TCP/BOT/0053
Field Document 2

LAND RESOURCE ASSESSMENT FOR AGRICULTURAL LAND USE PLANNING

BOTSWANA

CROP YIELD SIMULATION AND LAND ASSESSMENT MODEL FOR BOTSWANA

CYSLAMB

PART I

THEORY AND VALIDATION

Food & Agriculture
Organization of the
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Republic of
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PART I

THEORY AND VALIDATION

by

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Food & Agriculture
Organization of the
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United Nations
Development
Programme

JUNE 1993

This field document is one of a series of reports prepared during the course of the project identified on the title page. The conclusions and recommendations in the report are those considered appropriate at the time of its preparation. They may be modified in the light of further knowledge gained at subsequent stages of the project.

De Wit, P.V., Tersteeg, J.L. and Radcliffe, D.J. 1993. *Crop Yield Simulation and Land Assessment Model for Botswana (CYSLAMB). Part I Theory and Validation*. FAO/ Government of Botswana. Land Resource Assessment for Agricultural Land Use Planning Project TCP/BOT/0053. Field Document 2. 72 pp.

ABSTRACT

The *Crop Yield Simulation and Land Assessment Model for Botswana (CYSLAMB)* has been developed to serve the needs of land evaluation in a semi-arid environment. By modelling the interaction of environmental variables, physiological responses, inputs and management, CYSLAMB predicts the yield of a particular crop production system on a specified land unit. The use of actual rainfall data for individual years enables evaluation of interannual yield variability and quantification of risk in the specification of land suitability. Additionally, by modifying the input and management specifications of the production system, the impact of such changes on yield can be evaluated, and extension recommendations can be more closely targeted.

CYSLAMB is a summary mechanistic model with a cascading modular structure. The radiation and temperature limited biomass yields for all possible planting dekads (10 day periods) in the hydrological year are first calculated. A moisture balance is initiated from the first dekad, taking into account incident effective rainfall, bare soil evaporation or weed evapotranspiration and water losses due to percolation or run-off. Criteria for the definition of a planting opportunity are defined based on effective incident rainfall and stored soil moisture. When these criteria are met, the crop/soil water balance is then simulated through the crop growth cycle, and periods of moisture stress are accounted for in the calculation of the *moisture limited biomass yield*. The moisture limited yield is then adjusted to take account of the effects of drainage conditions, nutrient supply and toxicities. The biomass yield is converted to the yield of economic product by the harvest index.

The modules for radiation and temperature limited yield, moisture limited yield, and nutrient yield have been validated separately and in combination against historical crop trials of sorghum, maize and cowpea in Botswana. The maximum error of estimate for these crops was 15%. Yield reductions due to drainage conditions, excess of salts or sodium, and high pH, could not be validated locally due to lack of trial data.

The modular structure of CYSLAMB facilitates the replacement of current program modules with improved versions and the addition of new evaluation modules to the existing framework. The edit facilities allow for the construction of individual databases which can be customised according to the needs of a particular area or project, and information from established databases can be imported directly by building a simple ASCII interface. Thus, although the original data set refers to Botswana conditions, CYSLAMB can be customised for use in other countries with similar physical constraints to crop production, provided the necessary information on crop characteristics, management practices, climate and soils is available.

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GLOSSARY

Aeration porosity. The proportion of large non-capilliary soil pores, as a percentage of the total soil porosity.

Crop coefficient (*k*c). The coefficient used to calculate potential maximum crop evapotranspiration (ET_m) from the evapotranspiration of a reference crop (ET_0).

Crop group. A number of crops having particular physiological characteristics, or showing similar responses to environmental stress.

Dekad. A period of 10 days.

Electrical conductivity (ECe). Conductivity of a standard soil extract or paste, used as a measure of salt content. Normally expressed as $mS.cm^{-1}$.

Evapotranspiration. The combined loss of water from a given area over a specified period of time by evaporation from the soil surface and by transpiration by plants.

> **Actual crop evapotranspiration, ET_a**. Actual water loss from a specified crop, and from soil, taking account of water availability.
>
> **Crop evapotranspiration, ET_c**. A general term, which may be equivalent to ET_a or ET_m.
>
> **Maximum crop evapotranspiration, ET_m**. The maximum potential water loss from a specified crop, and from soil, when water is not limiting.
>
> **Reference crop, or Penman evapotranspiration, ET_0**. The maximum potential water loss from a reference crop of short grass and from soil, when water is not limiting.
>
> **Weed evapotranspiration, ET_w**. Estimated actual evapotranspiration from weeds and surrounding soil.

Exchangeable sodium percentage (ESP). Percentage saturation of soil cation exchange complex by sodium.

Harvest index. The produce as a proportion of dry above ground crop biomass.

Hydraulic conductivity. The rate at which water will flow through the soil in response to a hydraulic gradient.

Infiltration rate. The rate of water entry into the soil at the surface (under specified conditions).

Land. An area of the Earth's surface. In the context of land evaluation, land includes all properties of the surface, soil and climate, together with any resident plant and animal communities.

Land Characteristic. A property of the land that can be measured or estimated.

Land evaluation. The assessment of land performance when used for a specified purpose.

Land unit. A type of land with definable ranges of characteristics which are relatively homogenous with respect to other land units.

Land use planning. A logical procedure for decision making on land use, based on evaluation of possible land use alternatives, taking account of natural resources and socio-economic conditions, within the context of specified objectives.

Leaf area index. The total area of leaves and other foliar units per unit of ground area.

Management system. The component of the production system which describes the conditions under which the crop is grown. In CYSLAMB the management system specifies the period within which planting can take place and the criteria (rainfall and soil moisture) required to signal a planting opportunity. It also describes interventions in terms of irrigation, weeding and the timing of early ploughing.

Osmotic potential. The work that must be done per unit of water to overcome the effect of ions in solution. Saline soils exert an osmotic potential which impedes water movement from the soil solution into plant roots.

Phenological requirements. The requirements which affect the development of a crop in time, particularly in response to climate.

Photosynthesis. The synthesis of carbohydrates by plants from water and carbon dioxide, through the action of chlorophyll, using light as an energy source and with oxygen as a by-product.

Produce. A specified output of a production system. (e.g. grain, green fodder)

Production system. A particular series of activities (the management system) carried out to produce a defined set of commodities or benefits (produces).

Radiation and temperature limited yield. The potential maximum crop yield when factors other than radiation and temperature are not limiting.

Rainfall Station. A meteorological station at which only rainfall is recorded.

Respiration. The breakdown of metabolites to release energy and nutrients, using oxygen, and releasing carbon dioxide as a by-product.

Soil Moisture balance. A balance of the inputs, outputs and storage of water in the soil.

Stomata. Small openings in the surface of leaves at which gas exchange, particularly transpiration, takes place.

Synoptic station. A meteorological station at which a comprehensive range of weather data, such as temperature, relative humidity, windspeed etc. is recorded.

Target plant density. The crop density in plants/ha after germination.

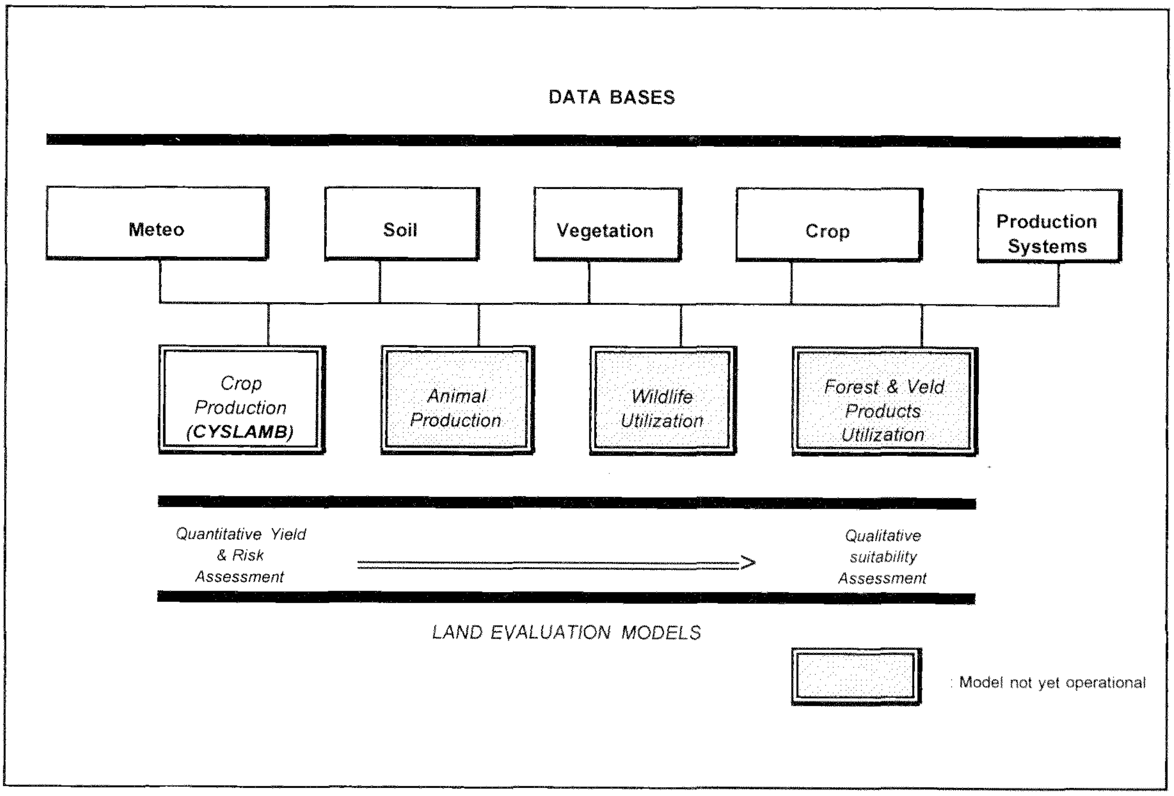
Transpiration. Release of water vapour by plants into the air through stomata.

INTRODUCTION

The Crop Yield Simulation and Land Assessment Model for Botswana (CYSLAMB) is a land evaluation model for crop production systems, which has been developed to support land use planning and agricultural extension. As shown in Figure 1, CYSLAMB is one of a suite of existing or proposed models to evaluate land for the different major categories of land use which are relevant in Botswana.

Figure 1

Schematic representation of Databases and Land Evaluation Models



Land evaluation is a technique which has been primarily used for mapping spatial differences in potential land performance under an assumed average set of environmental conditions. In most of Botswana rainfed cropping operates close to the margins of ecological suitability, and the rainfall induced temporal variation in land performance between years is often more significant than the spatial variation between different soil types. Under these semi-arid conditions farmers are as much concerned with reducing risks of crop failure in bad years as with maximizing production under "average" conditions, which rarely occur in practice. To be an effective tool for planning and extension in such an environment, land evaluation must be able to quantify the risks associated with practising a particular land use on a specified land unit. Conventional approaches to land evaluation, such as the one routinely used in Botswana until 1990 (Rhebergen, 1988), are unable to provide this information, and an alternative methodology, based on simulation modelling, was therefore investigated.

Models which simulate the response of crops to environmental variables, and to management practices, are particularly appropriate for the analysis of temporally and spatially variable land use systems. Crop simulation modelling, however, has been mainly developed by plant scientists as an aid to understanding the physiological processes governing crop growth and development. These models are usually related to a single crop and concentrate on a few factors such as radiation, water and nutrients which particularly lend themselves to detailed simulation exercises. Such models are of limited value in land evaluation because they do not cater for the range of suboptimal conditions of both environment and crop husbandry which are encountered in a typical land use situation.

Development of simulation models for land evaluation requires a different perspective and set of priorities. Models need to be extensive, covering the largest possible range of crops and the complete range of conditions which may affect crop performance in the target area. They also need to respond to variations in management operations and material inputs. What is needed are 'summary mechanistic models' (Dumanski and Onofrei, 1989), which calculate crop performance based on relationships between external variables and the intermediate and ultimate products. Such models should be sufficiently flexible to be applied to any crop production system, provided the essential crop characteristics are known and the management operations and inputs are defined.

With these objectives in mind, the *Soil Mapping and Advisory Services* Project commenced work on a land evaluation system based on simulation modelling in 1988. CYPPAC (De Baveye, 1986) was taken as the basis of model development as this was a generally applicable model derived largely from agro-ecological, rather than physiological considerations. The application of CYPPAC to land evaluation in Botswana was described by Nachtergaele and De Wit (1989) and the program was used in a pilot study in the Motloutse valley (De Wit and Cavaliere Parzaneze, 1990).

CYPPAC generates crop yields on specific land units for individual years. Time series of yields can be used to identify trends and quantify risks. However, the original program had limitations when applied to conditions in Botswana. Firstly, the range of soil factors considered is not comprehensive, and secondly the model was not responsive to changes in management or inputs. The latter factor is of particular importance if the performance of different *production systems*, as opposed to crops, is to be compared and if the impact of specific management practices is to be evaluated. Furthermore, crop characteristics used in CYPPAC were derived from high yielding cultivars grown under irrigation, which differ substantially from those for local cultivars in the marginal rainfed environment of Botswana (Radcliffe, De Wit and Tersteeg, 1991).

Experimental work with CYPPAC coincided with the adoption of a new agricultural policy by the Government of Botswana in 1991, placing emphasis on sustainable development and conservation of resources. More effective land use planning in the agricultural sector was highlighted as a major contributary factor to achieving this aim. In accordance with this policy, at the completion of the Soil Mapping and Advisory Services Project, the focus of FAO/UNDP assistance shifted from land resource mapping to land use planning. An effective and reliable system for predicting the performance of crops, on different soils in different climatic zones, and with different combinations of management practices and inputs, was seen as an essential support to land use planning. If such a system was scale independent, it could also support the agricultural extension service in formulating recommendations at the farm level.

CYSLAMB was developed to serve these needs. Although many components of the original CYPPAC model are retained, the program has been greatly extended and restructured and interactive user interfaces have been created. A major objective of bridging project TCP/BOT/0053 *Land Resource Assessment for Agricultural Land Use Planning*, which ran from January 1991 to early 1992, was this further development, and the testing and validation of CYSLAMB, so that it could be routinely applied for land use planning, particularly by the subsequent project *Land Use Planning for Sustainable Agricultural Development*. An extensive review of literature on crop trials and related physiological investigations in Botswana was carried out in early 1991 and specific characteristics of the cultivars commonly grown in Botswana were derived. The model was then validated for three crops using an independent set of crop yield data.

CYSLAMB has been applied at the national level in deriving the *National Map of Land Suitability for Rainfed Crop Production* (Radcliffe, Tersteeg, and De Wit, 1992). More detailed applications have been geared to evaluating specific recommendations on plant density (De Wit, 1992a), fertilizer applications (De Wit, 1992b), and on assessing the impact of draft power ownership (De Wit, 1992c).

Although specifically developed for Botswana, CYSLAMB is expected to be applicable in other semi-arid environments, although some of the crop parameters may have to be modified to cater for specific locally available varieties. It is essential, however, that the model is validated locally against crop yields recorded under controlled conditions, preferably including both on-station and on-farm trials, before it is routinely applied for planning or extension purposes.

The present document is structured in three parts, which are presented as separate volumes. Part I describes the structure of CYSLAMB, the theoretical background to the component modules, and the results of testing the modules, and the entire model, against actual yields obtained under experimental conditions. Part II is a practical users guide to operating the program, and Part III is a technical system description. All professional users should read Part I to gain an insight into the concepts of CYSLAMB. Part II is essentially a 'cook book' which can be followed by either professional or technical staff. Part III is written specifically for the computer specialist, who may wish to change some of the variables or add further program modules for applications in a specific environment.

1. CYSLAMB RATIONALE AND STRUCTURE

CYSLAMB is a simulation model developed specifically for the purposes of land evaluation. As illustrated in Figure 2, land evaluation rates the performance of a particular land area under a specified use by comparing the properties of land with the specific requirements of the land use. In this context *land characteristics* include the properties of the soil, the land surface and climate. *Land use requirements* include the physiological requirements of the crop, the requirements of the management system under which the crop is grown, and the requirement to conserve the resources on which long term production depends.

Figure 2: Land Evaluation Rationale

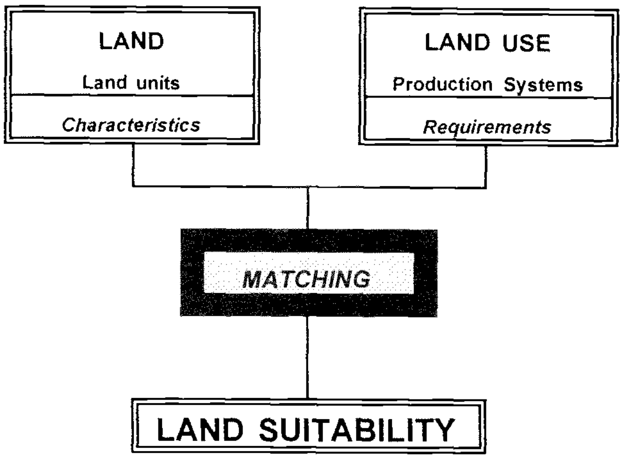
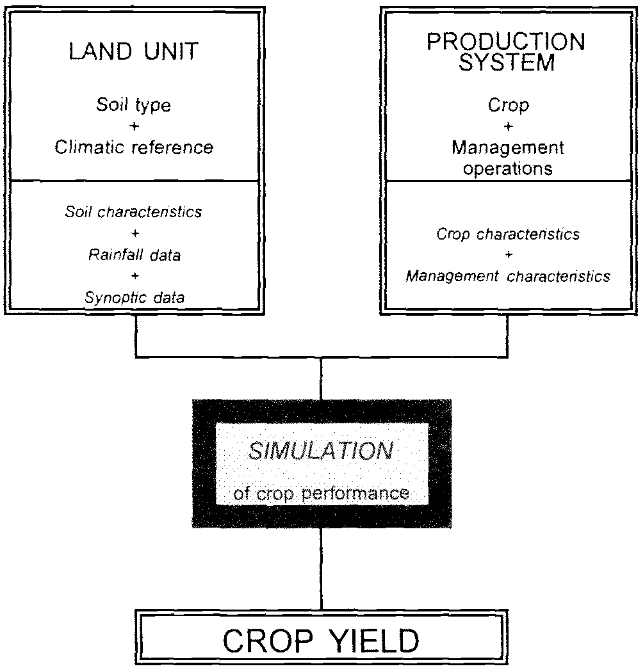


