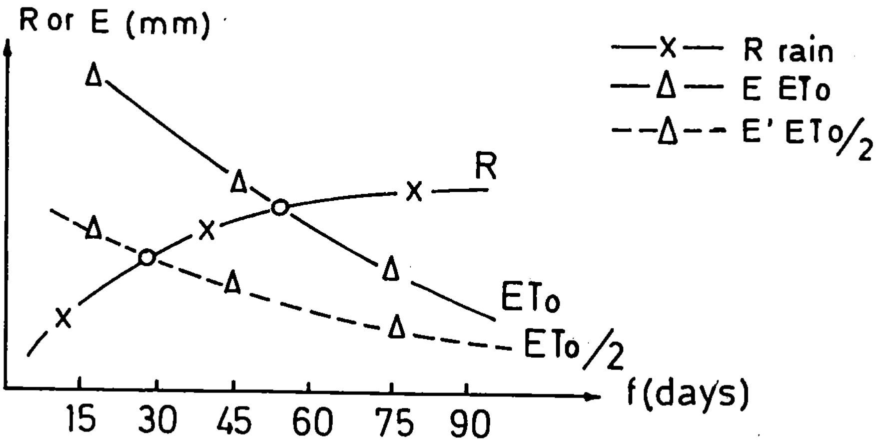


Fig. 23 *Variation of rain (R), ETo (E) and ETo/2 (E') over 3 consecutive months. The time scale is in days and each month is standardized to 30 days.*

with $\alpha = (15\ E1 - 10\ E2 + 3\ E3)/240$

$\beta = (-2\ E1 + 3\ E2 - E3)/900$

$\tau = (E1 - 2\ E2 + E3)/54000$

If one calculates the start of the growing period and the end of rains, the value of E1, E2 and E3 is replaced by the one for E1/2, E2/2 and E3/2 respectively. The start of the growing period, the end of the rains, the start and end of the humid period coincide with the points of intersection of two parabolas. This is mathematically expressed as

$$a + bt + ct^2 = \alpha + \beta t + \tau t^2$$

The time of start or end of a period is calculated as

$$t1 = [((\beta - b) + \delta) / 2(c - \tau)] - 30$$

with $\delta = (b-\beta)^2 - 4(a-\alpha)(c-\tau)$

$t2 = [((\beta-b) - \delta) / 2(c-\tau)] - 30$

with δ as above

The results, t1 and t2, are the days in the second (or middle) month at which R = ETo/2 or R = ETo. Whenever (t-30)<0 or (t-30)>30 the intersections fall in the first or third month respectively. One will repeat the calculation with 3 other months, of which the middle month is supposed to hold the start or the end of a period.

EXAMPLE

Data

Station : Garoua

Month	April	May	June
R [mm]	38	122	155
E [mm]	217	179	141
E/2 [mm]	108.5	89.5	70.5

Determination

$a = (15)(38)-(10)(122)+(3)(155)/240 \quad =-0.77$

$b = -2(38)+ (3)(122)- (155)/900 \quad = 0.15$

$c = (38)- (2)(122)+ (155)/54000 \quad =-0.00094$

$\alpha = (15)(109)- (10)(90)+ (3)(71)/240 \quad = 3.95$

$\beta = -(2)(109)+ (3)(90)- (71)/900 \quad =-0.02$

$\tau = (109)- (2)(90)+ (71)/54000 \quad = 0.00$

$\delta = (0.15+0.02)^2-4(-0.77-3.95)(-0.00094-0) \quad = 0.011$

t1= [((-0.02-0.15)+0.11)/2(-0.00094-0)]-30 = (31.9-30)= 1.9

The start of the growing period is according to the parabolic interpolation is May 1st.

3.4.3.5. Applications of the growing period concept

The first appraisal and interpretation of growing periods was performed **at continental scale.** Subsequent inventories were made **at country level** : in Mozambique (**Kassam et al., 1981-1982**) and in Tanzania (**De Pauw, 1982**).

The latter studies revealed problems related to the occurrence of more than one growing period per year. In areas with two or more growing periods per year, rainfall variability affects both the onset and duration of the growing period. The late start or exceptionally long duration of one growing period may cause close-by growing periods to merge. Growing periods mergers occur when the soil moisture storage bridges two peak periods of rainfall and thus creates a single continuous period for plant growth. It then becomes difficult to establish the start and duration of the growing period(s) in most years.

The growing period inventory in Mozambique differentiates two categorical levels : primarily the relative occurrence of the growing period pattern (number of growing periods), followed by the mean length of the growing period (if only one growing period occurs) or the total length of the dominant group of growing periods. Table 45 gives an example of the kinds of growing periods that were discerned in Mozambique. The spatial distribution of the growing periods is given in figure 24.

In **the growing period inventory of Tanzania** De Pauw (1982)

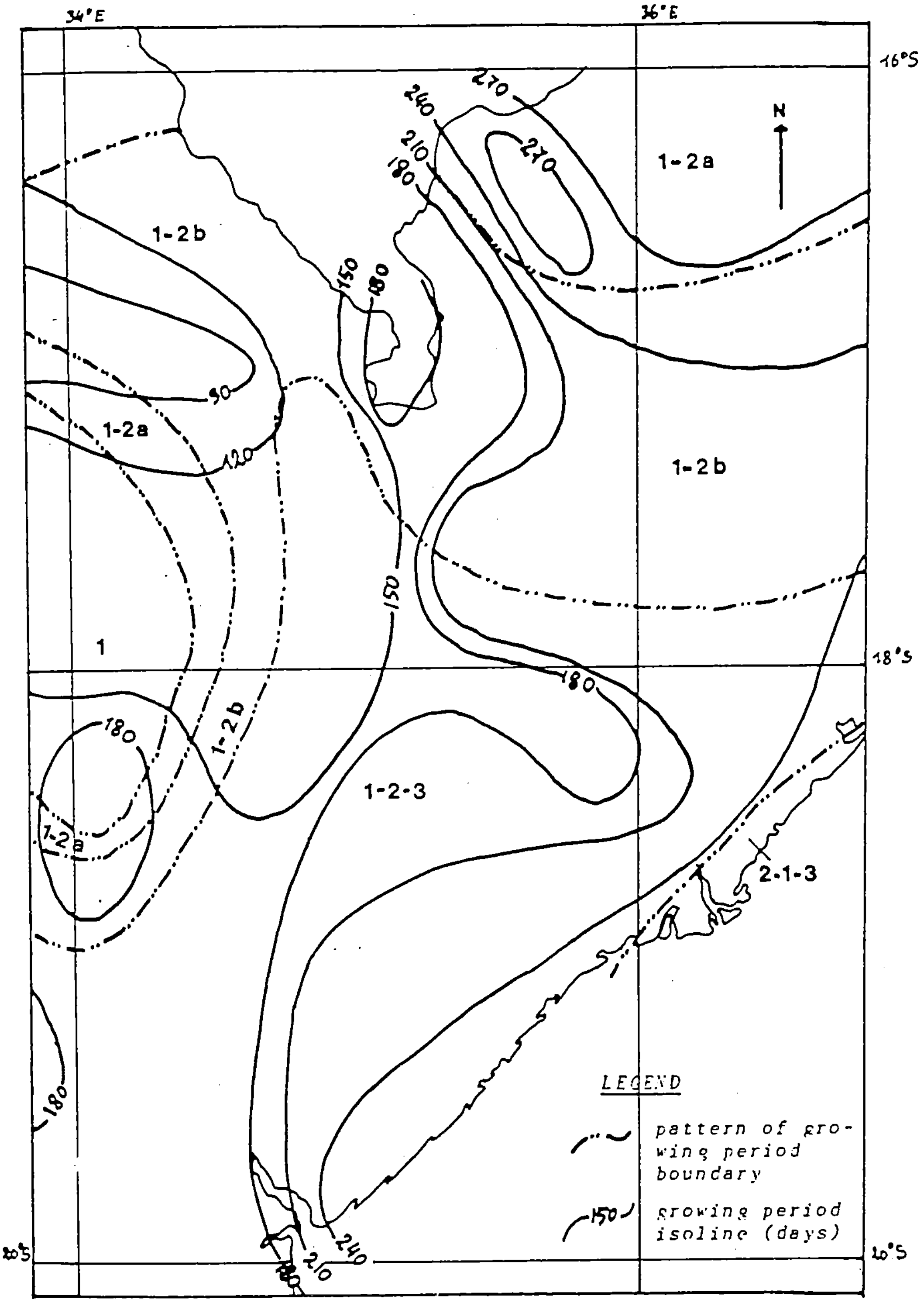


Fig. 24 *Climatic Resources Inventory Mozambique (excerpt from* ***Kassam et al., 1981-82****).*