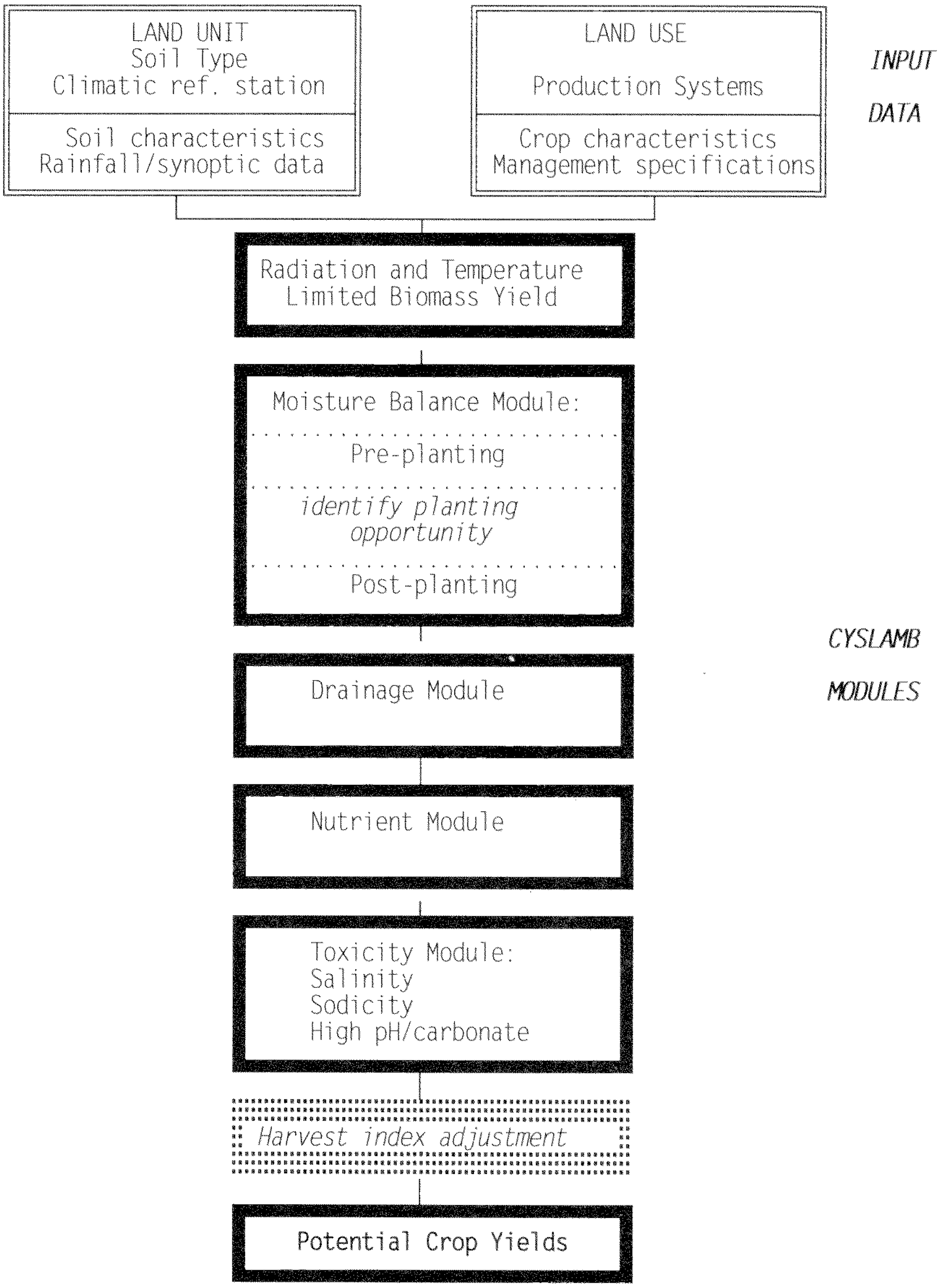
Figure 3 CYSLAMB Rationale



Using CYSLAMB, the operation of matching, which is central to land evaluation, is replaced by one of simulation of the performance of the crop under specified environmental and management conditions (Figure 3). Simulation requires that the inputs to the model are specified in quantitative terms. In turn, quantitative results are generated which can be tested and validated against field experimental data. Data is input in standardised formats to describe characteristics of the soil and climate, the requirements and characteristics of individual crops, and the inputs and operations which define the production system. Expression of the results as crop yields allows the performance of a wide range of production system / land unit combinations to be objectively and quantitatively compared. Yields can serve as the basis for financial and economic analysis, and by running CYSLAMB on a year by year basis, comparisons of risk and yield stability can also be included.

The structure of CYSLAMB is illustrated in Figure 4. The characteristics of the selected land units (effective rainfall and synoptic meteorological data, soil and weed characteristics) and production systems (crop characteristics, target plant densities and management practices) are read from separate databases. Using this input data, CYSLAMB then simulates crop biomass production and yield on an annual basis.

Figure 1: CYSLAMB Modules



CYSLAMB first calculates the radiation and temperature limited biomass yields for all possible planting dekads (10 day periods) in the hydrological year. A moisture balance is initiated from the first dekad, taking into account incident effective rainfall, bare soil evaporation or weed evapotranspiration and water losses due to percolation or run-off. Criteria for the definition of a planting opportunity are defined based on effective incident rainfall and stored soil moisture. When these criteria are met, the crop/soil water balance is then simulated through the crop growth cycle, and periods of moisture stress are accounted for in the calculation of the *moisture limited biomass yield*. The moisture limited yield is then adjusted to take account of the effects of drainage conditions, nutrient supply and toxicities. The biomass yield is converted to the yield of economic product by the *harvest index*. The harvest index is not constant for every crop, but varies with total plant weight (Section 7.1, p. 66).

The resulting yields reflect the production on the specified soil type under the climatic conditions prevailing in that particular year. If the model is run over a number of years the outputs can be analysed statistically to give estimates of the yield exceeded at stated levels of probability and the risks of crop failure.

The modular structure of CYSLAMB allows easy updating as additional information becomes available. Taken together, the modules encompass the range of physical yield determining factors in Botswana for which data is sufficient to model. However, these modules are not uniform in terms of their level of detail or reliability. The radiation / temperature module and the moisture balance module have been worked out in some detail from theoretical principles and the results have been validated against locally recorded yields. The nutrient module has been empirically derived from fertilizer trial data and has also been validated using a separate data set. The salinity and sodicity modules have been compiled from internationally established response curves, but it has not been possible to validate these locally due to a lack of trials on affected soils. Finally, the drainage and pH/ carbonate modules have been derived from first principles and are based on allocating crops to groups according to their relative sensitivity to adverse conditions. These latter modules have also not been locally tested due to a scarcity of trial sites.

It is significant that the moisture balance module has been elaborated in the most detail and has been subject to the most stringent testing because moisture stress is the single most important yield determining factor in the semi-arid environment

The next five chapters (Nos. 2 - 6) describe the theory underlying each of the component modules in the CYSLAMB program. Chapter 7 describes the validation of the entire model and discusses some of the underlying assumptions and their implications.

2. RADIATION AND TEMPERATURE LIMITED YIELD

2.1 Introduction

Plants have an obligatory developmental pattern in time which must be met if the photosynthetic assimilates are to be converted into economically useful yields of satisfactory quantity and quality. The developmental sequence of crop growth in relation to the crop phenology or crop calendar is influenced by climatic factors such as temperature and day length. In some crops both temperature and day length control the initiation of a particular development process, such as in flowering of photoperiodic winter cereals which have a vernalization requirement. In other crops, such as photoperiodic tropical cereals, day-length alone may determine the time of flowering. For successful growth and maturity of a crop, it is also necessary that there is a growing season that can contain the length of a specific crop cycle within which its phenological requirements are met. A shorter growing season does not necessarily result in crop failure but can cause reductions in yield.

Within the growing season, the choice of crop is governed by the temperature and photoperiodic regime. When these phenological requirements are met, then crop performance is determined by both the temperature regime and radiation regime within the limits imposed by the genetic resources of the crop. Evolutionary changes that have occurred in the biochemical and physical characteristics of photosynthesis have led to a large variation between crops. Different pathways of photosynthesis, based on either C_3 or C_4 primary assimilates are the result. The maximum rate of photosynthesis, its optimum temperature requirements and the response of photosynthesis to changes in temperature and radiation, are dependent on the photosynthetic pathway. Therefore, from a knowledge of the crop adaptability group, defined by the photosynthetic pathway, and of the temperature and radiation reponses of photosynthesis and the effect of temperature on respiration within that group, the impact of prevailing temperature and radiation regimes on crop productivity can be determined.

Thus once climatic phenological requirements are met, the rate of crop photosynthesis, growth and yield is directly related to the assimilation pathway and its response to temperature and radiation. In CYSLAMB the latter yield is referred to as the *radiation and temperature limited yield*. It gives the maximum yield level of a specific crop/cultivar under conditions where water, nutrients, pests and diseases are not limiting, and is primarily a product of the genetic characteristics of the crop and of its adaptation to the prevailing environment.

2.2 Model Description

2.2.1 General principles

Biomass production of plants is based on the interception of solar radiation and on exchanging carbon dioxide (CO_2) with oxygen in the air. The process where CO_2 from the air is converted into carbohydrates (CH_2O) is called *CO_2 assimilation*.

The following reaction takes place :

$$\mathbf{CO_2 + H_2O + solar\ energy \dashrightarrow CH_2O + O_2}$$

Part of the produced carbohydrates is used as building material for the plant biomass production and part is reconverted into energy. The release of energy from carbohydrates produced during the assimilation process is called *respiration* and is described by following generalised equation :

$$\mathbf{CH_2O + O_2 \dashrightarrow CO_2 + H_2O + chemical\ energy}$$

The underlying theory and series of equations used to derive net biomass production, which under optimum environmental and management conditions corresponds to the radiation and temperature limited biomass yield, is taken from FAO (1978).

The net biomass production (B_n) of a crop can be calculated by subtracting respiration losses (R) from gross biomass production (B_g), so that :

$$B_n = B_g - R \qquad (1)$$

The equation relating the *rate of net biomass production* or the growth rate (b_n) to the *rate of gross biomass production* (b_g) and the *rate of respiration* (r) is:

$$b_n = b_g - r \qquad (2)$$

Figures 5 and 6 schematize the course of biomass production (B) and of growth rate (b_n) of a crop.

The growth rates at any stage of the crop growing period are determined by the slope of the cumulative biomass production graph, so that :

$$\frac{dB}{dt} = b_n \qquad (3)$$

Three phases in growth rate can be distinguished :

- A phase of exponential growth when individual plants do not shade each other; a major part of the assimilates is reserved for leaf expansion. This leaf area increase is accompanied by a proportional increase in energy interception.

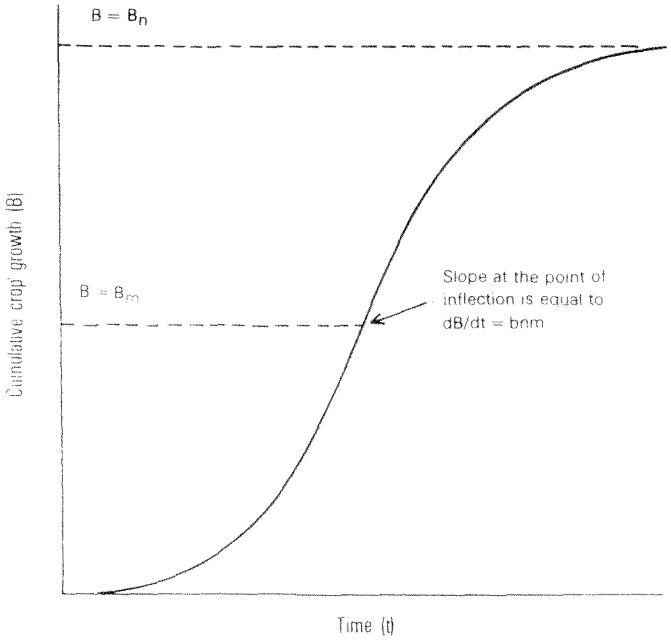
- A phase of constant growth at closed crop canopy; more leaf growth does not lead to more light interception, so that the growth rate remains constant and biomass weight increases linearly.

- A phase of decreasing growth when the crop is maturing and leaves are senescing.

A major part of the final biomass is produced during the second phase of constant growth. Thus the magnitude of this growth rate and the duration of the second phase largely determine total biomass production. The *maximum rate of net biomass production* (b_{nm}) is reached when the crop fully covers the ground surface. The *duration* of the linear growth period is species and cultivar specific, and is influenced by environmental conditions such as solar radiation, temperature, water and nutrient availability, soil toxicities, land management practices such as weeding, and pest control.

Figure 5

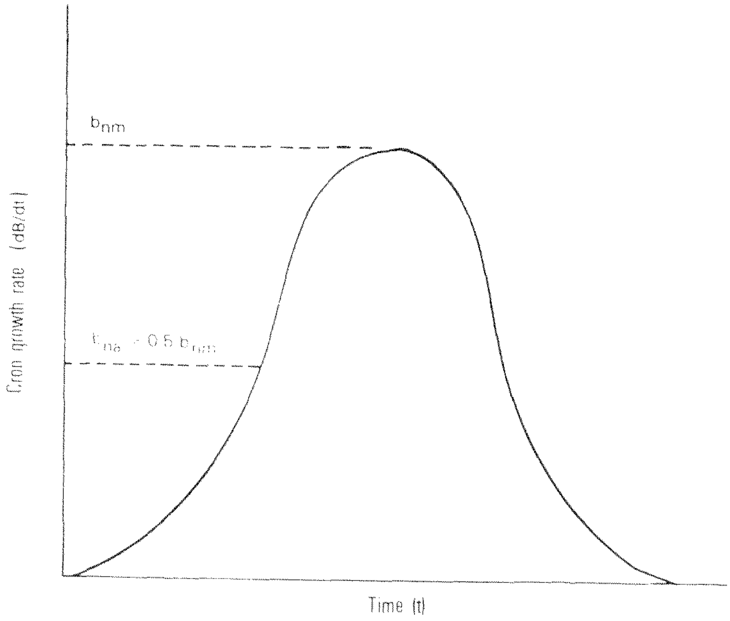
Typical Cumulative Crop Growth Curve



The graph shows the point of inflection during the period of maximum growth when the slope dB/dt is equivalent to the net biomass production (b_{nm})

Figure 6

Normal shape of curve of Crop Growth Rate against time showing average growth rate (b_{na}) = 0.5b_{nm}



Assuming water and nutrient availability are optimal and pests and diseases are absent, the growth rate of a specific crop is primarily determined by solar radiation and temperature. This potential growth rate corresponds with a potential biomass production which is called *radiation limited biomass production* in the CYSLAMB program. Assuming that the seasonal average rate of net biomass production is half the maximum crop growth rate (0.5 b_{nm}) (Figure 6), the net biomass production for a crop of N days is then:

$$B_n = 0.5 b_{nm} \times N \tag{4}$$

If b_{nm} can be calculated, then B_n can be computed according to equation (4), given an appropriate duration of crop growth. In order to calculate b_{nm} one can refer to equation (5), which is an adaptation of equation (2) for maximum rates of biomass production.

$$b_{nm} = b_{gm} - r_m \tag{5}$$

Thus if the maximum rate of gross biomass production (b_{gm}) and the corresponding respiration rate at that time (r_m) are known, the maximum rate of net biomass production (b_{nm}) can be computed.

2.2.2 Carbon dioxide assimilation of a single leaf

Photosynthetically active radiation, which is only part of the total solar radiation, is absorbed by green chlorophyll and used for the reduction of CO_2 into CH_2O. This conversion of CO_2 is crop specific. Two major photosynthetic pathways can be identified, i.e. the C_3 and the C_4 pathway. For crops following the first pathway, the first product of photosynthesis is 3-phosphoglyceric acid, a 3-carbon compound, while for C_4 crops malate and aspartate, 4-carbon organic acids are formed. The temperature at which the leaf photosynthesis process functions at maximum rate is also crop specific. Figure 7 gives the relationship between maximum leaf photosynthesis rate and temperature for the four major identified crop groups, while Table 2.1 gives an overview of some crop specific photosynthetic characteristics.

At the optimal temperature CO_2 assimilation rates and consequently CH_2O production rates can be determined at various radiation intensities, resulting in light response curves for leaves of the different plant species groups (Figure 8).

It must be noted that at a certain value of photosynthetically active radiation (PAR), the CO_2 exchange rate becomes constant at a maximum value, reflecting a *maximum leaf photosynthesis rate at light saturation* (P_m). The equation expressing the leaf photosynthesis function in terms of PAR is (FAO, 1978) :

$$P_1 = PAR \times \frac{P_m}{[PAR + (\frac{Pm}{E})]} \tag{6}$$

where P_1 = net rate of CO_2 exchange of leaves
PAR = photosynthetically active radiation
P_m = rate of CO_2 exchange at light saturation, or maximum net rate of CO_2 exchange of leaves
E = the efficiency of photosynthesis defined as P_m/A, where A is the radiation at which $P_1 = 0.5P_m$

Figure 7

Average Relationship between Maximum Leaf Photosynthesis Rate and Temperature for Different Crop Groups

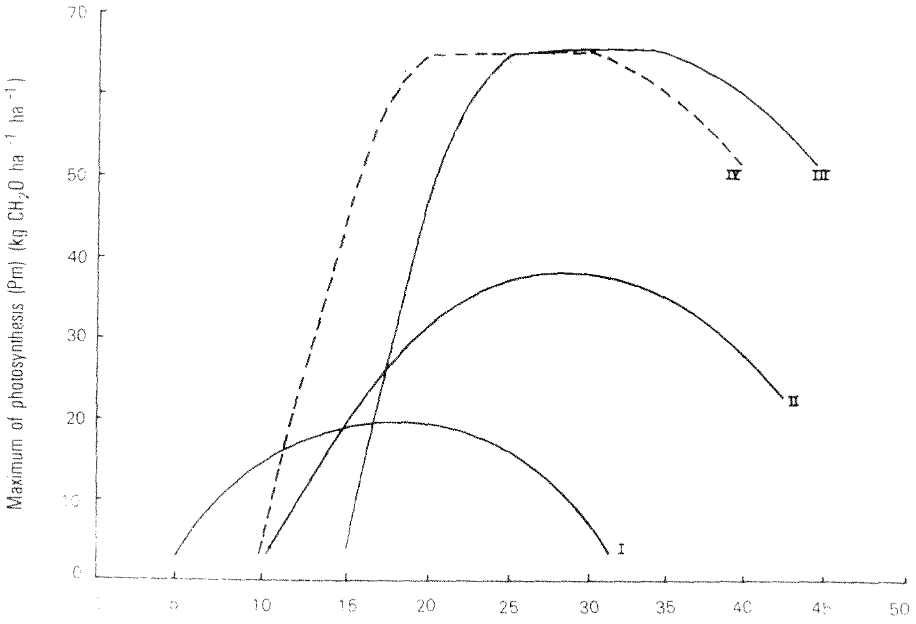
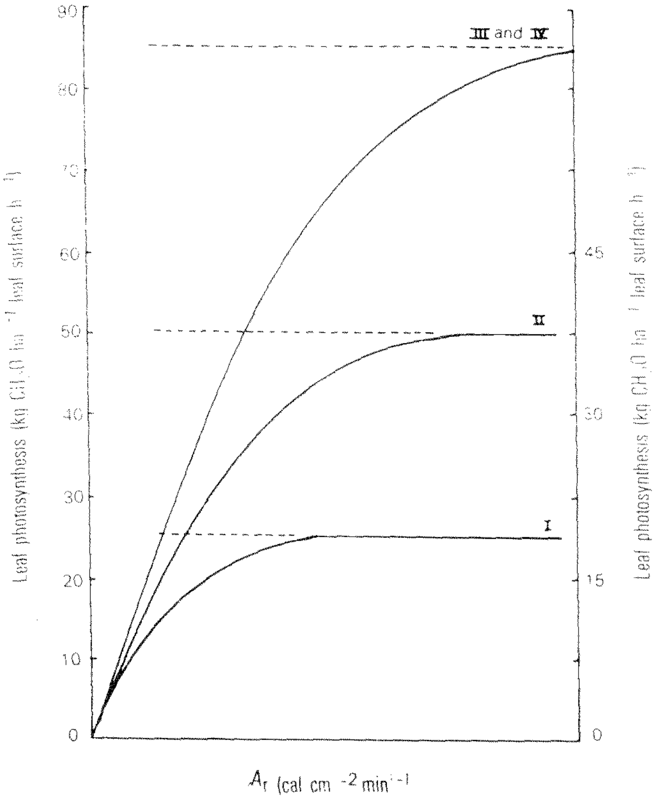


Figure 8

Relationship between Leaf Photosynthesis Rate at Optimal Temperature and Photosynthetically Active Radiation (A_r) for Different Crop Groups



P_m *is the maximum leaf photosynthesis rate at light saturation*

Table 2.1

Overview of some crop specific photosynthetical characteristics

Crop group 1

- assimilation pathway C_3
- response to temperature : optimum 15-20°C
  range 5-30°C
- radiation intensity at max.photosynthesis : 0.25-0.60 cal.cm^{-2}.h^{-1}
- max. net rate of CO_2 exchange at light sat.: 20-30 mg.dm^{-2}.h^{-1}
- maximum crop growth rate : 17-25 kg.ha^{-1}.h^{-1}
- specific crops : potato, chickpea, bean (Phaseolus v.), rape, cabbage, barley, wheat, tomato, grape

Crop group 2

- assimilation pathway C_3
- response to temperature : optimum 25-30°C
  range 10-35°C
- radiation intensity at max.photosynthesis : 0.30-0.80 cal.cm^{-2}.h^{-1}
- max. net rate of CO_2 exchange at light sat.: 45-55 mg.dm^{-2}.h^{-1}
- maximum crop growth rate : 30-40 kg.ha^{-1}.h^{-1}
- specific crops : groundnut, cowpea, soybean, bean (Phaseolus v.), tobacco, sunflower, sesame, tomato, safflower, rice, cotton, sweet potato, citrus, avocado.