*Table 45. Patterns of growing periods in Mozambique (from **Kassam et al.**, 1981-82)*

Pattern	Proportions	Meaning
1	100	occurrence of 1 growing period per year in all years;
1-2a	90:10	occurrence of 1 growing period per year in 90% of the years, with 2 growing periods per year in 10% of the years;
1-2b	75:25	occurrence of 1 growing period per year in 75% of the years, with 2 growing periods per year in 25% of the years;
1-2-3	60:30:10	occurrence of 1 growing period per year in 60% of the years, with 2 growing periods per year in 30% of the years, and 3 growing periods per year in 10% of the years;
2-1-3	45:30:25	occurrence of 2 growing periods per year in 45% of the years, with 1 growing period per year in 30% of the years and 3 growing periods per year in 25% of the years;
2-3-1	55:30:15	occurrence of 2 growing periods per year in 55% of the years, with 3 growing periods per year in 30% of the years and 1 growing period per year in 15% of the years.

presents a methodology based on rainfall variability that enables to determine the growing period length at a given probability level, the most appropriate planting time with acceptable risk, and that gives the possibility of double cropping.

3.4.3.6. **Recent developments in the growing period concept**

According to **De Pauw (1989)** the above approaches to the growing period suffer from some weaknesses that restrict its usefulness. A first weakness is that the model presents **an oversimplified picture of reality** : the outlined rainfall pattern for a given station may be valid for average conditions, but on a year by year basis considerable variation may occur in the onset date, duration and quality of the growing period (presence or absense of a humid period).

The model does not predict the growing period as a function of the farmer's planting behaviour e.g. fitting two crops in one climatic growing period.

The approach makes use of **aggregated climatic data,** usually on a monthly basis. The model is therefore unable to assess short-term droughts that may be particularly critical if they occur during sensitive growth stages.

The concept is **not crop-specific** : the crop water requirement is approximated using ETo. This is a useful approach if the season follows the normal pattern, but leads to errors if the crop cycle cannot be matched to the climatic growing period. Crop-specific temperature requirements are equally not incorporated into the model.

The concept is equally **not soil-specific** with regard to the soil moisture storage and release characteristics.
One has to keep this weaknesses in mind when applying the concept of growing periods.

Nachtergaele and De Pauw (1985) introduced a new approach in the determination of the growing period. They first calculate a simple water balance for different soil moisture storage capacities (50, 75, 100 ... mm/m) and obtain values for the actual evapotranspiration (ETa). They then represent the ratio of ETa/ETo on a time scale, as in figure 25, and define the growing period as the time in the year that ETa/ETo ≥ 0.5 . The humid period is the time that ETa/ETo = 1.

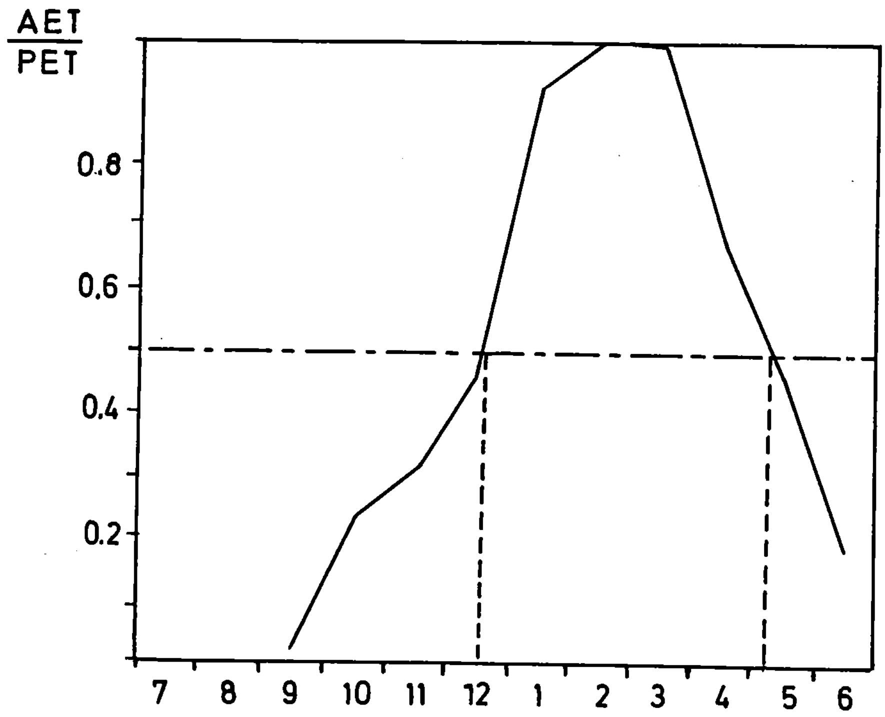


Fig. 25 *Normal growing period (**De Pauw, 1989**).*

3.4.4. CROP COEFFICIENT

The crop coefficient (kc) accounts for the effect of crop characteristics on crop water requirements : it relates the reference crop evapotranspiration (ETo) to the crop evapotranspiration (ETc) (**Doorenbos and Pruitt, 1977**).

$$ETc = kc \cdot ETo$$

By definition, kc relates to the evapotranspiration of a crop grown in large fields, optimally supplied with water and nutrients, free of diseases and achieving full production potential under the given growing environment. Therefore, the crop evapotranspiration (ETc) is equally the maximum evapotranspiration of the crop (ETm).

The crop coefficient (kc) is a dimensionless coefficient and its value is empirically determined from the ratio ETc/ETo. The crop coefficient is affected by crop characteristics, time of planting or sowing, stages of crop development and general climatic conditions.

The effect of crop characteristics on the relationship between ETo and ETc is shown in figure 26. Major crop groups show differences in kc value mainly as a result of differences in resistance to transpiration : the stomata close during the day in pineapple; leaves of citrus spp. are waxy. Differences in crop height, crop surface roughness, reflection and groundcover equally contribute to the variation in the crop coefficient.

Since climatic conditions vary throughout the year, the time of planting or sowing will affect the length of the crop cycle, the rate of crop development to full ground cover and onset to maturity. In selecting the appropriate kc value for each period in the crop cycle, the rate of development must be considered.