Crop group 3

- assimilation pathway C_4
- response to temperature : optimum 25-35°C
  range 15-45°C
- radiation intensity at max.photosynthesis : 1.0-1.4 cal.cm^{-2}.h^{-1}
- max. net rate of CO_2 exchange at light sat.: 80-90 mg.dm^{-2}.h^{-1}
- maximum crop growth rate : 50-70 kg.ha^{-1}.h^{-1}
- specific crops : millet, sorghum, maize, sugarcane

Crop group 4

- assimilation pathway C_4
- response to temperature : optimum 20-30°C
  range 10-35°C
- radiation intensity at max.photosynthesis : 1.0-1.4 cal.cm^{-2}.h^{-1}
- max. net rate of CO_2 exchange at light sat.: 80-90 mg.dm^{-2}.h^{-1}
- maximum crop growth rate : 50-70 kg.ha^{-1}.h^{-1}
- specific crops : millet, sorghum, maize

Remark

Temperature responses of photosynthesis can be changed through breeding and selection. Some temperate and highland cultivars of millet, sorghum and maize respond better to lower temperatures.

2.2.3 Carbon dioxide assimilation of a crop canopy

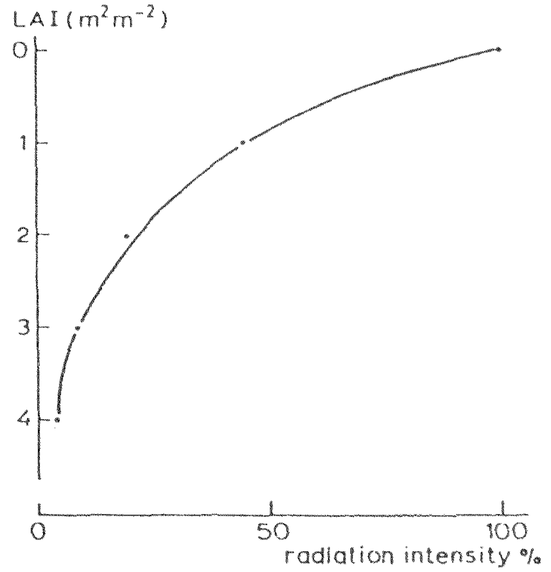
The principle of canopy CO_2 assimilation is in general the same as for a single leaf. The major difference is that there is an effect of shading on the lower leaves.

If one considers a crop where all the leaves are forming one horizontal layer covering the ground (leaf area index or LAI = 1), all of the PAR is absorbed by this layer. If another layer of leaves is situated under the first one, only that part of the radiation that is transmitted through the first layer can be photosynthetically active. The second layer of leaves will contribute to the assimilation rate of the first layer; this will result in an increase in assimilation rate for the total crop.

The radiation distribution within a field crop is determined by the arrangement of leaves in space and on the transmission and reflection properties of leaves. The distribution of radiation can be calculated by estimating the radiation intercepted in every layer of leaves for a given leaf distribution function. In general, as the radiation penetrates the canopy, its intensity decreases exponentially with the increase in leaf area. In practice this light extinction in a crop canopy can be determined by measuring the light intensity at different levels in the crop, together with measuring the cumulative leaf area at the same level. An exponential extinction curve can be established (see Figure 9).

Figure 9

Extinction of Radiation in a Crop Canopy



2.2.4 Calculation of the maximum rate of gross biomass production (b_{gm})

The maximum rate of gross biomass production of a crop under standard conditions, thus considering a LAI of 5 and a P_m value of 20 kg/ha.h at optimal temperature, can be calculated for a perfectly clear sky and a completely cloudy sky.

On a completely overcast day it is assumed that the incoming PAR which reaches the earth surface equals 10% of the daily global radiation. The latter can be calculated from the astronomic daylength and the earth declination in function of the considered time. On a perfectly clear day 50% of the daily global radiation is assumed to be photosynthetically active.

The following equation gives the maximum rate of gross biomass production for standard conditions (b_{gms}):

$$b_{gms} = f_o \times b_o + (1-f_o) \times b_c \qquad (7)$$

where f_o = the fraction of daytime the sky is overcast
b_o = the gross CO_2 assimilation rate on a completely overcast day
b_c = the gross CO_2 assimilation rate on a perfectly clear day

Values for b_o and b_c are tabulated by Goudriaan and Van Laer(1978a). The computer program developed by De Pauw and Nachtergaele (Nachtergaele, 1985), which yields a very good approximation of the tabulated b_c and b_o values, is used in CYSLAMB.

However according to Figure 8, the maximum leaf photosynthesis rate at light saturation (P_m) is dependant on both temperature and photosynthetic pathway of the species. It can be shown (FAO 1978) that '*y*' percent increase in P_m relative to P_m of 20 kg/ha.h leads to (*y* x 0.2) percent and (*y* x 0.5) percent increase in b_o and b_c respectively. Inversely '*y*' percent decrease in P_m relative to P_m of 20 kg/ha.h leads to (*y* x 2.5) percent and (*y* x 1) percent decrease in b_o and b_c respectively. Hence b_{gms} as calculated from equation (7) must be increased by:

$$b_{gmc} = (\frac{y/5}{100} \times f \times b_o) + (\frac{y/2}{100} \times (1-f) \times b_c \qquad (8)$$

for values of P_m greater than 20 kg/ha.h, and decreased by:

$$b_{gmc} = (\frac{2.5y}{100} \times f \times b_o) + (\frac{y}{100} \times (1-f) \times b_c) \qquad (9)$$

for values of *Pm* smaller than 20 kg/ha.h

Thus, if the above corrections are necessary, the following equation holds :

$$b_{gm} = b_{gms} \pm b_{gmc} \qquad (10)$$

2.2.5 Respiration rate at the maximum rate of gross biomass production (r_m)

In order to maintain the cellular organization in a plant, structural proteins, which are degrading constantly, have to be resynthesized. The energy requirements for this come from oxidation of primary produced carbohydrate called the *maintenance respiration*. The remaining primary photosynthetic products can be converted into new structural plant material, needing additional energy. The energy requirement for producing this new biomass comes from *growth respiration*. Unlike photosynthesis, respiration proceeds throughout the plant during both night and day time.

Maintenance respiration

Proteins in a plant, especially in the leaves, deteriorate and thus have to be resynthesized. The rate of protein disintegration is temperature dependant. The maintenance respiration is proportional to the mass of living tissue (Squire, 1990). Although few accurate data on maintenance respiration exist, van Heemst (1986) indicates that reasonable estimates can be made on the basis of the chemical composition of the biomass present. McCree (1974) found that the relative maintenance respiration rate (c) is dependent on both species and temperature. At 30°C the c-value for a legume crop (protein rich-crop) was 0.0283; for a non-legume crop c equalled 0.0108. Thus it requires more energy to maintain biomass richer in proteins.

The temperature dependence of c for both species was :

$$c_t = c_{30}(0.044 + 0.0019t + 0.0010t^2) \qquad (11)$$

Growth respiration

For the growth of plant material, substrate for building materials and energy for synthesis of the structures is needed. So part of the primary photosynthates are respired for energy production and part are used for conversion into cellulose, proteins, lignin, etc. It has been shown by McCree (1974) that the growth respiration is a linear function of the rate of gross biomass production. The rate of growth respiration (k) is independent of temperature and determined by the author as being 0.28 for both legume crops and non-legume crops.

When gross biomass is produced at its maximum rate (b_{gm}) the corresponding respiration rate (r_m) is then given by the following equation :

$$r_m = c \times B_m + k \times b_{gm} \qquad (12)$$

If B_m is known, r_m can thus be calculated from equation (12). Considering Figures 5 and 6, the rate of maximum gross biomass production (b_{gm}) calculated before (equation (7)) is the rate at the time of the point of inflection on the growth curve plotted against time. At this point in time the cumulative net biomass (B_m) of the crop is assumed to be equal to half of the net biomass that would be accumulated at the end of the crop's life.

Therefore $B = B_m = 0.5B_n$, and from equation (4) B_m for a crop of N days is :

$$B_m = 0.25 \times b_{nm} \times N \qquad (13)$$

2.2.6 Maximum rate of net biomass production (b_{nm})

Combining the respiration equation (12) with the net maximum biomass production rate equation (5) and by taking into account equation 11, the maximum rate of net biomass production is :

$$b_{nm} = \frac{0.72 b_{gm}}{(1 + 0.25 c_t \times N)} \qquad (14)$$

2.2.7 Net biomass production (B_n)

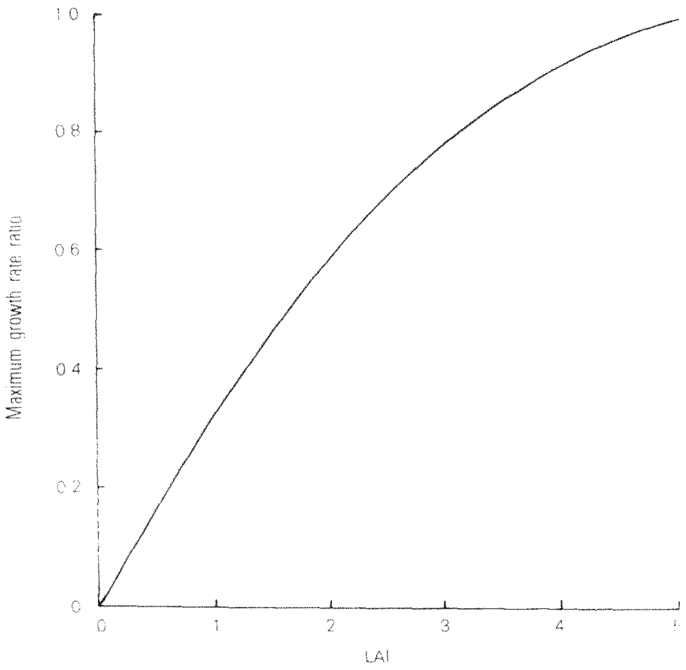
The net biomass production of a crop of *N* days is given by combining equation (4) with equation (14):

$$B_n = \frac{0.36 b_{gm}}{((1/N) + 0.25 c_t)} \qquad (15)$$

This equation is derived assuming that the LAI of the crop at the time of maximum gross biomass production rate (b_{gm}) equals five. Figure 10 (FAO 1978) shows that when the LAI at the time of maximum gross biomass production rate is less than five, the maximum gross biomass production does not reach its full potential.

Figure 10

Relationship between Leaf Area Index and Maximum Growth Rate as a ratio of the Maximum Growth Rate at LAI of 5



This is very true for Botswana where optimal planting densities for most rainfed crops will never achieve a LAI of five. So a correction factor should be applied if the LAI at full canopy is less than five. The correction *K* can be calculated by the equation :

$$K=-0.01+0.35LAI-0.003LAI^2 \tag{16}$$

The corrected net biomass production over the growing period is then obtained by :

$$B_n^{\prime}=K\times B_n\,(for LAI<5) \tag{17}$$

B_n corresponds with the radiation and temperature limited (biomass) yield used in CYSLAMB.

2.2.8 Relationship between leaf area index and plant density

Experiments on spacing of sorghum under close to optimal conditions in Botswana (DLFRS, 1980) suggest that LAI is closely correlated with the density of the plant stand. For the variety *Segaolane,* the following linear relationship between LAI at maximum crop cover (65 days after planting) and the plant population was found:

$$LAI = 0.833 + 0.192\times pd \tag{18}$$

pd = plant density
$r^2 = 0.96$

This relationship was tested for plant populations ranging from 13,000 to 120,000 plants per hectare. Although the LAI is influenced by the configuration of the crop stand (a combination of the distance between rows and the interplant distance within rows), this effect was minimized by averaging LAIs with the same plant density but with different row spacings.

Following a comparison of the leaf morphology of maize and sorghum through observation of stands of different plant densities in the field, and discussions with agronomists working for the Department of Agricultural Research and ALDEP (Persaud, MacPherson, *pers. com.*), it was concluded that the LAI for maize is approximately 20% higher than that for sorghum at the same plant density. Based on this assumption, equation (19) describes the relationship between LAI and plant density for maize.

$$LAI = 1.0 + 0.233\times pd \tag{19}$$

2.3 Minimum data set

The minimum data set required for the radiation simulation model is given in Table 2.2. The variables can be grouped into climatic and crop variables. The climatic parameters are derived from the Botswana Climatic Database (METEO). This database comprises data of all (9) operational synoptic stations in Botswana, as well as data from relevant stations from neighbouring countries.

Table 2.2

Minimum Data Set for Radiation and Temperature Limited Yield Model

Variable	Description	*Units*	Database
LAI	Leaf area index at full canopy cover	-	Crop
N	Maturation time	*days*	Crop
b_o	CO_2 assimilation rate on overcast day	$kg.ha^{-1}hr^{-1}$	Crop
b_c	CO_2 assimilation rate on clear day	$kg.ha^{-1}hr^{-1}$	Crop
P_m	Rate of leaf CO_2 exchange at light saturation	$kg.ha^{-1}hr^{-1}$	Crop
c_{30}	Maintenance respiration constant at 30°C	-	Crop
k	Growth respiration constant	-	Crop
LON	Longitude	°, ', "	METEO
LAT	Latitude	°, ', "	METEO
ADL	Actual day length	*hours*	METEO
TMA	Maximum daily temperature	°C	METEO
TMI	Minimum daily temperature	°C	METEO

The data are arranged on a 10 day period (dekad) basis. Crop parameters are contained in a crop database. They are collected from international literature and from local field research. It should be mentioned that very little crop physiological work has been carried out in Botswana, and that the work done is mostly related to sorghum. Therefore specific crop characteristics like respiration and assimilation rates are derived from literature.

2.4 Testing and Validation of the Radiation and Temperature Limited Yield

The radiation and temperature limited yield estimated by CYSLAMB can be validated against actual crop biomass production under optimal conditions, when such constraints as moisture stress, poor drainage, nutrient shortages or toxicities do not apply, and where pests, diseases and weeds do not occur.

A crucial parameter for this model is the LAI at full canopy cover. LAI at full canopy cover is very dependent on the planting density of the considered crops, at least for determinate crops or varieties. It is obvious that a sparse planted crop will not achieve the same LAI under optimal conditions as a very dense planted crop. According to the model this implies a lower biomass production for the former plant stand. The duration of the growing season of the crop (*N*) is also related to the amount of produced biomass. The longer the growing season the more biomass theoretically can be produced .

In order to test the radiation model for Botswana conditions, measured LAI at full canopy cover should be put into the model and the calculated biomass for a given period of time can then be compared with the measured biomass. Optimal conditions for water and nutrient supply as well as the absence of pests and diseases are required. Often these conditions are only met in Botswana under high management irrigation. The major problem however is the lack of LAI measurements in the field.

An alternative approach is to consider rainfed experiments under near to optimal water supply conditions (adequate and well distributed rainfall). A review of research data in Botswana reveals that the rainy season 1979-80 was such a year for Gaborone. The sorghum spacing experiments of DLFRS in that year (DLFRS Phase III, First Annual Report p.17) give valuable information on measured LAI and biomass production to test the model. The trial examined the effects of different sorghum (var. Segaolane) populations for a range of different row spacings on the growth and yield of the crop, the radiation and temperature environments and water relations. LAI was measured at full canopy cover (day 65) and total biomass production weighed at day 95. In order to eliminate the effect of different row spacings, figures are averaged for equivalent plant populations, if applicable.

Although rainfall was abundant and well distributed, the quality of the growing season was tested by simulating a water balance for the different plant populations. This showed that some stress (15% for lower plant densities and 20% for higher plant densities) occurred from day 60 on. Although this stress apparently did not affect the LAI measured at day 65, it probably had an influence on the final weighed biomass. Therefore the crop dry weights are corrected upwards by 15% and 20% respectively to approximate the biomass dry weights under optimal conditions. These values are given as corrected biomass production in Table 2.3.

Table 2.3

Comparison of measured Crop Biomass Production with that predicted by CYSLAMB

Measured LAI	**Total Crop Dry Weight (kg/ha)**		
	Measured	**Measured, corrected for moisture stress**	**Simulated by CYSLAMB**
Sorghum			
1.1	5610	6600	6500
1.4	7320	8600	8100
1.8	8830	10400	10000
2.7	12540	15700	13800
5.0	19630	24500	19000
Groundnut			
4.5	10400	13800	13100

If the measured LAI and the number of days of the growing period (95 days) are put into the model, together with the climatic parameters of the particular growing season, the expected biomass can be calculated. These figures are compared with the corrected measured biomass in Table 2.3.

The same simulation was done for the agronomic groundnut trial early planting for season 1990-91 (A. Mayeux, 1991). Although no visible stress occurred during the growing season (A.Mayeux, pers.com.) some stress (25%) could be calculated using a simple water balance. Measured biomass should thus again be corrected in order to reflect production under optimal conditions.

Comparing measured values with simulated values (Table 2.3) the model can be validated for Botswana conditions. The method of least squares was used for comparing measured with simulated biomass production. Considering the six data pairs, a coefficient of determination (r^2) of 0.75 was found; the standard error of estimate of predicted values on measured values is 2390 kg/ha. It is clear that the dry weights corresponding with a LAI of 5 for sorghum highly influence this result. For rainfed agriculture these high values are hardly representative; plant densities associated with such a high LAI for sorghum are never obtained by Botswana farmers, not even under very high management practices. Leaving this extreme value out of the data set, a coefficient of determination of 0.93 and a standard error of estimate of 951 kg/ha are obtained. Although the available data set is very limited for correlation purposes, these results are highly satisfactory.