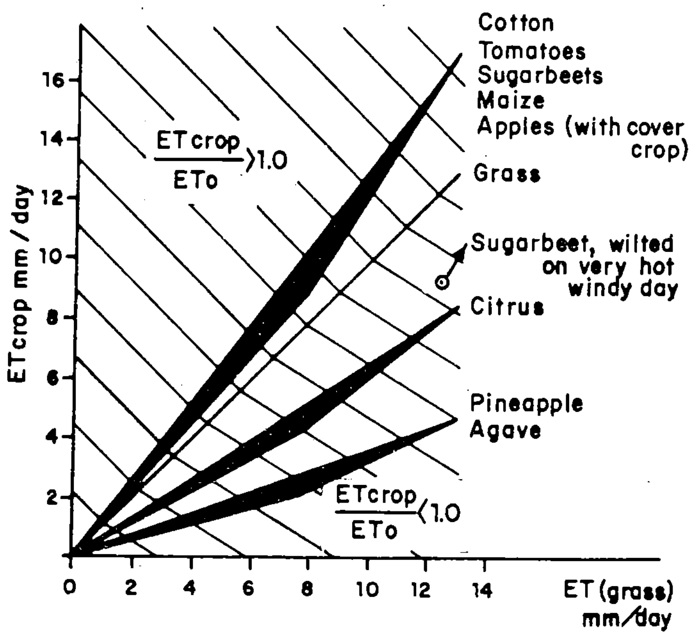


Fig. 26 *ETcrop as compared to ETo (**Doorenbos and Pruitt, 1977**).*

The general climatic conditions to be taken into account in the determination of kc are wind velocity and minimum relative air humidity. High wind velocities in dry climates largely increase the rate of transpiration, especially in tall crops. kc values for two levels of wind velocity and minimum relative air humidity are given in table 46.

The crop evapotranspiration ETc is the sum of transpiration by the crop and evaporation from the soil surface. At full ground cover, evaporation is negligible and ETc is determined almost entirely by crop transpiration. In the initial stage of the crop cycle however, crop transpiration may be low whilst the evaporation from the soil surface is considerable, particularly when the soil surface is moist for most of the time. The average kc value for the initial crop development stage is therefore determined as a function of ETo and the average recurrence interval of significant rain or irrigation. This relationship is given in figure 27.

Table 46. Crop coefficient (kc) for field and vegetable crops for different stages of crop growth and prevailing climatic conditions (from Doorenbos and Pruitt, 1977). kc-coefficient related to ETo with grass as a reference surface

Crop	Humidity		RHmin >70%		RHmin <20%	
	Wind m/sec		0-5	5-8	0-5	5-8
	Crop stage					
All field crops	initial	1	Use fig. 27			
	crop dev.	2	by interpolation			
Artichokes (perennial-clean cultivated)	mid-season	3	.95	.95	1.0	1.05
	at harvest or maturity	4	.9	.9	.95	1.0
Barley		3	1.05	1.1	1.15	1.2
		4	.25	.25	.2	.2
Beans (green)		3	.95	.95	1.0	1.05
		4	.85	.85	.9	.9
Beans (dry)		3	1.05	1.1	1.15	1.2
Pulses		4	.3	.3	.25	.25
Beets (table)		3	1.0	1.0	1.05	1.1
		4	.9	.9	.95	1.0
Carrots		3	1.0	1.05	1.1	1.15
		4	.7	.75	.8	.85
Castorbeans		3	1.05	1.1	1.15	1.2
		4	.5	.5	.5	.5
Celery		3	1.0	1.05	1.1	1.15
		4	.9	.95	1.0	1.05
Corn (sweet)		3	1.05	1.1	1.15	1.2
(maize)		4	.95	1.0	1.05	1.1
Corn (grain)		3	1.05	1.1	1.15	1.2
(maize)		4	.55	.55	.6	.6
Cotton		3	1.05	1.15	1.2	1.25
		4	.65	.65	.65	.7

Crop	Humidity		RHmin >70%		RHmin <20%	
	Wind m/sec		0-5	5-8	0-5	5-8
Crucifers (cabbage, cauliflower, broccoli, Brussels sprout)		3	.95	1.0	1.05	1.1
		4	.80	.85	.9	.95
Cucumber		3	.9	.9	.95	1.0
Fresh market		4	.7	.7	.75	.8
Machine harvest		4	.85	.85	.95	1.0
Egg plant (aubergine)		3	.95	1.0	1.05	1.1
		4	.8	.85	.85	.9
Flax		3	1.0	1.05	1.1	1.15
		4	.25	.25	.2	.2
Grain		3	1.05	1.1	1.15	1.2
		4	.3	.3	.25	.25
Lentil		3	1.05	1.1	1.15	1.2
		4	.3	.3	.25	.25
Lettuce		3	.95	.95	1.0	1.05
		4	.9	.9	.9	1.0
Melons		3	.95	.95	1.0	1.05
		4	.65	.65	.75	.75
Millet		3	1.0	1.05	1.1	1.15
		4	.3	.3	.25	.25
Oats	mid-season	3	1.05	1.1	1.15	1.2
	harvest/ maturity	4	.25	.25	.2	.2
Onion (dry)		3	.95	.95	1.05	1.1
		4	.75	.75	.8	.85
(green)		3	.95	.95	1.0	1.05
		4	.95	.95	1.0	1.05
Peanuts (groundnuts)		3	.95	1.0	1.05	1.1
		4	.55	.55	.6	.6
Peas		3	1.05	1.1	1.15	1.2
		4	.95	1.0	1.05	1.1
Peppers (fresh)		3	.95	1.0	1.05	1.1
		4	.8	.85	.85	.9

Crop	Humidity		RHmin >70%		RHmin <20%	
	Wind m/sec		0-5	5-8	0-5	5-8
Potato		3	1.05	1.1	1.15	1.2
		4	.7	.7	.75	.75
Radishes		3	.8	.8	.85	.9
		4	.75	.75	.8	.85
Safflower		3	1.05	1.1	1.15	1.2
		4	.25	.25	.2	.2
Sorghum		3	1.0	1.05	1.1	1.15
		4	.5	.5	.55	.55
Soybeans		3	1.0	1.05	1.1	1.15
		4	.45	.45	.45	.45
Spinach		3	.95	.95	1.0	1.05
		4	.9	.9	.95	1.05
Squash		3	.9	.9	.95	1.0
		4	.7	.7	.75	.8
Sugarbeet		3	1.05	1.1	1.15	1.2
		4	.9	.95	1.05	1.0
	no irrigation last month	4	.6	.6	.6	.6
Sunflower		3	1.05	1.1	1.15	1.2
		4	.4	.4	.35	.35
Tomato		3	1.05	1.1	1.2	1.25
		4	.6	.6	.65	.65
Wheat		3	1.05	1.1	1.15	1.2
		4	.25	.25	.2	.2

NB : Many cool season crops cannot grow in dry, hot climates. Values of kc are given for latter conditions since they may occur occasionally, and result in the need for higher kc values, especially for tall rough crops

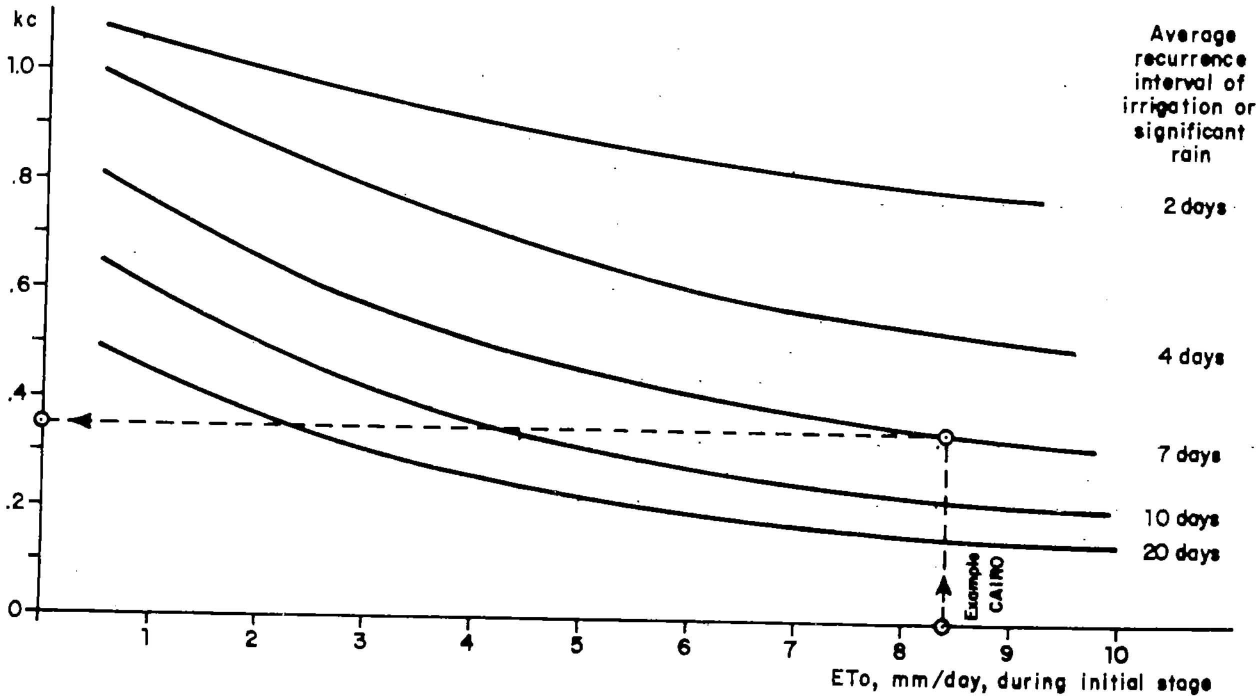


Fig. 27 *Average kc value for the growth stage where soil evaporation is considerable, as related to ETo level (reference surface = grass) and frequency of irrigation and/or significant rain (**Doorenbos and Pruitt, 1977**).*

For most crops, the kc value increases from a low value at the time of crop emergence to a maximum value during the period when the crop reaches full development, and declines as de crop matures, as shown in figure 28.

For field and vegetable crops the crop coefficient (kc) is determined for different crop development stages. Four stages are distinguished :

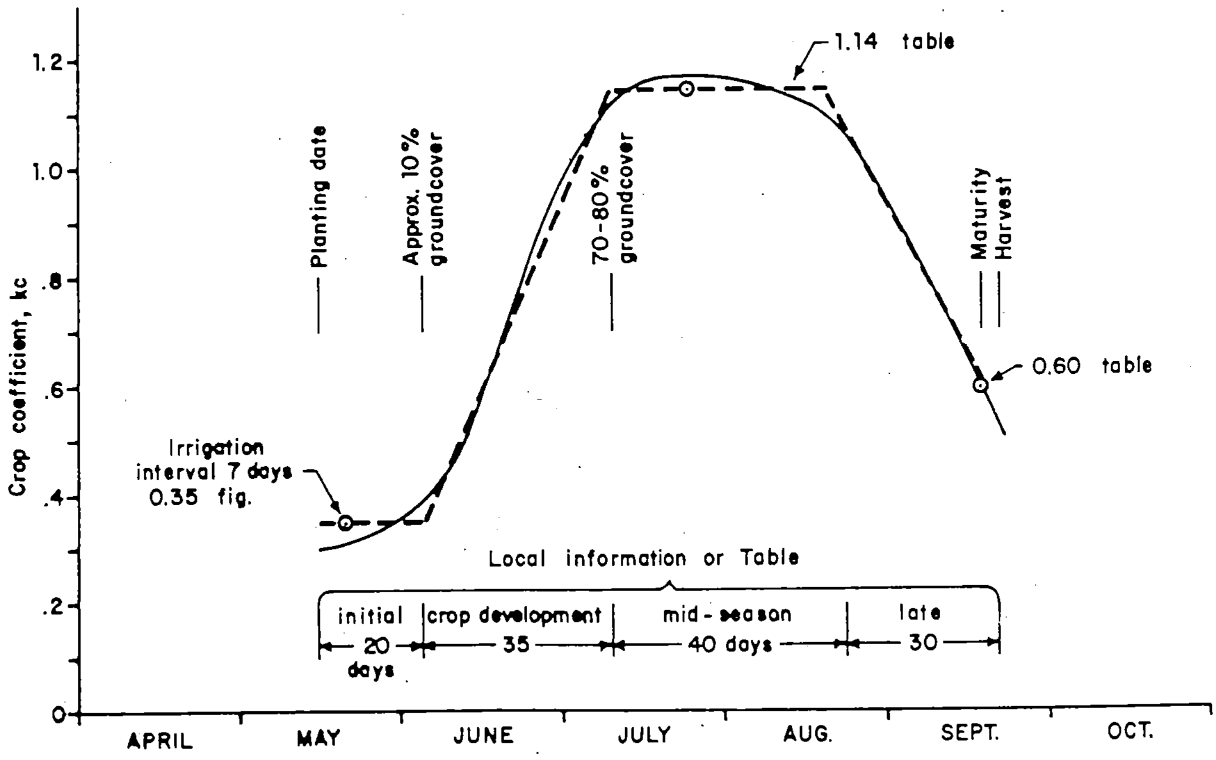


Fig. 28 *Example of the crop coefficient curve for corn* ***(Doorenbos and Pruitt, 1977).***

(i) Initial stage : germination and early growth (ground cover < 10%)

(ii) Crop development stage : from end of initial stage to effective full ground cover (70-80% ground cover)

(iii) Mid-season stage : from effective full ground cover to start of maturation (discolouring or shedding of leaves)

(iv) Late season stage : from end of mid-season to full maturity or harvest

The duration of each of the development stages is established from local information. Their duration can equally be estimated using the data in table 47.

Table 47. Duration of the crop development stages for a few important crops (after ***Doorenbos and Kassam, 1979****)*

Crop	Crop Development Stages (days)				
	Initial	Develop-ment	Mid-season	Late-season	Total cycle
Banana	60-90	90-120	120-150	90	300-365
Bean					
green	15-20	15-20	20-30	5-20	60-90
dry	15-20	15-20	35-45	20-25	90-120
Cabbage	20-30	30-35	20-30	10-20	100-150
Cotton	20-30	40-50	50-60	40-55	150-180
Grape	20-30	30-40	60	30	180-270
Groundnut	15-35	30-45	30-50	20-30	90-140
Maize	15-30	30-45	30-45	10-30	100-140
Onion	15-20	25-35	25-45	35-45	100-140
Pea					
fresh	10-25	25-30	25-30	5-10	65-100
dry	10-25	25-30	25-30	20-30	85-120
Pepper, fresh					
Potato	20-30	30-40	30-60	20-35	100-150
Rice					90-150
Safflower	20-35	35-75	45-65	25-40	120-160
Sorghum	20-25	30-40	40-45	30	100-140
Soybean	20-25	25-35	45-65	20-30	100-130
Sugarbeet	25-30	35-60	50-70	30-50	160-200
Sugar-cane	30-60	45-65	125-385	60-18	270-365
Sunflower	20-25	35-40	40-50	25-30	90-130
Tobacco	10	20-30	30-35	30-40	90-120
Tomato	10-15	20-30	30-40	30-40	90-140
Watermelon	10-20	15-20	35-50	10-15	80-110
Wheat	15-20	25-30	50-65	30-40	100-130

The kc value in the initial stage is determined from figure 27 as a function of ETo and the average recurrence interval of rain or irrigation. The kc values in the mid-season stage and at the time of harvest are obtained from table 46 as a function of the wind velocity range and the minimum relative air humidity. The kc values in the crop development stage and late season stage are obtained by linear interpolation between the kc values at the end of the initial and the beginning of the mid-season stage, and the kc value at the end of the mid-season stage and at the time of harvest respectively.