3. MOISTURE LIMITED YIELD

3.1 Model Description

3.1.1 General Principles

Water plays a central role in the metabolism of plants. It is a structural component often constituting more than 90% of the vegetative biomass. It is a vital component in the photosynthesis process, a product of respiration, and a solvent and conveyor of compounds in all living plants. Most water is taken up by the root system of the plant and transported to its photosynthetically active parts. Only a small part of the water absorbed by the plant is actually used for photosynthesis. Most escapes as vapour during transpiration from the plant canopies. To facilitate carbon dioxide assimilation large leaf surfaces with moist cells are exposed to a dry atmosphere so that transpiration is necessary for several reasons. The flow of CO_2 into the leaves is regulated by the stomata and thus loss of water through the same pores is inevitable. Moreover in order to control rising leaf temperatures during the day time, energy must be dissipated.

Under unlimited water supply conditions plants can transpire at a maximum rate. If water stress occurs several physiological processes will be affected. The aperture of the stomata will reduce, limiting vapour losses from the leaves but also decreasing CO_2-absorption. Cell expansion will slow down and, after prolonged desiccation, cease.

Nowadays, there is substantial evidence that the amount of dry matter accumulated by a crop is proportional to the amount of water that it transpires in the same time (Crout and Azam Ali, 1991). If a cropped field can transpire, or actually evapotranspire, at a maximum rate, full potential biomass production and yield can be obtained, provided that no other constraints such as pests and diseases occur. de Wit (1958) found that in climates with a large percentage of bright sunshine duration, such as arid and semi-arid regions, the following relation applies:

$$Y = m \times \frac{T_a}{E_0} \qquad (20)$$

The total dry matter yield (Y) is related to the ratio of actual transpiration (T_a) and potential evapotranspiration (E_0), with m being the proportionality coefficient. Later Doorenbos and Kassam (1979) proposed a modified method evaluating the yield response of crops to applied water in terms of the following relationship.

$$(1-\frac{Y_a}{Y_m}) = ky \times (1-\frac{ET_a}{ET_m}) \qquad (21)$$

Y_a is actual yield, Y_m is maximum attainable yield when full water requirements are met and no other limitations occur, ET_a is actual crop evapotranspiration, ET_m is potential crop evapotranspiration, and *ky* is an empirically derived yield response factor quantifying the effect of water stress. When crop water requirements are fully met by available supply, the crop in the field can evapotranspire at its maximum rate ($ET_a = ET_m$) and no yield reduction due to water stress occurs. When water supply does not meet crop water requirements, crops will transpire less and an evapotranspiration deficit will occur ($ET_a<ET_m$) resulting in a yield decrease ($Y_a<Y_m$). This method was developed for high producing varieties of crops, growing in large fields where optimum agronomic and

irrigation practices including adequate input supply, except for water, are provided.

In order to calculate Y_a, the maximum yield Y_m, ET_a and ET_m have to be known. The maximum yield corresponds with the *radiation and temperature limited yield*, the derivation of which is described in Chapter 2. The derivation of ET_m, ET_a and *ky* will be discussed in following sections.

3.1.2 Maximum crop evapotranspiration (ET_m)

Crop water requirements are mainly determined by climate and crop characteristics, and expressed by the rate of evapotranspiration *(ET)* in mm/period. The level of *ET* is related to the evaporative demand of the air. This evaporative demand can be related to the evapotranspiration of a reference crop(ET_0), comprising a closed, short, actively growing, green grass cover which is completely shading the ground and is well supplied with water. This *reference crop evapotranspiration*, which includes both transpiration by the crop and evaporation from the soil, can be related to the maximum potential evapotranspiration of individual crops by using specific coefficients. The reference crop evapotranspiration, at a given site and time, depends only upon the prevailing atmospheric conditions, such as radiation, temperature, humidity of the air and air movement, and on parameters determining atmospheric conditions, such as elevation, latitude and time of the year. Other possible influences like water stress, crop population density, soil fertility, crop height are excluded at this stage.

The reference crop evapotranspiration can be measured using lysimeters, estimated from measured pan evapotranspiration, or calculated using formulae such as those developed by Penman or Blaney and Criddle.

In order to account for the effect of crop characteristics on crop water requirements, crop coefficients *(kc)* are presented to relate ET_0 to crop evapotranspiration (ET_m). These crop coefficients are empirically determined for disease-free crops growing in large fields under optimal water and fertility conditions, and achieving full production potential under the given growing environment. Crop coefficients are specific for each crop and crop development stage.

For a given crop and crop development stage the maximum crop evapo-transpiration is given by the equation :

$$ET_m = kc \times ET_o \qquad \textbf{(22)}$$

ET_m is the maximum possible yield when water is adequate for unrestricted growth and development.

3.1.3 Reference crop evapotranspiration (ET_0)

The reference crop evapotranspiration is not an easy parameter to determine. Sophisticated equipment is necessary to compare the water application to the short grass with the water losses with the required precision of a few millimeters per month. Due to high equipment and working costs several methods to calculate ET_0 from simpler meteorological measurements have been derived. Vossen (1989) argues that, for application of ET_0 to crop yield modelling, the Penman equation can best be used for following reasons :

- As far as agro-climatological applications are concerned, the Penman approach as such is the most frequently used in Africa, and is used, among others, by FAO for it's worldwide Early Warning and Crop Monitoring Model (Frere, 1979; FAO, 1986), is recommended by FAO for the calculation of irrigation requirements (Doorenbos and Pruitt, 1977), and is in many countries used in agro-ecological zoning programmes (FAO, 1978).

- For reasons entirely due to the observation method itself, the Class "A" evaporation values available in Botswana are not reliable.

- The validation by SMEC (1987) of the Penman equation for Botswana resulted in a much more accurate simulation of the measured evaporation of the 2 only large dams in Botswana, for which both meteorological data and measured observations are available.

In the formula a_1 through a_9 are a set of coefficients depending on the particular location. They are empirically determined for estimating ET_0. These coefficients are discussed in Persaud *et al* (1990).

The first two terms of the Penman equation represent the water loss from the net incident solar radiation, i.e. the incoming solar radiation minus the net outgoing longwave radiation from the surface. It is usually denoted as the *energy* component. The third term represents the water loss caused by wind at a given level of dryness and is usually denoted as the *aerodynamic* component. The relative importance of these two components depends on climatic conditions.

3.1.4 Crop coefficients

Crop coefficients account for the effect of differences in the characteristics of specific crops on evapotranspiration. They relate the evapotranspiration of a short grass cover to the evapotranspiration of a specified crop under full production potential conditions.

The main characteristics affecting *kc* values are the adaptation to control crop transpiration, crop height, crop roughness, crop reflection, % groundcover, crop planting or sowing date, rate of crop development, length of the growing season, and, especially during the early growth stage, the frequency of rainfall. Sisal can close stomata during daytime, whereas citrus has waxy leaves to better control transpiration. Wind will affect the rate of transpiration of taller crops more due to air turbulence above the rougher crop surface, thus implying higher transpiration values than for a smooth short grass cover.

Crop evapotranspiration is the sum of transpiration of the crop and evaporation from the soil surface. During full ground cover, evaporation is negligible; immediately after sowing or planting, evaporation from the soil surface can be considerable, especially when the surface is wet after frequent rains. At full canopy cover, which approximately corresponds to flowering for cereals, ET_m is at its highest value. Figure 11 depicts the evolution of crop transpiration and soil evaporation under irrigated conditions.

PENMAN FORMULA

$$ET_o=\frac{\Delta}{\Delta+\gamma}R_a(1-r)(a_1+a_2\times\frac{n}{N})-\frac{\Delta}{\Delta+\gamma}\times\sigma T^4(a_3-a_4\sqrt{e_d})\times(a_5+a_6\times\frac{n}{N})+\frac{\Delta}{\Delta+\gamma}\times a_7(a_8+a_9\cdot u)\times(e_a-e_d) \quad \textbf{(23)}$$

where :

Δ = slope of the saturation vapour pressure versus temperature curve at the value for the mean air temperature of the considered period in millibars per °C

γ = constant in the wet and dry bulb psychrometer equation

R_a = short wave radiation received at the limit of the atmosphere (Angot's value) for a given location expressed in mm of evaporable water; can be calculated from the astronomical formulae given by Gommes (1983)

r = reflection coefficient or albedo for short green grass

n = mean hours bright sunshine of the considered period on Stokes-Campbell bright sunshine recorder

N = mean daylength for a given location and the considered period calculated from the astronomical formulae given by Gommes (1983)

σT^4 = blackbody radiation expressed in mm of evaporable water for the prevailing mean air temperature, in degrees Kelvin

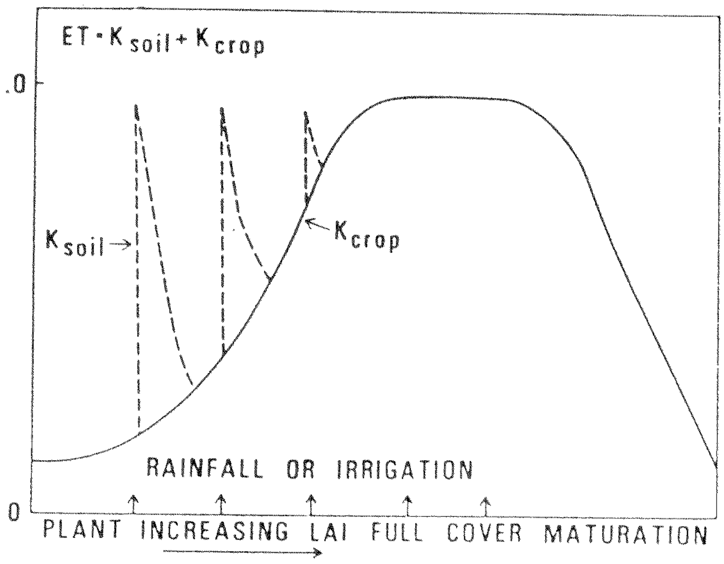
e_a = saturation vapour pressure in millibars

e_d = mean vapour pressure for the considered period in millibars

u = mean windspeed at an elevation of 2m for the given period and expressed in m/sec

Figure 11

Expected changes in crop coefficients as influenced by stage of growth and wet soil caused by irrigation or rainfall

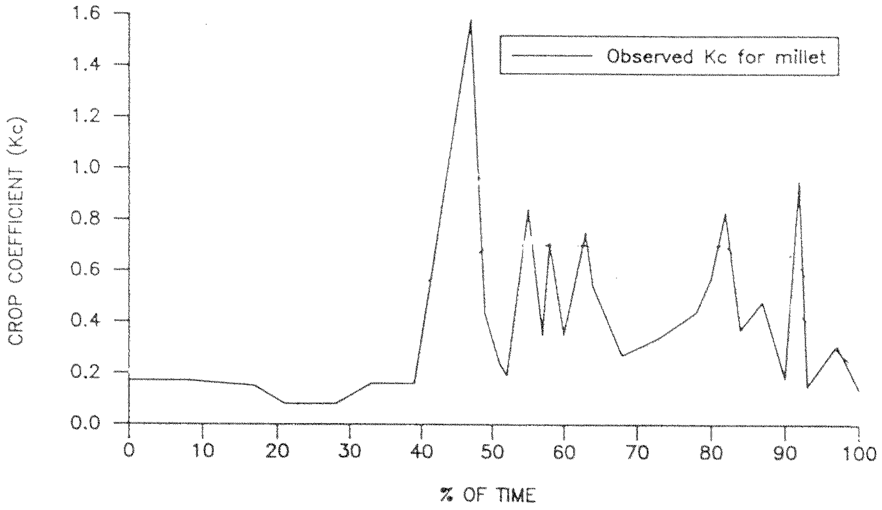


Source: Adapted from Shaw (1976)

Although crop transpiration and soil evaporation are governed by different physical processes, the kc-values represent herein the combined effect of both, thus relating ET_0 to ET_m. Measured *kc* values can differ considerably from day to day (see Figure 12). Therefore Shuttleworth (1988) suggests that this empirical approach of calculating ET_m can only be used for periods of 10 days or more.

Figure 12

Crop coefficients observed at the AGRHYMET Centre, Niamey.



Source: Adapted from Agnew (1991)

3.1.4.1 Calculation of *kc* under maximum potential production conditions

The calculation of crop coefficients follows the approach proposed by Doorenbos and Pruitt (1977). For field and vegetable crops, the growing season is divided into four stages as follows:

*(1) **initial stage**:*	*germination and early growth, when the soil surface is not covered or is sparsely covered by the crop (ground cover <10%)*
*(2) **crop development stage**:*	*from end of initial stage to attainment of effective full ground cover (ground cover = 70-80%)*
*(3) **mid-season stage**:*	*from attainment of effective full ground cover to time of start of maturing as indicated by discolouring of leaves or leaf abscission.*
*(4) **late season stage**:*	*from end of mid-season stage until full physiological maturity*

Examples of length of crop growth stages under average growing season conditions for the most important rainfed crops in Botswana are given in Table 3.1.

Table 3.1

Length of crop growth stages for important rainfed crops in Botswana

Crop	Variety	Duration of growth stages (days)			
		1	2	3	4
Sorghum	Segaolane	20	30	40	30
Maize	KEP	20	30	40	30
Millet	Serere 6A	20	30	30	20
Cowpea	Black eye	10	25	30	15
Groundnut	Sellie	20	30	40	30
Sunflower	Russian 4	20	35	45	25

Crop coefficients for each dekad of the different crop development stages can be calculated and attributed as follows :

(a) initial stage

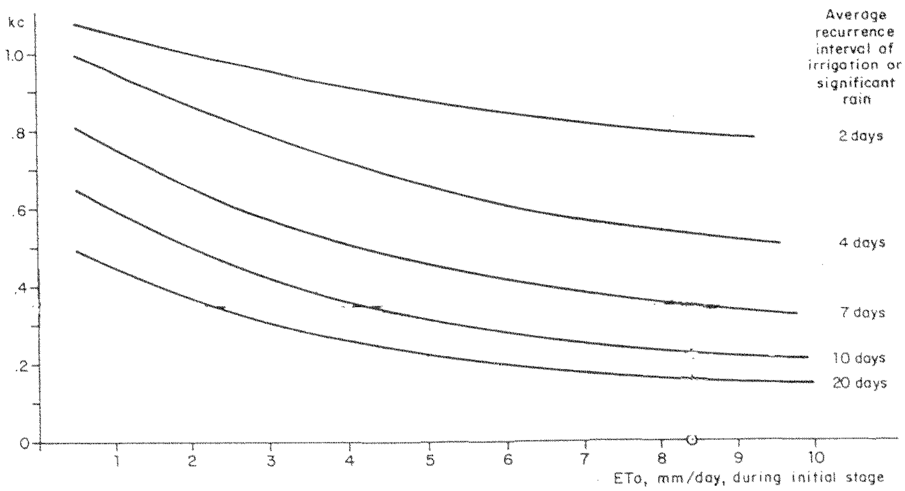
For the initial stage the crop evapotranspiration losses are similar to bare soil evaporation losses. Joshua (1990) mentions that bare soil evaporation occurs in three recognizable stages. In the *first stage* the soil is wet and water moves to the soil surface to meet the evaporation potential of the atmosphere. The evaporation rate at this stage is therefore controlled by atmospheric conditions. The *second stage* begins when the moisture content of the surface soil layers decreases to a point when water cannot move to the surface fast enough to meet the evaporative demand of the atmosphere. The evaporation rate then falls progressively below the potential rate reflecting the decreasing ability of the drying profile to transmit soil water. Thus, the onset of the second stage and the subsequent evaporation rates are controlled by the hydraulic properties of the soil. The *third stage* is established when the surface layer becomes so desiccated that the evaporation takes place at a constant slow rate by vapour diffusion.

In practice the first and second stage account for most of the bare soil evaporation during the planting season in Botswana. The evaporation potential of the atmosphere is assumed to be equal to the potential evapotranspiration rate as calculated by the Penman equation (ET_0). Figure 13 shows that if the soil stays wet (average recurrence interval of significant rain of 2 days) the bare soil evaporation (E_b), or initial crop development stage evapotranspiration, approximates to ET_0. As the soil desiccation is prolonged (e.g. 10 days) the ratio E_b/ET_0 decreases fast.

Figure 13 can be used to determine *kc* values for the initial crop development stage. The rainfall frequency is predicted and for the calculated ET_0 a corresponding *kc* factor is obtained. Data presented in Figure 13 assume a medium textured soil. Given the different hydraulic properties of coarser and finer textured soils, derived *kc* values should be downward adjusted by 30% and upward by 15% respectively.

Figure 13

Average *kc* value for initial crop development stage or for bare soil as related to level of ET_0 and frequency of rainfall



(b) Mid-season stage

Crop coefficients for the mid-season stage, corresponding with maximum water use, are derived from tabulated values (Doorenbos & Pruitt, 1977). It is assumed that during the entire mid-season stage the selected kc-value is constant.

(c) Crop development stage

Dekadal crop coefficients for this stage are obtained by linear interpolation between the *kc* value of the initial stage and the *kc* value of the mid-season stage (see Figure 14).

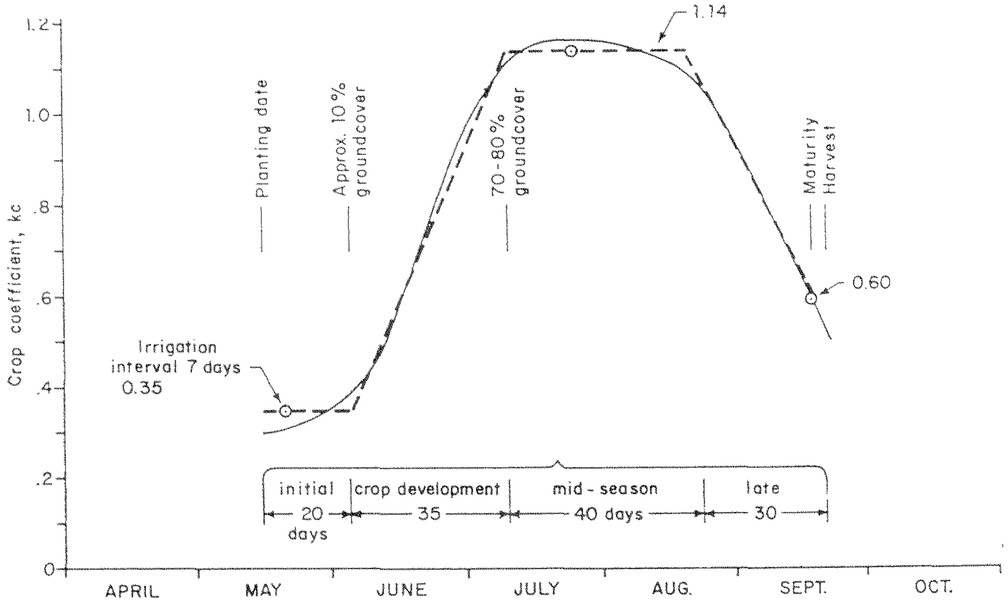
Thus as the crop ground cover increases the crop evapotranspiration will also increase.

(d) Late season stage

A *kc* value at physiological maturity of the crop is selected from the Doorenbos and Pruitt (1977) tables. The dekadal *kc* values for the late season stage are linearly interpolated between *kc* mid-season and *kc* maturity values. Figure 14 and Table 3.1 illustrate this procedure.