EXAMPLE

Data

Crop name : grain maize
Planting date : May 1st
Length of the crop cycle : 120 days
Length of the growth stages : (table 47)

initial [days] : 20
crop development [days] : 40
mid-season [days] : 40
late season [days] : 20

Result

Plot the duration of the successive stages on the time axis.

kc initial stage (figure 27) : May 1-May 20th

ETo = 188:30 = 6.27 mm
Number of significant rains : 5
Recurrence interval : 6 days
kc = 0.54

kc mid-season (table 46) Jul 1 - Aug 10th

wind velocity : 2.6 m/s
min. air humidity : mean value 77.9%
kc = 1.05

kc at harvest (table 46)

wind velocity : 2.5 m/s

min. air humidity : mean value 79.1%

kc = 0.55

Plot the kc values for the corresponding time periods. Draw a straight line between kc at the end of the initial phase and kc at the beginning of the mid-season stage, and between kc at the end of the mid-season stage and kc at harvest.

Read the kc value from the graph for the middle of each decade in the crop cycle, as shown in figure 29.

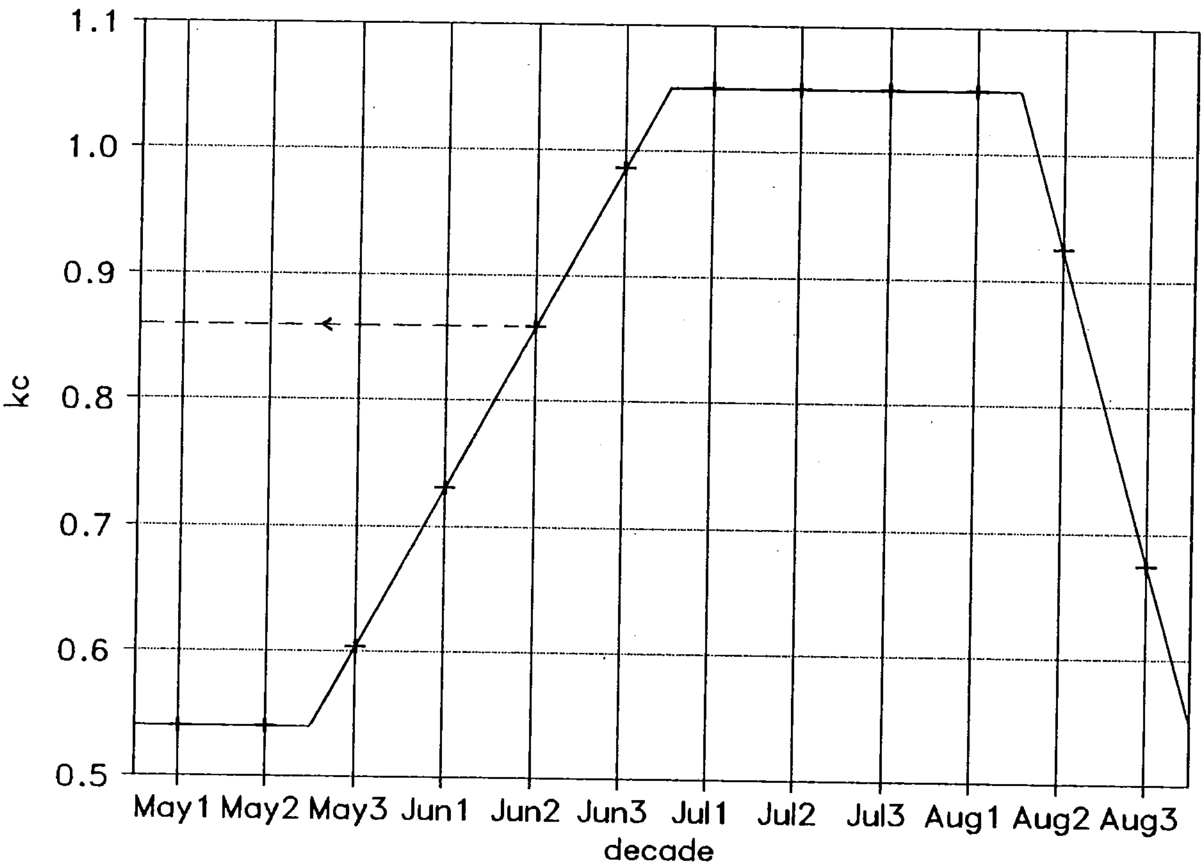


Fig. 29 Crop coefficient (kc) curve for grain maize, grown in Garoua

3.4.5. MAXIMUM CROP EVAPOTRANSPIRATION

In the traditional two-step approach, the maximum crop evapotranspiration is obtained by combining the values of the reference evapotranspiration (ETo) and of the crop coefficient (kc) in the following way :

$$ETc = ETm = ETo \cdot kc$$

Figure 30 shows the values of ETo and of ETc = ETm for grain maize grown in Garoua. The decade values of ETc are calculated using the kc values obtained from figure 29 and the decade values of ETo.

In the near future, the value of ETc will be calculated directly from climatic data and the crop canopy resistance, as determined by crop height and/or LAI. This one-step method is made possible through the Penman-Monteith approach in calculating the evapotranspiration. Research is focussed in this field (**Smith, 1991**).

3.4.6. ACTUAL EVAPOTRANSPIRATION

If the soil moisture, available for uptake by the plant through the root system, is adequate to meet the crops' demand for water, then the actual evapotranspiration of the crop (ETa) equals the maximum crop evapotranspiration (ETm) or crop evapotranspiration (ETc).

$$ETa = ETm$$

When the amount of available soil moisture is limited, the actual evapotranspiration (ETa) will be less than the maximum crop evapotranspiration (ETm).

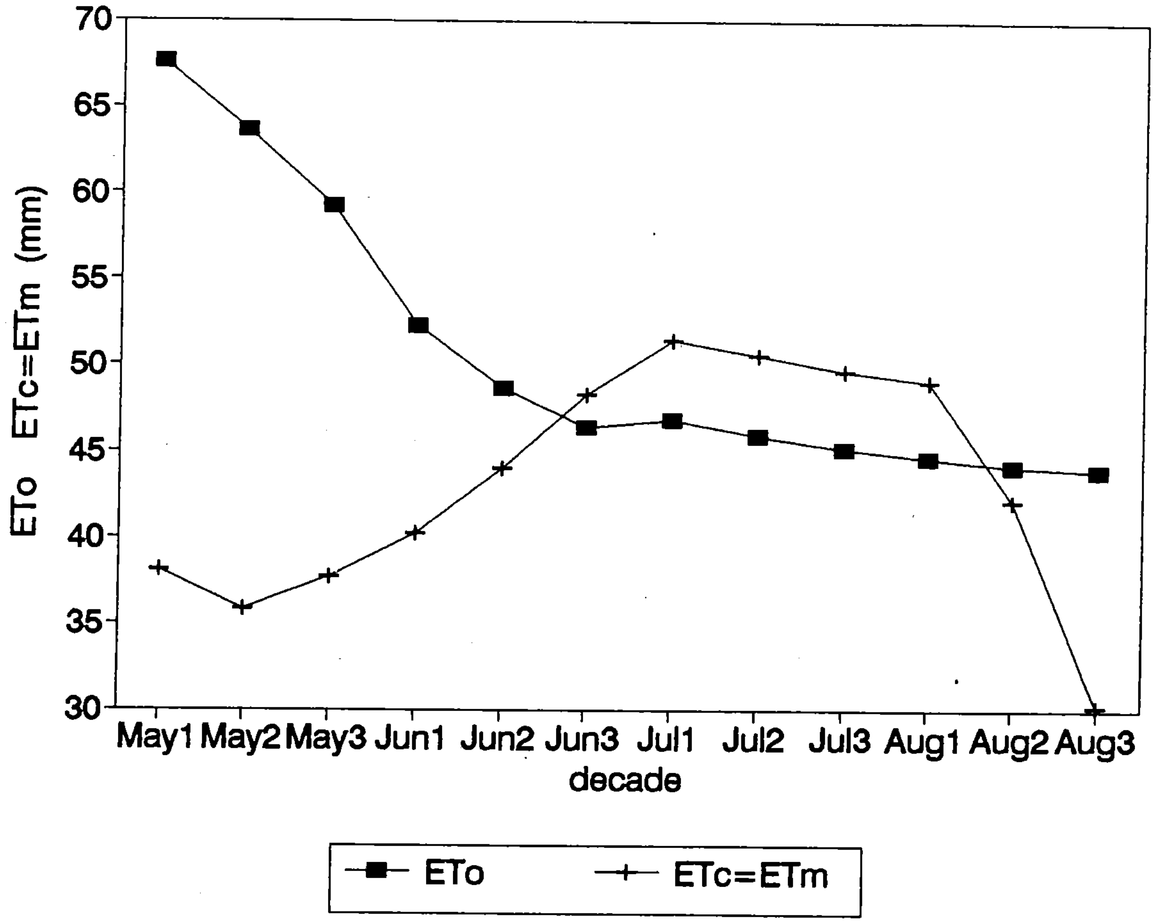


Fig. 30 *Crop evapotranspiration (ETc) for grain maize in Garoua and the reference evapotranspiration (ETo)*

ETa < ETm

The total available soil water (Sa) is the depth of water (in mm/m soil depth) between the soil moisture content at field capacity and at wilting point. At wilting point the soil moisture is held to the soil with a tension of 15 bar (pF 4.18). At field capacity the soil moisture is retained in soil with a tension of 0.1 to 0.2 bar (pF 2 or 2.3). One bar corresponds with 100 kPa or 100 J/kg.

The easily available soil water is defined as the fraction (p) of the total available soil water (Sa) to which the total available soil water can be depleted without causing ETa to become less than ETm. The value of the fraction (p) depends on the crop and time in the crop cycle, the magnitude of ETm and the soil texture.

Crops can be grouped according to the fraction (p) to which the available soil water (Sa) can be depleted while maintaining ETa equal to ETm. If the harvested part of the crop in the fleshy or fresh form, such as fruit, vegetable or forage, the tolerable range for p is narrow. This range is wider when the harvested part of the crop is in the dry form, such as in cereals for dry grain, cotton, oil seeds. The value of p is usually greater during the ripening period of a crop as a result of a lower ETm. Table 48 presents the grouping of crops according to the soil water depletion level as determined by ETm.

*Table 48. Crop groups according to Soil Water Depletion (**Doorenbos and Kassam, 1979**)*

GROUP	CROPS
1	onion, pepper, potato
2	banana, cabbage, grape, pea, tomato
3	alfalfa, bean, citrus, groundnut, pineapple, sunflower, watermelon, wheat
4	cotton, maize, olive, safflower, sorghum, soybean, sugarbeet, sugarcane, tobacco

Table 48 (ctnd). Soil Water Depletion Fraction (p) for Crop Groups and Maximum Evapotranspiration (ETm)

CROP GROUP	ETm mm/day								
	2	3	4	5	6	7	8	9	10
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

Maximum evapotranspiration (ETm) is maintained until the fraction (p) of the available soil water (Sa) over the depth (D) of the root zone has been depleted. Beyond the depletion level (p), the actual evapotranspiration (ETa) becomes increasingly smaller than ETm. The magnitude of ETa will depend on the remaining soil water relative to the amount of scarcely available soil water (1-p)Sa.D and on ETm. **Rijtema and Aboukhaled (1975)** formulated these relationships as follows :

Since evapotranspiration implies a decrease of the actually available soil moisture over the rooting depth per time unit:

$$ETa = \frac{(St.D)}{(1-p)Sa.D} \cdot ETc = -\frac{d(St.D)}{dt}$$

where $St.D < (1-p)Sa.D$

and Sa.D = the total available soil water over the root depth

St.D = the available soil water at time t over the root depth

p = fraction of easily available soil water

(1-p)= fraction of scarcely available soil water

The above relationship can equally be written as

$$\frac{ETc}{(1-p)Sa.D}\ dt = \frac{d(St.D)}{St.D}$$

In a time interval of t days, the available soil moisture content will change from an amount (St.D) to (St.D-ETa). Integration of the above equation between t=0 and t=t days and between the available soil water at time t=0 (St.D) and at time t=t days (St.D - ETa) yields (**Debaveye, 1986**) :

$$\frac{ETc}{(1-p)Sa.D}\ .\ t = \ln\ (St.D) - \ln\ (St.D - ETa)$$

$$\frac{ETc}{(1-p)Sa.D}\ .\ t = \ln\ \frac{(St.D)}{(St.D - ETa)}$$

$$ETa = St.D - St.D\ (e^{-ETc.t/(1-p)Sa.D})$$

This is the expression for the actual evapotranspiration (ETa) during a period of t days (mm/period) after a fraction (p) of the total available soil moisture (Sa) over the rooting depth (D) has been depleted. The actual available soil moisture content at the beginning of the period is St.D and the potential crop evapotranspiration during the period is ETc.

In order to take into account a changing rooting depth with crop development, a linear increase of the root depth with time can be assumed from emergence up till the moment of effective full ground cover (beginning of the mid-season stage). From that time onwards the root depth remains at its maximum value. Indicative values for the rooting depth of different crops is given in table 49.

Table 49. Mean rooting depth (D) with regard to water uptake for some annual crops (after ***Doorenbos and Kassam, 1979****)*

	D (m)
Banana	0.5-0.8
Bean	0.5-0.7
Cabbage	0.4-0.5
Cotton	1.0-1.7
Grape	1.0-2.0
Groundnut	0.5-1.0
Maize	1.0-1.7
Onion	0.3-0.5
Pea	0.6-1.0
Pepper	0.5-1.0
Potato	0.4-0.6
Rice	0.7-1.0
Safflower	1.0-2.0
Sorghum	1.0-2.0
Soybean	0.6-1.3
Sugarbeet	0.7-1.2
Sugarcane	1.2-2.0
Sunflower	0.8-1.5
Tobacco	0.5-1.0
Tomato	0.7-1.5
Watermelon	1.0-1.5
Wheat	1.0-1.5
Alfalfa	1.0-2.0
Citrus	1.2-1.6
Olive	1.2-1.7

EXAMPLE

Data

Crop: grain maize

Soil moisture content at field capacity: 130 mm/m
Soil moisture content at wilting point: 30 mm/m
Total available water (Sa): 100 mm/m
Rooting depth (D): 0.50 m
Total available water over the root depth (Sa.D): 50 mm
St.D at the start of the decade: 10 mm

ETc=ETm: 3.5 mm/day during the decade considered

Determination

Crop group (table 48): group 4
p (table 48): by interpolation (0.8+0.7)/2 = 0.75
(1-p)Sa.D = (1-0.75)(50) = 12.5 mm

since St.D < 12 mm, ETa is smaller than ETm. For the entire decade (t=10 days) the value of ETa is obtained from:

$$ETa = St.D - St.D\ (e^{-ETc.t/(1-p)Sa.D}) = 9.39\ \text{mm/decade}$$

The soil moisture storage at the end of the decade is:

$$St.D\ (i) = St.D\ (i-1) + R - ETa \quad \text{or}$$

$$St.D\ (i) = 10 + 0 - 9.46 = 0.61\ \text{mm.}$$

3.4.7. WATER UTILIZATION EFFICIENCY

When the crop water requirements are fully met by the water supply, the amount of total dry matter and yield produced per unit of water (kg/m^3) varies with the crop. The water utilization efficiency for total dry matter is represented by Em and for harvested yield (fresh matter, FM) by Ey. Both water utilization efficiencies are related by the following equation (**Doorenbos and Kassam, 1979**) :

$$Em \cdot Hi. [100/(100 - Mp)] = Ey$$

where

Em = water utilization efficiency for total DM (kg DM/m^3 water)
Ey = water utilization efficiency for harvested yield (kg FM/m^3 water)
Hi = harvest index
Mp = moisture content of the harvested part (%)

Table 50 presents the values of Ey for different crops.