Figure 14

Example of crop coefficient curve



3.1.4.2 Adjustment of *kc* under conditions of restricted potential production

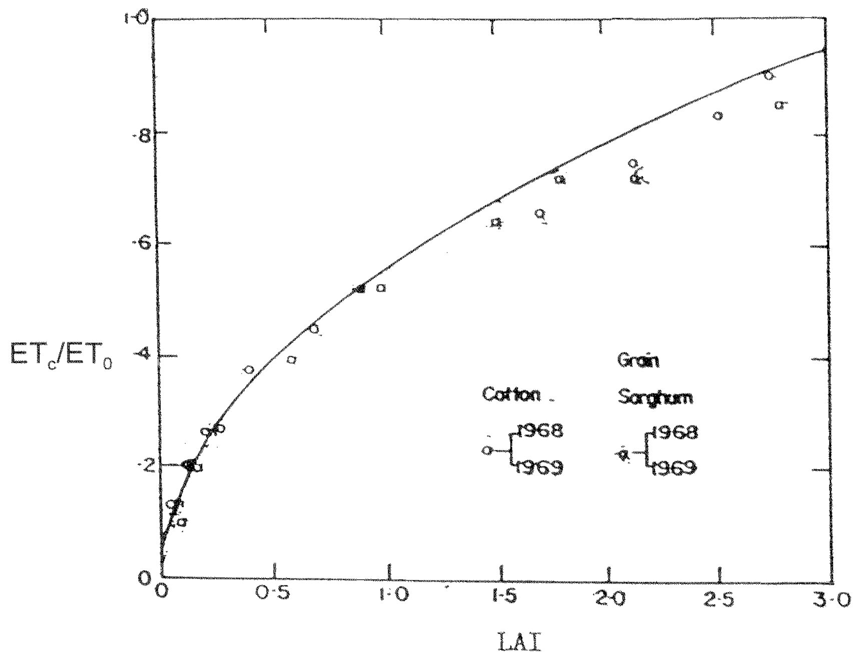
Calculated *kc* factors according to the Doorenbos and Pruitt methodology assume management levels for achieving full production potential under a given growing environment. In reality these management levels do not often occur in the rural areas of Africa. Although water supply and nutrient availability can be sufficient for optimal crop production, the full production potential may not be achieved. For the latter, among other conditions, a dense crop population is necessary. This implies that crop coefficients are management specific. Ritchie and Burnett (1971) demonstrate that the leaf area index (LAI) of a plant population under ample water supply severely influences the ratio between plant transpiration (and thus also ET_m) and ET_0, in other words, the crop coefficient (see Figure 15). This ratio approaches the value of one at about a LAI of three. The crop coefficient value of one can be regarded here as the value under full production potential management conditions. The relationship proposed by Ritchie and Burnett in Figure 15 can be closely approximated by the equation :

$$ET_m = ET_o(1 - \frac{1}{e^{0.8LAI}}) \qquad (24)$$

for $LAI<3$

Figure 15

Plant evapotranspiration (ET_c) relative to potential evapotranspiration (ET_o) as influenced by LAI when the soil water is not limited



Source: Adapted from Ritchie and Burnett (1971)

A similar relationship is used in the CERES-Maize model (Jones *et al*, 1986)

$$ET_c = ET_o(1 - \frac{1}{e^{LAI}}) \qquad (25)$$

The relationship in equation (25) is used for maize in CYSLAMB.

There is a direct relation between *LAI* of a plant population and the plant density (De Wit, 1992a), and sparse stands with a *LAI* smaller than three consume less water for achieving optimal plant growth. Consequently crop coefficients proposed by Doorenbos and Pruitt should be adjusted downwards for plant populations with a *LAI* smaller than three, using the equation or Figure 15. If, for example, a crop stand at maximum groundcover under unlimited water supply corresponds with a *LAI* of two, then the crop coefficients (crop development, mid-season and late season stage) should be downgraded by 20%. As the crop coefficient for the initial stage is comparable to the bare soil evaporation rate, no adjustment should be made here.

3.1.5 Water balance of a soil-plant system

The measurement of evaporation and transpiration or, for simplicity, evapo-transpiration can be made in the liquid phase as a rate of loss of water from the soil, or in the vapour phase as a rate of gain of water vapour by the atmosphere. Techniques for estimating evapotranspiration can therefore be considered in principal categories, those using a liquid water balance and those where the flow of water vapour into the air is measured (Wallace, 1991).

Usually, evapotranspiration is indirectly estimated by measuring changes in the water content of the soil. For the latter soil moisture balance studies are a widely used technique. Lysimetry is one of the most common hydrological methods which gives a complete knowledge of the water balance equation. For several reasons, not least the costs and time involved in such studies, modelling provides a useful short cut for estimating the soil water balance parameters.

The water balance is simply a statement of the law of conservation of matter, i.e. matter can neither be created nor destroyed but can only change from one state or location to another. The water content of a given volume of soil cannot increase without addition from outside, nor can it diminish unless transported to the atmosphere by evaporation, or to deeper zones by drainage (Hillel,1971).

In its most general form the water balance equation states that changes in volumetric water content of soil over a certain period of time (δSM) are equal to the difference of the amount of water coming into the soil and the amount of water withdrawn from the soil over that period :

$$\delta SM = W_{in} - W_{out} \tag{26}$$

At the level of the individual cropped field under rainfed conditions, water gains can be described as follows :

$$W_{in} = P + W_{lin} + W_{g} + W_{on} \tag{27}$$

where: P : rainfall
W_{lin} : incoming water from lateral seepage
W_{g} : groundwater contribution
W_{on} : gain of water by run-on from adjacent fields

Water losses can be described by :

$$W_{out} = E_{b} + T_{c} + T_{w} + W_{d} + W_{lout} + W_{off} \tag{28}$$

where: E_{b} : bare soil evaporation
T_{c} : crop transpiration
T_{w} : weed transpiration
W_{d} : water loss due to deep drainage
W_{lout} : outgoing water from lateral seepage
W_{off} : loss of water by run-off to adjacent fields

All itemized losses and contributions are expressed in volumetric percentages or mm water, and summed over a time period.

The integral form of the water balance equation, or the change in soil moisture (δSM) over a defined period is thus given by :

$$\delta SM = P + (W_{lin} - W_{lout}) + W_g - W_d + (W_{on} - W_{off}) - E_b - T_c - T_w \qquad \textbf{(29)}$$

When the above equation (29) is used at the level of agricultural fields in Botswana several simplifications can be made :

(i) Run-off on farmed fields is not yet a problem in Botswana. Biot (1988) and L&WMRP (1991) report very low net losses of water in rural rangeland where a run-off from one site normally results in run-on to another site of a same micro-environment. Vossen (1989) also observed that if run-off within a farmer's field occurred, it mostly resulted in infiltration or temporary surface storage somewhere else in the same field. Redistribution of water within the field is associated with micro-topography but counteracted by the tilt of the soil after ploughing. It is concluded that, at the scale of a farmer's field, run-off and run-on compensate each other (W_{on} - W_{off} = zero).

(ii) No data on lateral seepage at the farm level are available in Botswana. It is assumed that the gains equal the losses so that (W_{lin} - W_{lout}) equals zero.

(iii) Groundwater tables in Botswana usually occur at considerable depth, often exceeding 30m (Gieske & De Vries, 1985; Arntzen & Veenendaal, 1986) The contribution of groundwater (W_g) to the arable profile can thus be omitted. An exception can be made for areas around the Okavango delta where groundwater levels are much shallower.

(iv) Drainage can contribute significantly to the recharge of aquifers on the hardveld; Arntzen & Veenendaal (1986) mention up to 100 mm/year of recharge in a wet year. It is reasonable to assume that drainage out of the maximum rooting zone of a crop occurs when that particular soil section is at field capacity. Thus water in excess of the maximum available water holding capacity of the soil within the maximum crop rooting depth is lost for plant growth. The amount that can be stored in the soil after a rainfall event equals the difference between the maximum available water holding capacity and the water already stored. All water from a shower exceeding this value is assumed to drain freely down. This fraction of water from a shower potentially useful for crop growth coincides with the upper limit of the effective rainfall of that shower. Therefore the rainfall term and the drainage term in equation (26) can be substituted by an effective rainfall term (EP). The lower threshold value for effective rainfall equals the daily evapo-transpiration.

Taking the above observations into account, the following simplified equation for the waterbalance at field level is proposed :

$$\delta SM = EP - E_b - T_c - T_w \qquad \textbf{(30)}$$

In arid and semi-arid regions evaporation from the soil (E_b) can be a substantial component of total water use (evapotranspiration), especially when sparse crop stands are considered. Different techniques can be used to measure evaporation from a soil surface and transpiration from a crop separately, but the measurements are difficult and very time consuming (Gregory, 1991).

For practical purposes, evaporation from a soil surface and transpiration from plants can be combined into an evapotranspiration term. Evapotranspiration is widely used in modelling water consumption by crops.

3.1.5.1 CYSLAMB moisture balance output

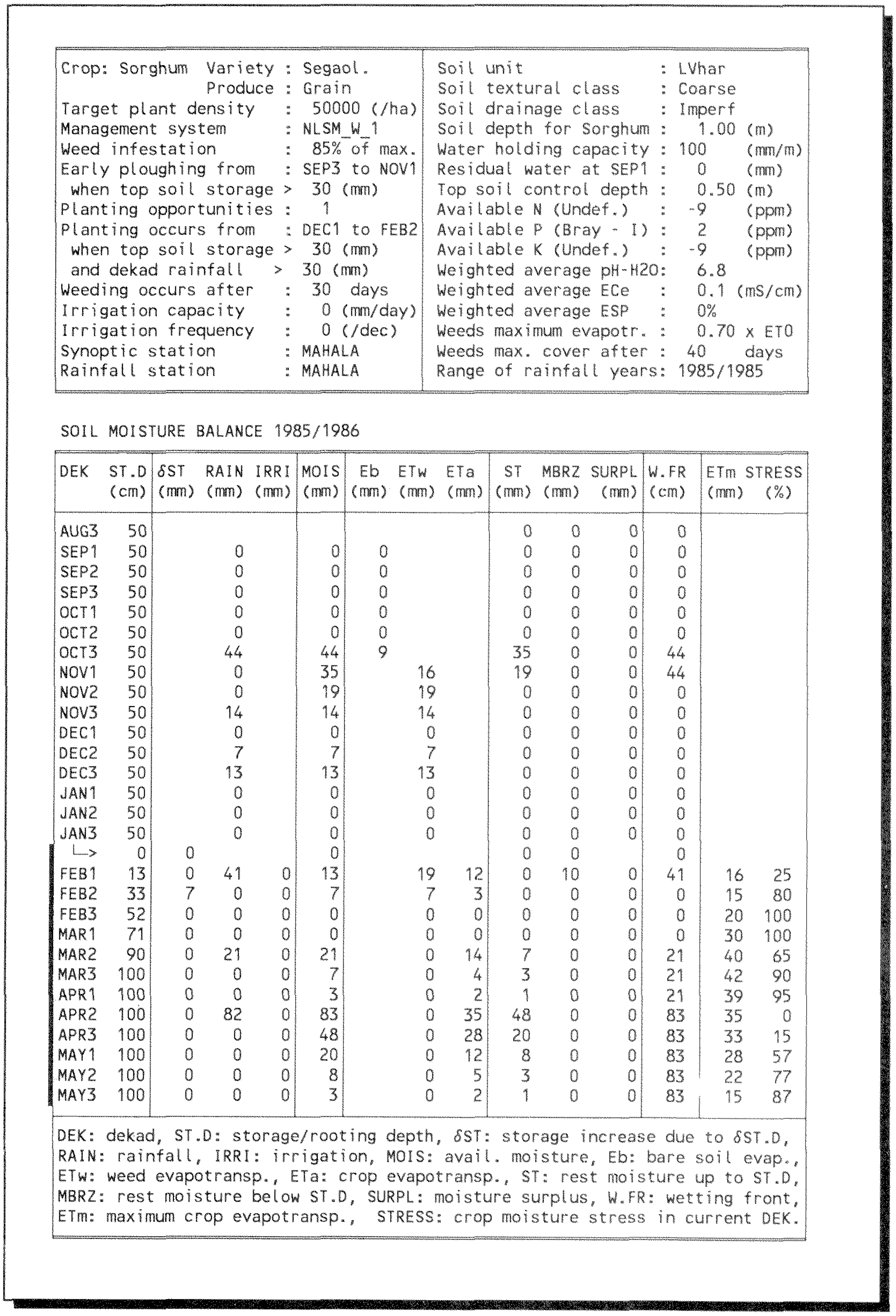
Equation 30 describes the moisture balance which is calculated for each dekad by CYSLAMB. The results can be viewed in the *comprehensive report* which is an option available for presenting the results from evaluation runs of the program. Figure 16 gives an example of a typical report based on actual rainfall data for the hydrological year 1985/86 at Mahalapye

The columns in the soil moisture balance report (Figure 16) refer to inputs, storage parameters and outputs. In any dekad the net moisture balance is zero.

The column headings are as follows:

> ***DEC*** is the dekad for which the moisture balance is calculated. Dekads are listed chronologically from the start of the hydrological year. A default starting dekad of *SEP1* has been set for Botswana. The storage functions listed for *AUG3* in Figure 16 refer to conditions at the end of that dekad. The symbol └──> indicates that the specified criteria for a planting opportunity are met in the subsequent dekad.
>
> ***ST.D*** is the soil depth within which water can be extracted by crop roots. After a planting opportunity has been identified *ST.D* increases progressively until the maximum rooting depth is attained (100 cm in the example). Prior to planting, an arbitrary *ST.D* is set in order to calculate the soil moisture storage necessary to signal a planting opportunity. A default of 50 cm was used for the national land suitability assessment in Botswana.
>
> ***δST*** is the additional stored moisture accessible to the crop due to an increase in rooting depth relative to the previous dekad. *δST* is important in modelling moisture availability to the crop in its early stages of development. After maximum rooting depth is attained *δST* is zero.
>
> ***RAIN*** is the effective rain falling at the site. Effective rainfall is calculated by eliminating daily values of less than the Penman potential evapotranspiration (ET_0). Daily falls > ET_0 are considered effective and are summed to give the dekadal figures used in the model. In calculating outputs, all the dekadal rainfall is assumed to be available from the first day of the dekad.

Figure 16 Example of CYSLAMB Moisture Balance



```
Crop: Sorghum  Variety : Segaol.          | Soil unit                 : LVhar
               Produce : Grain            | Soil textural class       : Coarse
Target plant density   :  50000 (/ha)     | Soil drainage class       : Imperf
Management system      : NLSM_W_1         | Soil depth for Sorghum    :   1.00 (m)
Weed infestation       :  85% of max.     | Water holding capacity    : 100    (mm/m)
Early ploughing from   : SEP3 to NOV1     | Residual water at SEP1    :   0    (mm)
 when top soil storage >  30 (mm)         | Top soil control depth    :   0.50 (m)
Planting opportunities :   1              | Available N (Undef.)      :  -9    (ppm)
Planting occurs from   : DEC1 to FEB2     | Available P (Bray - I)    :   2    (ppm)
 when top soil storage >  30 (mm)         | Available K (Undef.)      :  -9    (ppm)
 and dekad rainfall    > 30 (mm)          | Weighted average pH-H2O:      6.8
Weeding occurs after   :  30  days        | Weighted average ECe      :   0.1 (mS/cm)
Irrigation capacity    :   0 (mm/day)     | Weighted average ESP      :   0%
Irrigation frequency   :   0 (/dec)       | Weeds maximum evapotr.    :   0.70 x ETO
Synoptic station       : MAHALA           | Weeds max. cover after    :  40     days
Rainfall station       : MAHALA           | Range of rainfall years: 1985/1985

SOIL MOISTURE BALANCE 1985/1986

DEK   ST.D|δST   RAIN IRRI| MOIS|  Eb  ETw  ETa|  ST MBRZ SURPL| W.FR|  ETm STRESS
      (cm)|(mm)  (mm) (mm)| (mm)|(mm) (mm) (mm)|(mm) (mm)  (mm)| (cm)| (mm)    (%)

AUG3    50|               |     |              |   0    0     0|    0|
SEP1    50|         0     |    0|   0          |   0    0     0|    0|
SEP2    50|         0     |    0|   0          |   0    0     0|    0|
SEP3    50|         0     |    0|   0          |   0    0     0|    0|
OCT1    50|         0     |    0|   0          |   0    0     0|    0|
OCT2    50|         0     |    0|   0          |   0    0     0|    0|
OCT3    50|        44     |   44|   9          |  35    0     0|   44|
NOV1    50|         0     |   35|       16     |  19    0     0|   44|
NOV2    50|         0     |   19|       19     |   0    0     0|    0|
NOV3    50|        14     |   14|       14     |   0    0     0|    0|
DEC1    50|         0     |    0|        0     |   0    0     0|    0|
DEC2    50|         7     |    7|        7     |   0    0     0|    0|
DEC3    50|        13     |   13|       13     |   0    0     0|    0|
JAN1    50|         0     |    0|        0     |   0    0     0|    0|
JAN2    50|         0     |    0|        0     |   0    0     0|    0|
JAN3    50|         0     |    0|        0     |   0    0     0|    0|
└─>      0|   0           |    0|              |   0    0      |    0|
FEB1    13|   0    41    0|   13|       19   12|   0   10     0|   41|   16     25
FEB2    33|   7     0    0|    7|        7    3|   0    0     0|    0|   15     80
FEB3    52|   0     0    0|    0|        0    0|   0    0     0|    0|   20    100
MAR1    71|   0     0    0|    0|        0    0|   0    0     0|    0|   30    100
MAR2    90|   0    21    0|   21|        0   14|   7    0     0|   21|   40     65
MAR3   100|   0     0    0|    7|        0    4|   3    0     0|   21|   42     90
APR1   100|   0     0    0|    3|        0    2|   1    0     0|   21|   39     95
APR2   100|   0    82    0|   83|        0   35|  48    0     0|   83|   35      0
APR3   100|   0     0    0|   48|        0   28|  20    0     0|   83|   33     15
MAY1   100|   0     0    0|   20|        0   12|   8    0     0|   83|   28     57
MAY2   100|   0     0    0|    8|        0    5|   3    0     0|   83|   22     77
MAY3   100|   0     0    0|    3|        0    2|   1    0     0|   83|   15     87

DEK: dekad, ST.D: storage/rooting depth, δST: storage increase due to δST.D,
RAIN: rainfall, IRRI: irrigation, MOIS: avail. moisture, Eb: bare soil evap.,
ETw: weed evapotransp., ETa: crop evapotransp., ST: rest moisture up to ST.D,
MBRZ: rest moisture below ST.D, SURPL: moisture surplus, W.FR: wetting front,
ETm: maximum crop evapotransp.,  STRESS: crop moisture stress in current DEK.
```

Note: -9 = missing value

IRRI refers to any irrigation applied. Net irrigation amounts and frequency of applications can be specified and are input to the model after a rainfall generated planting opportunity. It is assumed that irrigation water is only added until field capacity is attained within the *ST.D* layer. In calculating outputs, the irrigation applications are assumed to be regularly distributed according to the given frequency. For example, if the specified frequency is 1 application per dekad, water is assumed to be available from the fifth day of each dekad.

IRRI was originally designed to cater for supplementary irrigation of primarily rainfed production systems. However, appropriate specification of the allowable planting dekads and of the topsoil storage/ rainfall requirements enables CYSLAMB to be used for wholly irrigated systems.

MOIS summarises the moisture potentially available for crops, weeds or bare soil evaporation within the depth, *ST.D*. Essentially:

$$MOIS = RAIN + IRRI + ST_p + \delta ST \qquad \textbf{(31)}$$

where ST_p = Stored water from previous dekad

Please note that *MOIS* cannot exceed the potential moisture storage of the layer, *ST.D*. Any additional water must be allocated to *MBRZ* or *SURPL*.

Eb refers to bare soil evaporation. *Eb* is only considered when neither crops nor weeds are present, as the *ETa* and *ETw* factors are inclusive of bare soil evaporation between plants. *Eb* values are derived from Penman ET_0 estimates using a coefficient which is dependent on rainfall frequency and soil texture. This coefficient is equivalent to *kc* for the initial crop development stage.

ETw is the weed evapotranspiration. *ETw* is also derived from ET_0 using a crop coefficient (kc). The maximum kc, and the time to maximum weed cover, at which maximum kc is achieved, are user defined parameters, and the degree of weed infestation and the timing of any weeding operations can also be set when defining the characteristics to be evaluated (Figure 16). It is assumed that weeds can extract water from the entire soil profile down to the maximum crop rooting depth and that water is extracted from the *ST* and *MBRZ* reserves in amounts proportional to thier relative depths, taking account of the wetting front, *W.FR*.

ETa is the actual crop evapotranspiration, which is taken from *MOIS*, within the limit set by maximum potential crop evapotranspiration (*ETm* = ET_0 * kc). Not all the water in *MOIS* is equally available and ETa is constrained by water which is held at high tensions close to permanent wilting point (Section 3.1.5.3, p.39). When weeds are present, *MOIS* is apportioned between *ETa* and *ETw* as described above.

ST is the water stored in layer *ST.D at the end of the dekad* indicated. Effectively this is the remaining water after evapotranspiration has occurred. *ST* is added to *MOIS* in the following dekad.

MBRZ is moisture below the root zone, and refers to the water stored in the layer between the crop rooting depth in the particular dekad (*ST.D*), and the maximum rooting depth (Figure 17). In the pre-planting period *MBRZ* refers to water in the layer between 50cm and the maximum rooting depth, and after maximum root extension *MBRZ* becomes zero. In a similar way to *ST, MBRZ* refers to the storage *after* depletion due to weeds or bare soil evaporation in the particular dekad indicated. Crops do not have access to *MBRZ* although a proportion of MBRZ accounts for ***δ****ST* in the succeeding dekad. Weed evapotranspiration (ETw) and bare soil evaporation (Eb) are assumed to deplete *MOIS* and *MBRZ* water in amounts proportional to their availablity.

SURPL is surplus water after *ST* and *MBRZ* have been filled to field capacity. Depending on soil and site drainage characteristics, *SURPL* will either be lost to deep percolation, will run off the surface, or will waterlog the soil profile with possible detrimental effects on crop growth (Chapter 4)

W.FR is the depth of the wetting front. This is determined by the soil available water holding capacity, which is assumed to be uniform down to the maximum rooting depth.

ETm is the maximum potential crop evapotranspiration, determined by mutiplying the Penman evapotranspiration (ET_0) by the crop coefficient (kc). ***STRESS*** gives the relative evapotranspiration deficit [(1-ETa/ETm)*100] per dekad, indicating the periods during the crop growth cycle when moisture shortage is most severe.

In a typical crop growing season four distinct phases of different evaporation and transpiration processes can be distinguished:

(1) After the first rain water will be stored in the soil. Before weed growth starts, the water balance equation can be written as follows :

$$\delta SM = RAIN - E_b \qquad \textbf{(32)}$$

Thus in the absence of any living plants only bare soil evaporation occurs. On early ploughed fields, which can be more or less weed free, this situation will continue until the crop is planted.

(2) If weed growth starts after a significant rain, a second phase commences where :

$$\delta SM = RAIN - ET_w \qquad \textbf{(33)}$$

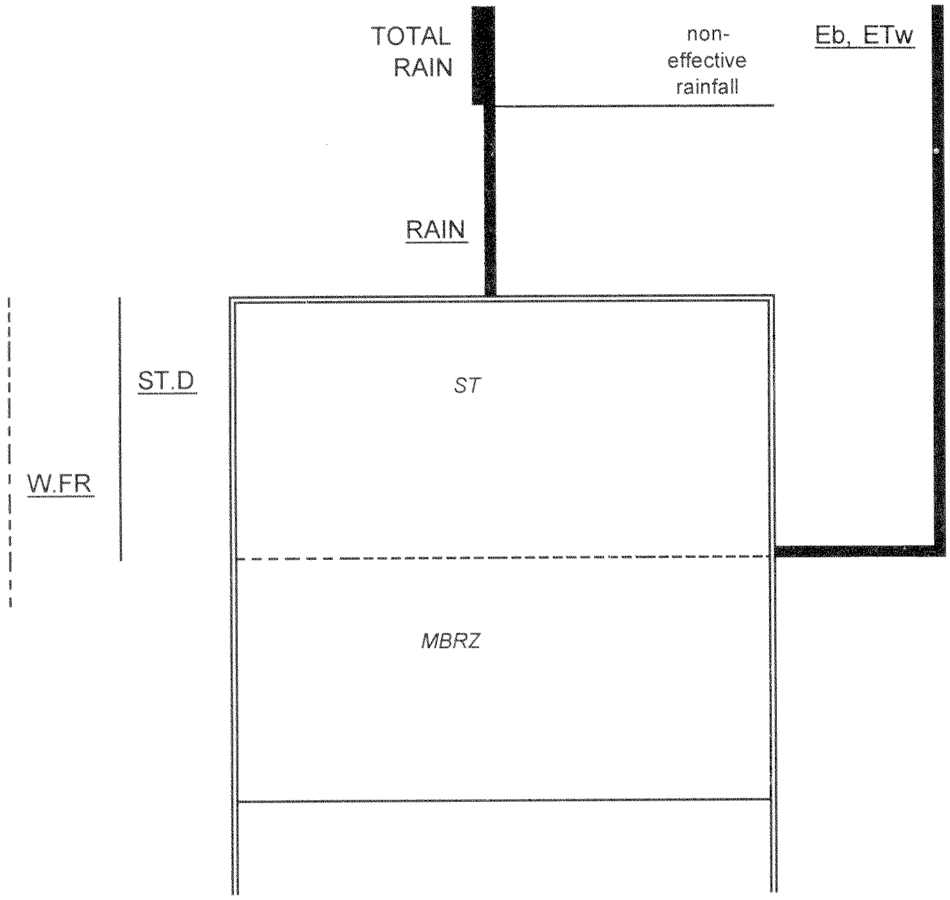
with ET_w combining E_b and T_w into a weed evapotranspiration factor.

Figure 17 gives a schematic illustration of the moisture balance in the pre-planting period.

(3) When the crop starts growing, the following equation applies:

$$\delta SM = EP - ET_w - ET_c \qquad \textbf{(34)}$$

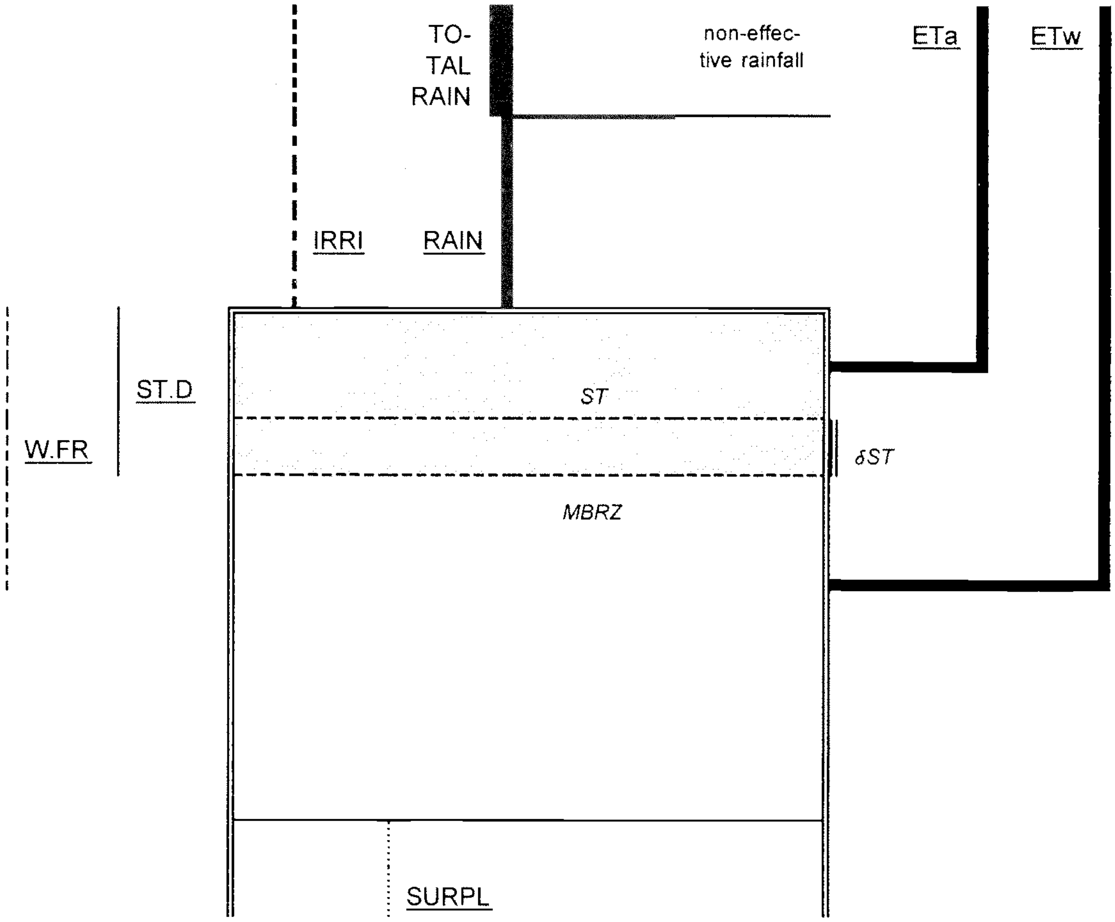
Figure 17: Pre-planting Moisture Balance



Unless weed control is specified or the level of weed infestation is set to zero, it is assumed that weed growth will result from available moisture in the preplanting and early growth stages of the crop (before full canopy cover is attained). Tillage and planting operations are assumed to destroy any existing weeds. After planting, the crop and weeds will directly compete for available moisture. Assuming an absolute priority on dekadal moisture supplies by either crops or weeds seriously distorts the result of the simulation. For this reason, the dekadal moisture supply (*MOIS*) is depleted daily, by weeds and crops sequentially, until exhausted. Weeds can then also deplete any moisture stored in *MBRZ*.

Figure 18 illustrates the moisture balance in the crop growth stages prior to maturity, when water in the *MBRZ* layer is inaccessable to the crop. Figure 19 shows the moisture balance at crop maturity.

Figure 18: Moisture Balance during Early Crop Growth Stages

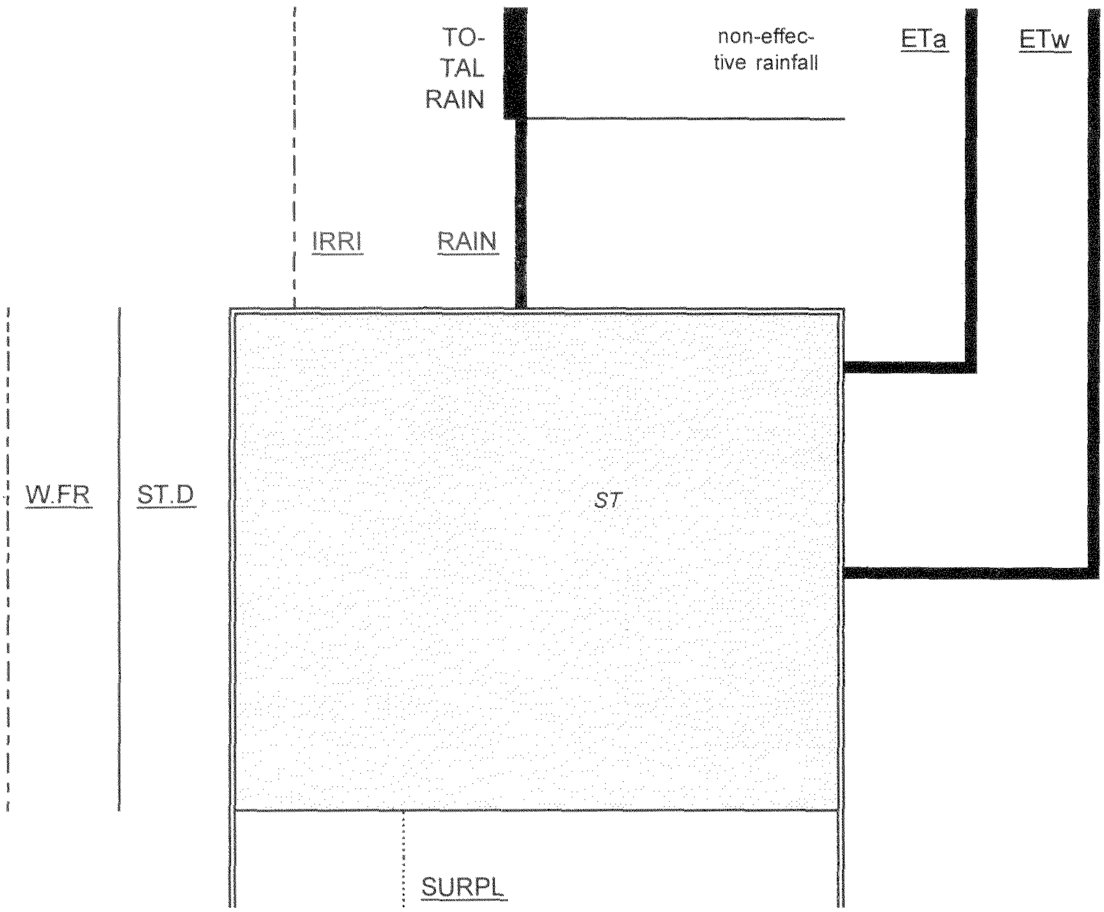


3.1.5.2 Bare soil evaporation model

Stored soil water before the beginning of a crop season can be crucial for crop production. In order to enhance water storage and control weeds, winter or early season ploughing is recommended. In drier parts of the country like in Tsabong, water stored after a fallow period can give considerable advantages for sorghum cultivation later in the year (R. White, pers. com.). However stored soil water is subject to evaporation before plants are established.

Joshua (1990) proposed a model to predict bare soil evaporation. This model was validated for a ferric Luvisol in Botswana. It predicts bare soil evaporation over minimum periods of a few days, based on water flow theory using soil physical parameters as input (bulk density, infiltration, hydraulic conductivity, water retention curve). These parameters are normally measured in detailed soil characterizations. In addition to the latter variables, a field measurement of a single cycle of evaporation for each soil type is necessary to derive some other indispensable parameters. This constitutes a major limitation for a routine application of this model.

Figure 19: Moisture Balance with Crop at Maximum Rooting Depth



Doorenbos and Pruitt (1977) proposed a much simpler method using the wetting frequency at different levels of ET_0 (see also crop coefficient initial growth period p. 26). Although this method is mainly used for the determination of the crop coefficient of the initial crop development stage, it proved to be adequate and useful for bare soil evaporation calculations. A recent revision of the methodology (FAO, 1991) concluded that it is still considered satisfactory. The small data set required for this model is certainly advantageous.

The model argues that for a fixed ET_0 value (e.g. approximately 6mm/day during the growing season in Gaborone) evaporation from a bare soil increases with an increase in wetting frequency (see Figure 14, p. 28). This agrees with the three evaporation stage theory (Joshua, 1990). If a soil profile is regularly wetted evaporation and hydraulic conductivity determine evaporation (stage 1). In drier soils evaporation is independent of the evaporation potential of the atmosphere, and is controlled by unsaturated water flow to the soil surface (stages 2 and 3). Evaporation in these latter stages is much less than during stage 1.

In practice, a *kc* factor for bare soil is derived from ET_0 values and effective rainfall frequencies. The bare soil evaporation is then computed as:

$$E_b = kc \times ET_0 \qquad (35)$$

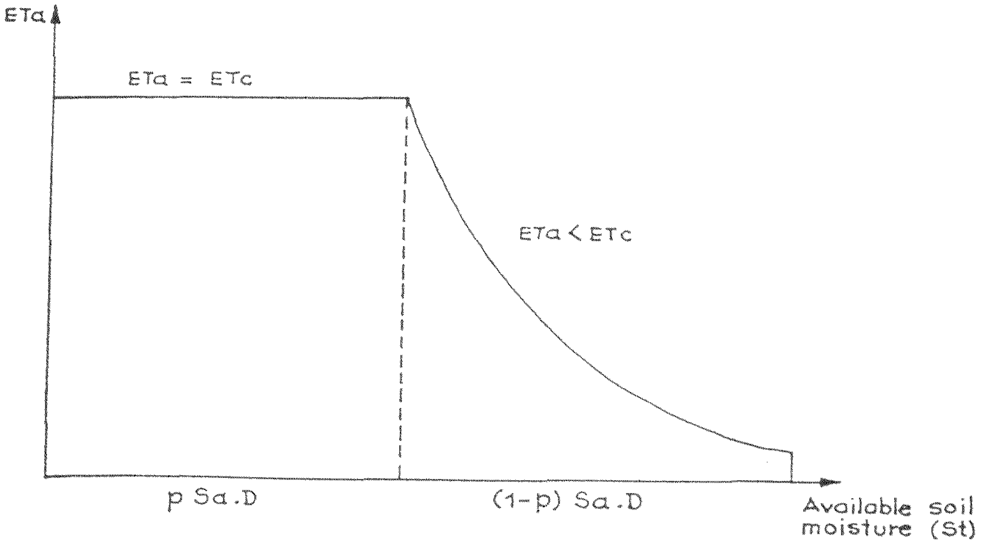
Data presented in Figure 13 (p.29) assume a medium textured soil. For light and heavy textured soils, *kc* values need downward adjustment by 30% and upward adjustment by 15% respectively.

3.1.5.3 Actual crop evapotranspiration under moisture stress

In calculating the soil moisture stored at the end of a dekad it is assumed that actual evapotranspiration (ET_a) equals maximum evapotranspiration (ET_m) until a fraction (p) of the total available soil water (Sa) over the root depth (D) has been depleted. For a given crop ET_a is determined by the evaporative demand of the air when available soil water does not restrict evapotranspiration. Beyond the depletion of the fraction (p) of total available soil water ($Sa.D$), ET_a will fall below ET_m and ET_a will depend on the remaining soil water and on ET_m (see Figure 20).

Figure 20

The assumed evolution of the actual crop evapotranspiration with a changing available soil moisture reserve.