When the water supply in an irrigation scheme is limited, the water utilization efficiency can be an important tool in deciding which of the climatically suitable crops should be selected. Preference will be given to crops with the highest Ey.

When the water requirements of crops are not met, they may, depending on the crop species, either increase or decrease their water utilization efficiency.

Table 50. Water utilization efficiency for harvested yield (Ey) of a few important crops (after ***Doorenbos and Kassam, 1979****)*

Crop	harvested yield	Moisture content	Ey (kg/m^3)
Alfalfa	hay	10-15 %	1.5-2.0
Banana	fruit	70%	2.5-4.0 (plant crop)
			3.5-6.0 (ratoon)
Bean	lush	80-90 %	1.5-2.0
	dry	10 %	0.3-0.6
Cabbage	head	90-95 %	12.0-20
Citrus	fruit	85 % (lime 70%)	2.0-5.0
Cotton	seed cotton	10 %	0.4-0.6
Grape	fruit	80 %	2.0-4.0
Groundnut	unshelled dry nut	15 %	0.6-0.8
Maize	grain	10-13 %	0.8-1.6
Olive	fruit	30 %	1.5-2.0
Onion	bulb	85-90 %	8.0-10
Pea	shelled fresh	70-80 %	0.5-0.7
	dry	12 %	0.15-0.2
Pepper	fresh fruit	90 %	1.5-3.0
Pineapple	fruit	85 %	5.0-10 (plant crop)
			8.0-12 (ratoon)
Potato	fresh tuber	70-75 %	4.0-7.0
Rice	paddy	15-20 %	0.7-1.1
Safflower	seed	8-10 %	0.2-0.5
Sorghum	grain	12-15 %	0.6-1.0
Soybean	grain	6-10 %	0.4-0.7
Sugarbeet	beet	80-85 %	6.0-9.0
	sugar	0 %	0.9-1.4
Sugar-cane	cane	80 %	5.0-8.0
	sugar	0 %	0.6-1.0
Sunflower	seed	6-10 %	0.3-0.5
Tobacco	cured leaves	5-10 %	0.4-0.6
Tomato	fresh fruit	80-90 %	10.0-12
Watermelon	fruit	90 %	5.0-8.0
Wheat	grain	12-15 %	0.8-1.0

3.4.8. YIELD RESPONSE FACTOR

When the water supply is unable to meet the water requirements of the crop and water stress develops in the plant, both crop growth and yield may be adversely affected. The effect of water stress on growth and yield depends on the crop species and variety on the one hand, and on the intensity and time of occurence in the crop cycle of the water deficit on the other hand.

Some crops react on a water deficit with an increase in water utilization efficiency (Ey), as in sorghum spp., while other crops may decrease their Ey, as in maize. Although the yield for both crops will be lower when the water supply over the crop cycle is limited, the yield reduction in maize will be greater than in sorghum.

Within the same crop species, the yield response to a water deficit can vary among varieties. Most often, high yielding varieties are more sensitive to drought stress than the traditional low yielding varieties.

When a water deficit occurs during a particular growth period in the crop cycle, the yield response will depend on how sensitive the crop is to a water deficit in that growth period. In general, crops are more sensitive to a water deficit during emergence, flowering and early yield formation than they are during the vegetative (after establishment) and ripening periods.

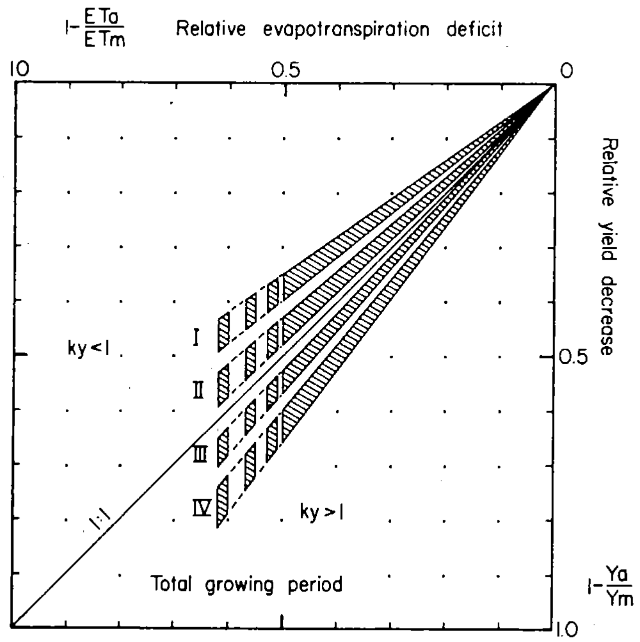
Doorenbos and Kassam (1979) quantified the yield response to water supply through the yield response factor (ky). This factor relates the relative yield decrease (1-Ya/Ym) to the relative evapotranspiration deficit (1-ETa/ETc) as follows :

$$(1 - Ya/Ym) = ky\ (1 - ETa/ETc)$$

where

Ya = actual yield (kg/ha)
Ym = maximum or potential yield (kg/ha)
Ya/Ym = relative yield
$1-Ya/Ym$ = relative yield decrease
ky = yield response factor
ETa/ETc = relative evapotranspiration
$1-ETa/ETc$ = relative evapotranspiration deficit

This relationship is valid for both individual growth periods and for the entire crop cycle. The general effect of water shortage on crop yield, as expressed by the value of the yield response factor, is given in figure 31, for both the total crop cycle and the individual growth periods. If a water deficit is observed continuously over the total growing period, the decrease in yield is, with an increase of the water deficit, proportionally less ($ky < 1$) in crops as alfalfa, groundnut, safflower and sugarbeet, while it is proportionally greater ($ky > 1$) in crops as banana, maize and sugar-cane. If a water shortage occurs in one or more of the individual growth periods, its effect on yield is relatively small for the vegetative (1) and ripening period (4) and relatively large for the flowering (2) and yield formation (3) period.
Values for the yield response factor (ky) have been established empirically, based on an analysis of experimental field data that covered a large range of growing conditions. For different crops, individual growth periods and the entire crop cycle, the ky values were derived on the assumption that the relationship between the relative yield (Ya/Ym) and the relative evapotranspiration (ETa/ETc) is linear and valid for water deficits of up to 50 % or (1-ETa/ETc) = 0.5. These data are presented in table 51. Table 52 gives the periods in the crop cycle of a number of annual crops that are particularly sensitive to drought stress.



I alfalfa, groundnut, safflower, sugarbeet

II alfalfa, cabbage, citrus, cotton, grape, sorghum, soybean, sugarbeet, sunflower, tobacco, wheat

III bean, citrus, onion, pea, pepper, potato, tomato, water melon, wheat

IV banana, maize, sugarcane

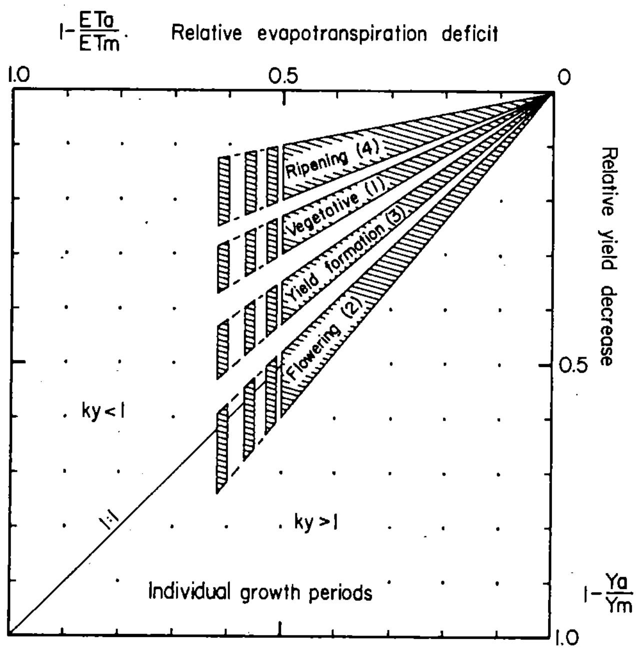


Fig. 31 *Generalized relationship between relative yield decrease (1-Ya/Ym) and relative evapotranspiration (1-ETa/ETm) (**Doorenbos and Kassam, 1979**)*