Under these assumptions the following relationships hold (Rijtema and Aboukhaled, 1975) :

$$ET_a = ET_m = -\frac{dSM_t.D}{dt} \qquad (36)$$

where $SM_t.D > (1\text{-}p)Sa.D$

where $SM_t.D < (1\text{-}p)Sa.D$

$$ET_a = \frac{SM_t.D}{(1-p)Sa.D} \times ET_m = -\frac{dSM_t.D}{dt} \qquad \textbf{(37)}$$

where : $Sa.D$ = total available soil moisture over the root depth
$SM_t.D$ = available soil moisture at time t over the root depth
p = depletion factor of the crop

The calculation of the available soil water at the end of the considered dekad is obtained by integration of the above mentioned differential equations. Three different situations can be considered :

(i) $SM_1.D > (1\text{-}p)Sa.D$ and $\dfrac{SM_1.D - (1\text{-}p)Sa.D}{ET_m(\text{dekad})} > 1$

or in other words $SM_1.D$ is high enough to allow maximum crop evapotranspiration over 10 days.

Under these conditions :

$$SM_{10}.D = SM_1.D - ET_m(dekad) \qquad \textbf{(38)}$$

(ii) $SM_1.D > (1\text{-}p)Sa.D$ and $\dfrac{SM_1.D - (1\text{-}p)Sa.D}{ET_m(\text{dekad})} < 1$

These conditions imply that during a certain amount of days (10-t) ET_a equals ET_m, but that after (10-t) days ET_a is smaller than ET_m for a period of t days.

Thus :

$$SM_{10}.D = (1-p)Sa.D.e^{-ETm\,(dekad).\frac{t}{10(1-p)\,Sa.D}} \qquad \textbf{(39)}$$

(iii) $SM_1.D < (1\text{-}p)Sa.D$

or the initial available moisture reserve never allows maximum crop evapotranspiration.

Under these conditions integration of equation 39 gives :

$$SM_{10}.D = SM_1.D.e^{\frac{-ETm\,(dekad)}{(1-p)\,Sa.D}} \qquad \textbf{(40)}$$

Having calculated the available moisture at the beginning and end of the ten-day period, the actual evapotranspiration of the crop can be determined by equation (38).

3.1.6 Yield response factor (*ky*)

The response of yield to water stress is quantified through a proportionality factor, namely the yield response factor, relating relative yield decrease ($1-Y_a/Y_m$) to relative evapotranspiration deficit ($1-ET_a/ET_m$). This yield response factor expresses the sensitivity of the crop to moisture stress.

Evapotranspiration deficits may either occur continuously over the total growing period of the crop or over any one of the individual growth periods. Generally five crop growth periods can be identified for tropical cultivars as follows:

establishment period
vegetative period
flowering
yield formation
ripening

The definition of each of these periods is crop specific; they are given in Appendix A2 in Part 2 of this Manual for five Botswana crops.

The generalized effect of water deficit on crop yield is schematically presented in Figure 21 for both the total growing period and the individual growth periods.

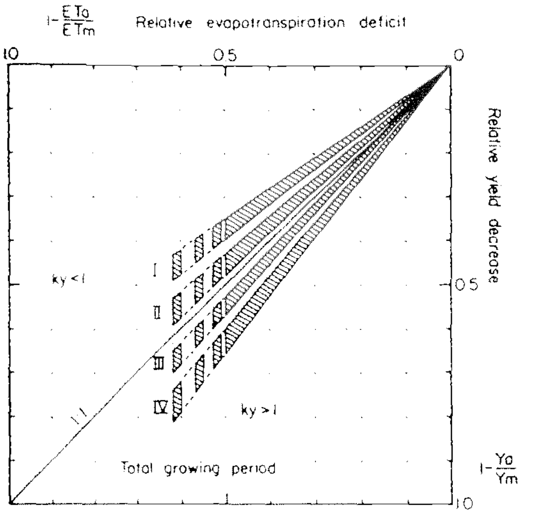
In general, for the total growing period the decrease in yield relative to the increase in water deficit ($ky<1$) is proportionally less for crops such as groundnut, millet and sorghum, while it is proportionally greater ($ky>1$) for more drought sensitive crops such as maize. For the individual growth periods, the decrease in yield due to water deficit during that growth period is relatively small for the vegetative and ripening period, and relatively large for the flowering and yield formation periods. Selection of the correct *ky* value is critical in model validation. After extensive testing it was found that combining *ky* calculated for individual growth periods tended to overestimate the total yield reduction due to moisture stress over the whole crop growth cycle. Conversely, use of the 'total growing period' *ky*s proposed by Doorenbos and Kassam (*op. cit.*) resulted in predicted crop yields which showed good agreement with measured yields (Section 3.3.3, p. 46). In most cases 80 to 85% of the yield variation due to different water treatments can be explained.

The empirical *ky* values for most crops are derived on the assumption that the relationship between relative yield (Y_a/Y_m) and relative evapotranspiration (ET_a/ET_m) is linear and is valid for water deficits of up to about 50%.

It is possible that *ky* values calibrated under irrigated conditions where water deficits are not severe may require adjustment for droughty rainfed conditions but no empirical data was available on which such adjustments could be based. In practice, under severe stress, this relationship may depart from linearity (FAO, 1985), and this would particularly apply to crops with $ky < 1$, which would otherwise yield in conditions of 100% moisture deficit.

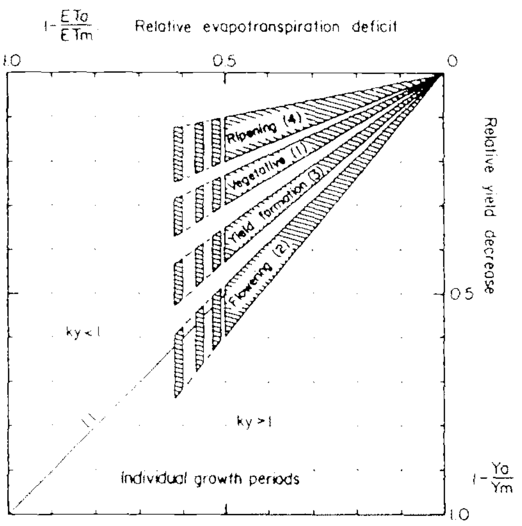
Figure 21

Generalized relationship between relative yield decrease and relative evapotranspiration deficit.



Crop Groups

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	



3.2 Minimum Data Sets

Table 3.2

Minimum Data Set for Bare Soil Evaporation Model

Variable	Description	*Units*	Database
ET_0	Reference evapotranspiration	*mm.dekad* $^{-1}$	METEO
F	Frequency of effective rainfall events	*events.dekad* $^{-1}$	METEO
AWHC	Available water holding capacity of the soil	*mm.m* $^{-1}$	Soil
D	Soil depth	*cm*	Soil

Table 3.3

Minimum Data Set for Actual Crop Evapotranspiration Model

Variable	Description	*Units*	Database
Crop	Crop name	-	Crop
RDR	Maximum rooting depth of crop	*cm*	Crop
D_{dec}	Dekadal crop rooting depth	*cm*	Crop
StageA	Duration of initial stage	*days*	Crop
StageB	Duration of crop development stage	*days*	Crop
StageC	Duration of mid season stage	*days*	Crop
StageD	Duration of late season stage	*days*	Crop
kc1	Crop coefficient mid-season stage	-	Crop
kc2	Crop coefficient at harvest	-	Crop
p	Crop soil moisture depletion factor	-	Crop
PDENS	Planting density of crop	*number.ha* $^{-1}$	Production system
ET_0	Reference evapotranspiration	*mm.dekad* $^{-1}$	METEO
F	Frequency of effective rainfall	*events.dekad* $^{-1}$	METEO
EP	Effective rainfall	*mm.dekad* $^{-1}$	METEO
AWHC	Available water holding capacity	*mm.m*	Soil

Table 3.4

Minimum Data Set for Moisture Limited Yield Model

Variable	Description	Units	Source
Y_m	Radiation and Temperature Limited Yield	$kg.ha^{-1}$	Calculated
ET_m	Maximum crop evapotranspiration	$mm.dekad^{-1}$	Calculated
ET_a	Actual crop evapotranspiration	$mm.dekad^{-1}$	Calculated
ky	Yield response factor over total growing period	-	Crop

3.3 Testing and validation

3.3.1 Bare soil evaporation model

An experiment on bare soil evaporation was conducted at two sites in Sebele during the 1988/1989 cropping season (Joshua, 1990). The two sites, separated by a distance of 2 km, are characterized by a medium textured ferric Luvisol. Rainfall was measured daily. Actual evaporation was estimated by a water balance using weekly profile moisture contents measured by a neutron moisture probe. There was no run-off from rainfall except on one occasion. Moisture content measurements at lower depths indicated no water loss by deep percolation. The available water holding capacity was estimated at 130mm/m.

Table 3.5

Comparison of monitored ET_b with estimated ET_b values

Period	Bare soil Evaporation (ET_b) (mm)		
	Measured	Predicted: FAO	Predicted: Joshua
10/10-24/10	29	46	41
24/10-07/11	36	35	36
07/11-21/11	36	25	23
21/11-05/12	17	17	17
05/12-19/12	28	25	23
19/12-09/01	28	25	30
09/01-23/01	47	46	36
23/01-07/02	30	32	34
07/02-21/02	36	42	47
10/10-21/02	287	293	287

Table 3.5 compares the measured values with values computed by the FAO-model (Doorenbos and Pruitt, 1977) and the Joshua model for periods of 14-21 days.

For practical purposes, such as the estimation of the moisture content in a soil profile before planting, the proposed model is reliable. Model predictions agree well with measured values and with the values obtained from the more complicated Joshua model. However it should be noted that the FAO model is only reliable for periods of minimum 10 days.

3.3.2 Actual crop evapotranspiration model

Evapotranspirational deficit over the entire crop growing period is used to predict an eventual yield decrease due to moisture stress. Data from the National Tillage Trials (Persaud, 1990; Persaud *et al*, 1991) are used to test predicted ET_a values against measured values. In order to eliminate the effect of different tillage treatments, gravimetrically measured soil moisture contents were averaged over the treatments. The measured water consumption of a crop over a given period of time is :

$$ET_a \text{ measured} = EP - \delta S$$

where: EP = cumulative amount of effective rainfall for the considered period
δS = the difference in soil water stored at the end and the beginning of the considered period

Table 3.6

Observed effective rainfall and soil moisture changes in some tillage trials.

Trial site	Period	EP (mm)	δS (mm)	$EP-\delta S$ (mm)
Francistown 1	22/12/88-17/04/89	157	-28	185
Sebele 1	05/12/88-09/03/89	215	+16	199
Tswidi 1	16/01/88-30/03/89	244	-73	317
Tswidi 2	12/01/88-30/03/89	244	-64	310
Sebele 1	20/11/89-12/02/90	109	-20	129

Table 3.6 gives the respective values of effective rainfall and soil moisture changes for the considered trials. The choice of these trials was inherent to the completeness of the required minimum data set.

The effective rainfall amounts are calculated from the water balance of the crop. The simulated ET_a values are derived from the water balance .

Using the information from the trials listed in Table 3.6, Table 3.7 compares measured ET_a values with predicted ET_a values.

Predicted values agree well with measured values although the latter are generally somewhat higher. This discrepancy could possibly be attributed to water consumption by weeds, which is not simulated here.

Table 3.7

Measured ET_a versus predicted ET_a values

Trial site	Season	ET_a (mm)	
		Measured	Predicted
Francistown 1	88/89	185	171
Sebele 1	88/89	199	229
Tswidi 1	88/89	317	265
Tswidi 2	88/89	310	278
Sebele 1	89/90	129	127

3.3.3 Testing and validation of moisture limited yield model

The crop yield obtained at this stage in the model refers to the yield mainly determined by radiation, temperature and water availability. As mentioned before it is referred to as the moisture limited yield. Other yield related variables like drainage conditions, nutrient availability, occurrence of weeds, toxicities, pests and diseases are assumed to be not limiting crop production.

After validating the bare soil evaporation model and the water balance model, the overall outcome of the equation relating evapotranspiration deficits to yield decreases, thus the predicted yields, should be tested against actual yields measured in the field. The choice of trials that can be considered for this testing procedure depends largely on :

- the absence of any limiting factors affecting crop production, other than radiation, temperature and moisture
- the availability of data necessary for the crop simulation

3.3.3.1 Brief description of relevant trials

(1) Maize population trial

A maize population trial was conducted by the Dryland Farming Research Project (DLFRS) during season 1980/81 (see DLFRS phase III, second annual report, p.183). In three locations, Sebele, Good Hope and Motopi, the effect of different maize var. NPPxK64r row spacings and plant densities on yields was examined. In Good Hope heavy rain caused local water logging followed by severe plant yellowing. In Motopi nutrient deficiency and stunted growth was observed. It was only at the Sebele site that the conditions described in previous section were met. Table 3.8 compares measured yields with simulated yields for different planting densities at Sebele. In order to eliminate the geometric effects of similar populations at different row spacings, yield data from plots with similar population densities are averaged.

Table 3.8

Measured yields versus predicted yields for the Sebele maize population trial in 1980/81

Plant population (plants/ha)	Row spacing	Yield (kg/ha)	
		Mea-sured	Predicted
10800	wide	2300	3500
11600	standard	3000	3500
Average		**2650**	**3500**
15900	wide	3100	3700
21100	standard	3800	4000
22200	narrow	4700	4000
Average		**3900**	**3900**
24700	wide	3100	3800
27100	standard	4200	3900
Average		**3650**	**3850**
37500	standard	4700	4200
40000	narrow	5000	4300
Average		**4850**	**4250**
59200	narrow	**4900**	**4500**
78000	narrow	**4700**	**4500**

Table 3.9

Measured yields versus predicted yields for the maize National Tillage Trials in season 1989/90

Trial Site	Treatment	Yield (kg/ha)	
		Mea-sured	Predicted
Sebele 1	double plough	815	1063
	plough/cultivate	1033	1059
	average	**924**	**1061**
Tswidi 2	double plough	1725	2701
	plough/cultivate	2201	2814
	average	**1963**	**2758**
Sese 1	double plough	1356	1697
	plough/cultivate	1112	1709
	average	**1234**	**1703**

(2) National Tillage Trials

As mentioned before the national tillage trials were set up to evaluate the effects of several tillage operations on crop yields. Most of these trials were planted with sorghum, only a few with maize. Table 3.9 compares measured values with estimated yields for three locations with maize.

In order to eliminate as far as possible the effect of weeds on yields, only the treatments *double ploughing* and *ploughing followed by cultivation* are retained. Yields obtained with these two tillage options are averaged and used for final testing.

Identical procedures were followed for the sorghum tillage trials. It should be noted that only the trials in Sebele, Sese and Tswidi are relevant. In Sebele no nutrient (at least phosphorus) deficiencies occurred. For Sese and Tswidi, only the fertilized plots were considered. The measured yields corresponding with the *best* P-application are retained as it is thus assumed that these do not suffer any nutrient deficiency. Table 3.10 compares the measured yields with the predicted yields.

Table 3.10

Measured yields versus predicted yields for sorghum national tillage trials in seasons 1988/89 and 1989/90

Trial site	Season	Treatment	Yield (kg/ha)	
			Measured	Pre-dicted
Sebele 1	88/89	double plough	2674	2421
		plough/cultivate	2634	2670
		average	**2654**	**2546**
Sebele 1	89/90	double plough	1326	1490
		plough/cultivate	1237	1505
		average	**1282**	**1498**
Sese	88/89	fertilized	**2787**	**2885**
Sese	89/90	fertilized	**2022**	**1693**
Tswidi	89/90	fertilized	**2155**	**2394**

(3) Cowpea trials

As part of a sorghum / cowpea intercropping programme, cowpea experiments were conducted in the mid eighties by the DLFRS phase III project. Often these trials are not completely documented[1].

Two trials with a reasonable data set were retained for testing purposes.

Table 3.11

Measured biomass versus predicted biomass for different cowpea trials

Trial site	Season	Plant Population (plants /ha)	Biomass yield (kg/ha)	
			Measured	Predicted
Sebele H	82/83	20000	**1900**	**1847**
Sebele F	83/84	4400	**492**	**316**
Sebele F	83/84	13000	**539**	**423**
Sebele F	83/84	40000	**669**	**745**

During the crop physiological trial in Sebele, in season 1982/83, biomass production of a 20000 plants/ha cowpea population was measured on site H (site L has no soil data). The intercrop trial D in Sebele during season 1983/84 investigated the influence of different cowpea populations on biomass production. Table 3.11 compares measured moisture limited cowpea biomass production with predicted biomass production.

Comparing the results of above mentioned trials (yields in bold), the moisture limited yield model can be validated. The method of least squares was used for comparing predicted with measured yields. Considering the eighteen data pairs (see Table 3.12), representing three crops, a coefficient of determination of 0.93 was found.

The standard error of estimate of predicted values on measured values are 494 kg/ha for maize, 216 kg/ha for sorghum and 115 kg/ha for cowpea. The relative errors of estimate, derived from comparing the standard error of estimate with the average yield values, are 15%, 10% and 14% for maize, sorghum and cowpea respectively.

Figure 22 compares the predicted values obtained with the CYSLAMB model with the measured values. The 1:1 line is also plotted on the graph.

Table 3.12

Measured versus predicted yields for testing the moisture limited yield model

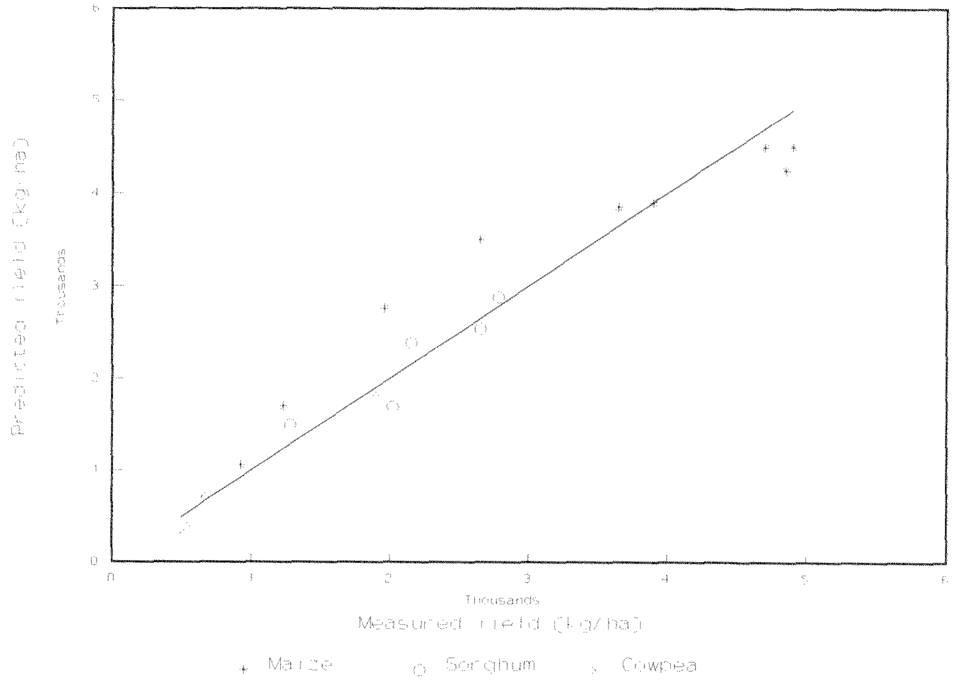
Crop	Yield (kg/ha)	
	Measured	Predicted
MAIZE	2650	3500
	3900	3900
	3650	3850
	4850	4250
	4900	4500
	4700	4500
	924	1061
	1963	2758
	1234	1703
SORGHUM	2654	2546
	1282	1498
	2787	2885
	2022	1693
	2155	2394
COWPEA	1900	1847
	492	316
	539	423
	669	745

---

[1] e.g. The 1981/82 physiological trial does not mention the planting date

Figure 22

Measured and predicted moisture limited yields for maize, sorghum and cowpea



4. DRAINAGE LIMITED YIELD

4.1 Introduction

The relationship between drainage impedence and crop yield is complex. This is particularly true in the semi-arid zone where moisture stress is often the most critical yield constraint. The balance between conditions of shortage, sufficiency and excess of water is difficult to predict using a model based on 10 day periods. However, it is an established fact that drainage constraints adversely affect crop yields, and any crop simulation model designed as a tool for land evaluation must make a reasonable attempt to evaluate the impact of restricted drainage, using whatever data is available.