*Table 51. Yield Response Factor (ky) (**Doorenbos and Kasam, 1979**)*

CROP	VEGETATIVE PERIOD (1) early (1a)	late (1b)	total	FLOWERING PERIOD (2)	YIELD FORMATION (3)	RIPENING (4)	TOTAL GROWING PERIOD
Alfalfa			0.7-1.1				0.7-1.1
Banana							1.2-1.35
Bean			0.2	1.1	0.75	0.2	1.15
Cabbage	0.2				0.45	0.6	0.95
Citrus							0.8-1.1
Cotton			0.2	0.5		0.25	0.85
Grape							0.85
Groundnut			0.2	0.8	0.6	0.2	0.7
Maize			0.2	1.5	0.5	0.2	1.25
Onion			0.45		0.8	0.3	1.1
Pea	0.2			0.9	0.7	0.2	1.15
Pepper							1.1
Potato	0.45	0.8			0.7	0.2	1.1
Safflower		0.3		0.55	0.6		0.8
Sorghum			0.2	0.55	0.45	0.2	0.9
Soybean			0.2	0.8	1.0		0.85
Sugarbeet							
beet							0.6-1.0
sugar							0.7-1.1
Sugarcane			0.75		0.5	0.1	1.2
Sunflower	0.25	0.5		1.0	0.8		0.95
Tobacco	0.2	1.0			0.5		0.9
Tomato			0.4	1.1	0.8	0.4	1.05
Water melon	0.45	0.7		0.8	0.8	0.3	1.1
Wheat							
winter			0.2	0.6	0.5		1.0
spring			0.2	0.65	0.55		1.15

*Table 52. Sensitive Growth Periods for Water Deficit (**Doorenbos and Kassam, 1979**)*

Alfalfa	just after cutting (and for seed production at flowering)
Banana	throughout but particularly during first part of vegetative period, flowering and yield formation
Bean	flowering and pod filling; vegetative period not sensitive when followed by ample water supply
Cabbage	during head enlargement and ripening
Citrus	
grapefruit	flowering and fruit set > fruit enlargement
lemon	flowering and fruit set > fruit enlargement; heavy flowering may be induced by withholding irrigation just before flowering
Orange	flowerinng and fruit set > fruit enlargement
Cotton	flowering and soil formation
Grape	vegetative period, particularly during shoot elongation and flowering > fruit filling
Groundnut	flowering and yield formation, particularly during pod setting
Maize	flowering > grain filling; flowering very sensitive if no prior water deficit
Olive	just prior flowering and yield formation, particularly during the period of stone hardening
Onion	bulb enlargement, particularly during rapid bulb growth > vegetative period (and for seed production at flowering)
Pea	flowering and yield formation > vegetative, ripening for dry peas
Pepper	throughout but particularly just prior and at start of flowering
Pineapple	during period of vegetative growth
Potato	period of stolonization and tuber initiation, yield formation > early vegetative period and ripening
Rice	during period of head development and flowering > vegetative period and ripening
Safflower	seed filling and flowering > vegetative
Sorghum	flowering yield formation > vegetative; vegetative period less sensitive when followed by ample water supply
Soybean	yield formation and flowering; particularly during pod development
Sugarbeet	particularly first month after emergence
Sugarcane	vegetative period, particularly during period of tillering and stem elongation > yield formation
Sunflower	flowering > yield formation > late vegetative, particularly period of bud development
Tobacco	period of rapid growth > yield formation and ripening
Tomato	flowering > yield formation > vegetative period, particularly during and just after transplanting
Water melon	flowering, fruit filling > vegetative period, particularly during vine development
Wheat	flowering > yield formation > vegetative period; winter wheat less sensitive than spring wheat

3.4.9. ANTICIPATED RAINFED CROP YIELD

The potential irrigated yield of a crop can be calculated using one of the crop growth models outlined in section 3.3.2. This is the yield that can be obtained with high yielding varieties, optimally supplied with nutrients, that do not suffer from water stress, pests or diseases. The crop is assumed to be grown on a constraint-free soil.

If water stress occurs in the crop cycle, the potential irrigated yield will be reduced. The anticipated rainfed yield can be calculated from the potential irrigated yield and a reduction factor that expresses the relative yield loss as a result of a water deficit.

From the formula for the yield response factor (ky) by **Doorenbos and Kassam (1979)** the anticipated rainfed yield can be calculated from data on the relative evapotranspiration (ETa/ETc) and ky in the crop cycle, and the potential irrigated yield :

$$Ya = Ym\ [1 - ky\ (1-ETa/ETc)\ ]$$

or the relative yield is given by :

$$Ya/Ym = [1 - ky\ (1-ETa/ETc)\ ]$$

A supplementary reduction may have to be imposed on the anticipated rainfed yield as a result of soil constraints : poor drainage, shallow depth, low O.C content, dominance of low activity clays. The reduction factor can be obtained by calculating an index as the product of evaluation ratings for individual soil characteristics, expressed as fractions (values between 0 and 1), as obtained in the parametric approach of the qualitative land evaluation.

EXAMPLE

Grain maize with a crop cycle of 120 days is grown in Garoua between May 1st and August 30th. For each of the growth periods and for the entire crop cycle the duration, ky-value and relative evapotranspiration ETa/ETc have been calculated. The corresponding relative yields Ya/Ym are determined and presented below. When considering individual growth periods, we assume that the lowest relative yield equals the final yield.

Grain Maize

Crop growth periods	duration [days]	ky	ETa/ETc	Ya/Ym
Establishment	15	-	50.7/56= 0.91	-
Vegetative	30	0.4	116.1/117.8=0.99	0.99
Flowering	20	1.5	94.2/95.9= 0.98	<u>0.97</u>
Yield Formation	40	0.5	195.45/195.85= 1	1.00
Ripening	15	0.2	51.25/51.7= 0.99	1.00
Total crop cycle	120	1.25	507.7/517.2=0.98	<u>0.98</u>

Since the potential irrigated yield was equal to 7.66 ton grain per ha, the anticipated rainfed yield is calculated as :

(7.66)(0.98) = 7.51 ton grain/ha.

Assume that the soil index, calculated for a particular soil unit is equal to 0.50, the anticipated rainfed yield for that soil unit is expected to be :

(7.51)(0.50) = 3.75 ton grain/ha.

3.4.10. WATER REQUIREMENTS FOR MAXIMUM YIELD

As mentioned in detail in section 3.4.6., the maximum evapotranspiration (ETm) is maintained until the fraction (p) of the available soil water (Sa) over the depth (D) of the root zone has been depleted.

When calculating the irrigation requirement for maximum yield, one will determine the water required to maintain the soil moisture content at or above (1-p)Sa.D mm, or the minimum soil moisture stored St.D minimum = (1-p)Sa.D mm.

If the soil is completely dry at the time of planting or sowing, an initial irrigation application of Sa.D mm is required. If the soil is partly moist, the irrigation depth is (Sa.D - St.D) mm. The soil moisture content is then at field capacity. As the crop consumes soil moisture, the soil moisture content over the rooting depth (St.D) will decrease gradually. When the soil moisture content reaches a value equal to (1-p)Sa.D, a new irrigation application is required. The irrigation depth required to bring the soil to field capacity is equal to p.Sa.D. This procedure is continued until the crop has reached maturity.

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