Drainage conditions determine the availability of air filled pores which control the supply of oxygen to roots. Poor or imperfect drainage results in periods of anaerobism, which not only result in oxygen shortage but also enhance denitrification and may lead to nutrient imbalances and toxicities.

As water accumulates faster than it can be dissipated, the soil first reaches field capacity. The larger pores, which normally contain air, progressively become filled with water until the whole profile is saturated. Any further surplus water then stands on the soil surface resulting in surface waterlogging. Key soil properties determining the tendency to saturation and waterlogging are the *aeration porosity* and the *saturated hydraulic conductivity*. The aeration porosity refers to the proportion of non-capilliary pores in relation to the total porosity. As a general rule, when the aeration porosity is less than 10% of total soil volume, crops may become susceptible to anaerobic effects (Vomocil, 1957). Saturated hydraulic conductivity describes the rate of water movement through the soil under saturated conditions. The soil drainage class, routinely recorded in soil profile description, is intended to indicate the frequency and duration of periods when the soil is saturated, and to reflect climate, soil and landscape features (FAO, 1990). In Botswana, Joshua (1991) demonstrated that aeration porosities and infiltration rates are lower in soils which are poorly or imperfectly drained. However soil drainage classes, as recorded by soil surveyors, do not always reflect the current hydraulic conditions at the site, and do not take account of the variation between wet and dry years which is particularly important in the semi arid zone.

Drainage conditions are not solely a product of the soil drainage class, but are affected by incoming moisture from precipitation, run-on, ground water tables and subsurface water movement. Bearing in mind the interannual variability of rainfall, it can be assumed that, on soils with some drainage impedence, *the impact of adverse drainage conditions varies according to the rainfall experienced in any particular year*. Thus soils with poor or imperfect drainage may perform relatively well in dry years but exhibit severe yield reductions in relatively wet years.

The impact of water excess varies according to its magnitude, the rate it can be dissipated either by deep percolation, run-off, lateral subsurface flow or evapotranspiration. The impact varies according to the crop and the developmental growth stage. In principle, it should be possible to relate moisture excess to a yield response factor using a similar model to that for predicting moisture limited yield (Chapter 3). Data on crop reponse to moisture excess is sparse, however, and the complex interactions between soil/crop water and nutritional factors have not been sufficiently researched for model building at this level. It is significant that the *CERES* models developed by IBSNAT (e.g. Ritchie *et al*, 1989) do not take yield depletion due to poor drainage into account.

4.2 Model Description

Shortages of key physical data for a sufficiently broad range of soils, coupled with the lack of a consistent set of experimental data to relate crop yield response to drainage factors, necessitate a generalised assessment based on soil drainage class and moisture surplusses from rainfall. The temporal resolution of CYSLAMB, which is limited to 10 day periods also prevents a more detailed modelling of moisture surplusses. Given these constraints, the CYSLAMB drainage module attempts to:

> *Estimate the approximate number of days within the crop growth cycle when the soil is above or near saturation, match this with crop sensitivity to excess moisture, and attribute a yield reduction factor which also takes account of soil drainage class.*

The starting point is the *moisture limited yield* explained in Chapter 3. Two possible conditions apply. For soils with drainage classes of *well, somewhat excessive* or *excessive* it is assumed that hydraulic conductivity is adequate to dissipate any moisture surplusses. Thus:

$$Y_a = Y_m \qquad \textbf{(41)}$$

where Y_m = maximum yield when drainage is not limiting
Y_a = drainage limited yield

For soils which are rated as *moderately well, imperfect, poorly*, and *very poorly*[2] drained, the drainage limited yield is related to the moisture limited yield by a correction factor, *kd*.

$$Y_a = kd \times Y_m \qquad \textbf{(42)}$$

kd is determined by the soil drainage class, an indicative number of days during the crop growth cycle that soil moisture is in excess of field capacity, and the crop sensitivity to waterlogging (Table 4.1). The indicative "number of days of saturation" is calculated by the moisture balance model for each 10-day period assuming that any water surplus to crop or weed evapotranspiration requirements, and soil water holding capacity in the top metre of soil, is dissipated at a rate equivalent to pan evaporation. Dekadal calculations are then summed to give an estimate of the number of days when the soil is potentially saturated during the crop growth cycle.

In the absence of more precise information, hydraulic conductivity, which together with evaporation determines the rate of excess water dissipation, is assumed to be reflected by the soil drainage class.

---

[2] For the crops currently considered for Botswana, the drainage limited yield on very poorly drained soils is assumed to be zero.

4.3 Minimum Data Set

The minimum data set required to determine drainage limited yield comprises the *soil drainage class* and the *crop sensitivity* to conditions of poor drainage.

Table 4.1 lists the yield correction factors (*kd*) for crops in different sensitivity groups, based on drainage class and the indicative period of saturation predicted by the moisture balance model.

Table 4.1

Yield Correction Factors for Moisture Excess

Indicative days saturated conditions	Drainage Class	Crop Sensitivity Group			
		Sensitive	Moderately Sensitive	Moderately Tolerant	Tolerant
0-5	Moderately well	1.0	1.0	1.0	1.0
	Imperfect	0.8	0.9	1.0	1.0
	Poor	0.2	0.5	1.0	1.0
5-20	Moderately well	0.7	0.9	1.0	1.0
	Imperfect	0.4	0.6	0.9	1.0
	Poor	0.0	0.1	0.2	0.8
20-50	Moderately well	0.5	0.7	0.9	1.0
	Imperfect	0.2	0.5	0.7	0.8
	Poor	0.0	0.0	0.1	0.5
> 50	Moderately well	0.0	0.5	0.7	0.9
	Imperfect	0.0	0.2	0.5	0.7
	Poor	0.0	0.0	0.0	0.5

Table 4.2 gives a suggested grouping of 28 crops in relation to their sensitivity to waterlogged or saturated conditions. Sensitivity groups correspond to those in Table 4.1. This list should be extended and revised as further data is collected.

4.4 Testing and Validation

Due to a lack of field trials on soils with impeded drainage, it has not yet been possible to check the assumptions in this model. The yield correction factors should be periodically reviewed after more experience is gained.

Table 4.2

Crop Groups based on Drainage Sensitivity

Sensitive	Moderately Sensitive	Moderately Tolerant	Tolerant
Cowpea	Maize	Sorghum	Rice
Chickpea	Millet	Wheat	
Lentil	Sesame	Barley	
Citrus	Chilli pepper	Pea	
Potato	Shallot	Haricot bean	
	Tomato	Broad bean	
	Cabbage	Soybean	
	Sisal	Cotton	
	Groundnut	Sunflower	
	Tobacco	Safflower	
		Sugarcane	
		Sweet potato	

Source: compiled from Adjei Twum (1987) and Radcliffe (1989)

5. NUTRIENT LIMITED YIELD

5.1 Introduction

The basis for deriving a model of nutrient limited yield is a systematic programme of fertilizer trials covering a variety of soil and climatic conditions.

Major fertilizer research in Botswana was conducted by FAO under project TF/AFR 51 during the period 1969 - 1975. The final report (FAO,1976) proposed recommendations for fertilizer use on arable land based on the results of several hundred field trials and demonstrations on farmers' fields in eastern Botswana. Several weaknesses were perceived leading to harsh criticism of the validity of the recommendations which were subsequently never adopted.

The major flaws identified were:

- The lack of site rainfall data.
- The lack of information on planting and harvest dates.
- Fertilizer recommendations are not soil specific.
- Mostly only a zero control and two levels of application were used so that the calculation of response curves was hardly justified.
- Most of the fertilizer was band placed, not reflecting the farmer's practice of broadcasting fertilizer.

Jones (1984) made a reappraisal of the FAO data. He regrouped the plot data by district and by the quality of the rainy season, and concluded that the following trends could be observed :

- The most general and reliable yield response of both sorghum and maize was to phosphate. Consideration should only be given to the first increment because additional responses to further increments were very much more stable.
- Responses were generally lower in dry years than in wet years.
- In no trial was there any significant response to potassium.
- There was a total lack of any significant positive N x P interaction; so it is valid to consider phosphate and nitrogen sequentially.
- The first increment of nitrogen increased sorghum and maize yields but differences between years were large and, for sorghum at least, nitrogen was of no benefit at all in a dry year.
- Significant responses to residual phosphate continued strongly into the third season. Residual nitrogen had no effect at all.

In 1988 the National Tillage Research Programme started. The main aim of this research is to provide clear recommendations on tillage and fertilizer management practices for dryland crops in Botswana. Nitrogen x phosphate factorial trials are carried out at several sites. The results of these trials are probably more reliable than previous work discussed above, and thus more indicative for general recommendations. The trials are very well monitored and soil characteristics, especially available P before fertilizer application are determined. The main results after two years of trials are :

- A positive response to phosphate for the sites where the soil level of P, determined by the Bray 2 analytical procedure, was less than 10 ppm in the topsoil, and where rainfall during the growing period was greater than 120mm.
- No significant interaction between N and P rates on yield.
- Different responses to P in relation to initial soil P content; higher responses when initial soil P was low.
- Only a response to nitrogen fertilizer when the overall yield is high, implying high well distributed rainfall and much better crop management.

5.2 Model description

Data of the 1988 (Persaud, 1990) and 1989 (S.Beynon, pers.com. and Persaud, *et al*, 1991) trials were used to establish a phosphorus response model to be incorporated into the CYSLAMB program (see Table 5.1).

Actual yields (Y_a) of sorghum at different P application levels (0, 20, 40, 60 and 80 kg P/ha) were compared with maximum yields (Y_m) obtained at the optimal application level. Phosphate rates were recalculated in parts per million (ppm) P in the top 25cm of the soil, taking into consideration the initial topsoil P content. The relation Y_a/Y_m, on a scale between 0 and 1.0, can thus be derived as a function of the available soil phosphorus, with a ratio of 1.0 occurring at optimal P application level.

Equation (43) was derived relating the Y_a/Y_m ratio to the P content of the topsoil.

$$\frac{Y_a}{Y_m} = 0.452 + 0.0685P - 0.00223P^2 \tag{43}$$

for $P < 15$ppm

n = 23
r = 0.78
standard error of estimate = 0.137

The parabolic-shaped curve (Figure 23) indicates that, for sorghum, once the topsoil P content equals 10 ppm, 91% of the potential yield can be expected. Further P application can only result in a yield increase of maximum 9%.

At the present time, no similar P response curves have been derived for other crops in Botswana.

Table 5.1

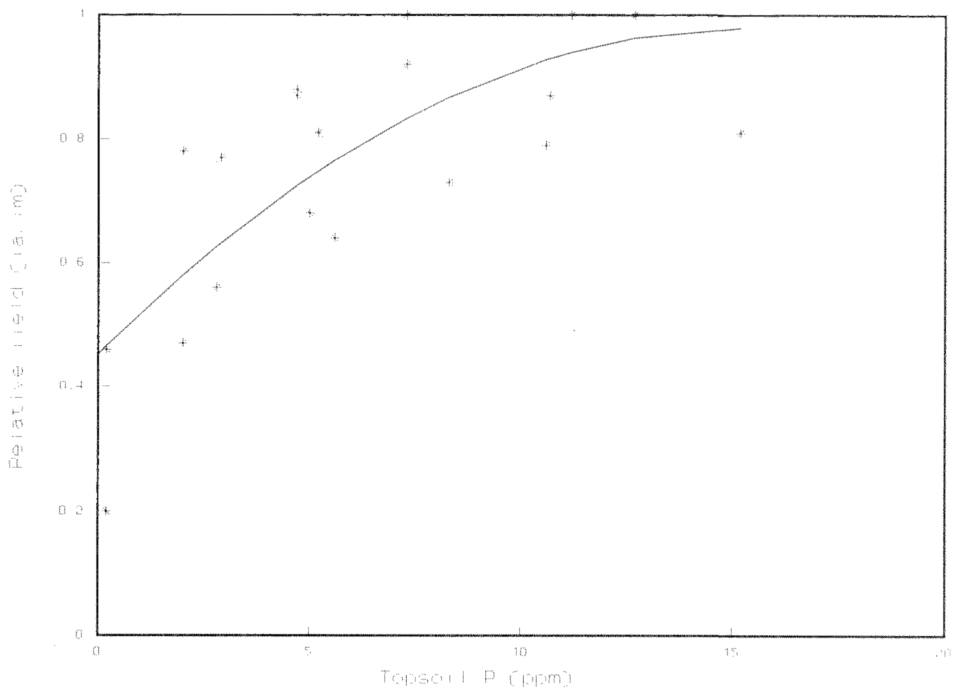
Yield response of sorghum to different P application levels

Trial Number	P application (kg/ha)	Topsoil P (ppm)	Measured Yield (kg/ha)	Y_a/Y_m
Tswidi-88	0	2.0	946	0.47
	10	4.7	1780	0.88
	20	7.3	1863	0.92
	40	12.7	2016	1.00
Sese-88	0	0.2	552	0.20
	10	2.8	1567	0.56
	20	5.0	1903	0.68
	40	10.7	2435	0.87
	80	21.3	2787	1.00
Moshupa-89	0	5.6	2977	0.64
	10	8.3	3355	0.73
	20	10.6	3633	0.79
	40	16.2	4618	1.00
Matsaudi-89	0	15.2	1421	0.81
	10	17.9	1367	0.78
	20	20.2	1753	1.00
Tswidi-89	0	2.0	3222	0.78
	10	4.7	3575	0.87
	20	7.3	4105	1.00
Sese-89	0	0.2	1819	0.46
	10	2.9	3070	0.77
	20	5.2	3248	0.81
	40	11.2	3990	1.00

Given the very erratic response of crop yields to nitrogen fertilizer applications under average climatic conditions, no attempt has been made yet to model this.

Figure 23

Relative Yield versus Topsoil Phosphorus



5.3 Minimum data set for nutrient limited yield

The minimum data set for the nutrient limited yield model consists of only the phosphorus content of the top 25cm of the soil profile, determined according to the Bray-2 method. This information is available for a large number of soil profiles from the Botswana Soils Data Base. If the phosphorus content of the topsoil was determined using the Bray-1 method, the following conversion should be applied (S.Beynon, pers. com.):

$$P_{Bray-2} = 1.153 \times P_{Bray-1} \qquad (44)$$

5.4 Testing and validation

The validity of the equation (44) has been tested against tillage trials conducted during the 1988 and 1989 seasons in Francistown and Mahalapye (Table 5.2). In order to avoid interference of weeds on predicted yields, only those production systems with tillage practices of double ploughing, or ploughing followed by a cultivation are considered.

The two trials situated on a lower valley soil in Mahalapye (MAHA2-88a and MAHA2-88b) were severely infested by stalk borer, resulting in a considerable yield decrease. As pests and diseases are not modelled at this stage, these trials have to be omitted for validation purposes. Simulated yields are compared with measured yields using the method of the least squares. The standard error of estimate of predicted yields on measured yields is 123 kg/ha. This corresponds with a relative standard error of estimate of 11%. The coefficient of determination between measured and estimated yields is 0.84.

Table 5.2

Testing and Validation of Nutrient Limited Yield

Trial number	Y_m (kg/ha)	Y_a/Y_m	Y_a (kg/ha)	Measured Yield (kg/ha)
FRAN1-88a	2002	0.49	981	921
FRAN1-88b	1946	0.49	954	997
FRAN1-89a	2087	0.49	1022	865
FRAN1-89b	2080	0.49	1019	998
MAHA1-88b	2279	0.62	1413	1352
MAHA2-88a	2442	0.76	1856	656
MAHA2-88b	2515	0.76	1911	1255
MAHA3-88a	1127	0.69	778	618
MAHA3-88b	1193	0.69	823	670
MAHA3-89a	2261	0.69	1560	1358
MAHA3-89b	2182	0.69	1506	1617

6. SALINITY AND TOXICITY LIMITED YIELD

6.1 Excess of Salts

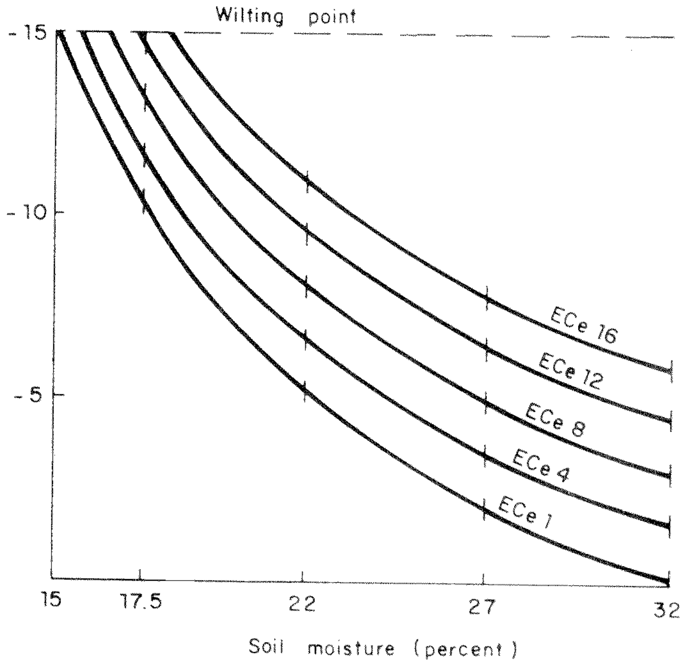
6.1.1 Introduction

The presence of free salts in the soil can significantly affect crop yields as well as the relationship between yield and evapotranspiration. Plants transpire pure water and only pure water evaporates from the soil, leaving soluble salts within the soil solution. In order to extract water from the soil, a plant must exert a force greater than that which holds the water to the soil; this force is known as the matric potential. If the salt content in the soil solution increases, more energy per unit of water must be expended by the plant to absorb water from this solution; thus the osmotic potential increases. Childs and Hanks (1975) showed that these two components of soil water potential are additive in terms of their effects on crop transpiration and should be additive in terms of their effect on crop production. Crop production can be interpreted here as either above ground dry matter production or as economic yield components (Bresler and Hoffman, 1986).

The additive nature of matric and osmotic potential is illustrated in Figure 24. It not only results in an important reduction in crop available water as salinity increases, but also, and much more so, in a decrease in easily available soil moisture at higher salinities (Figures 25 and 26). Thus, salinity effects are closely analogous to those of drought as both result in water stress and reduced growth.

Figure 24

Variation in moisture retention curves with salinity in a clay loam



Source: Ayers and Westcot, 1985

Figure 25

Reduction in Water Availability with Increasing Salinity

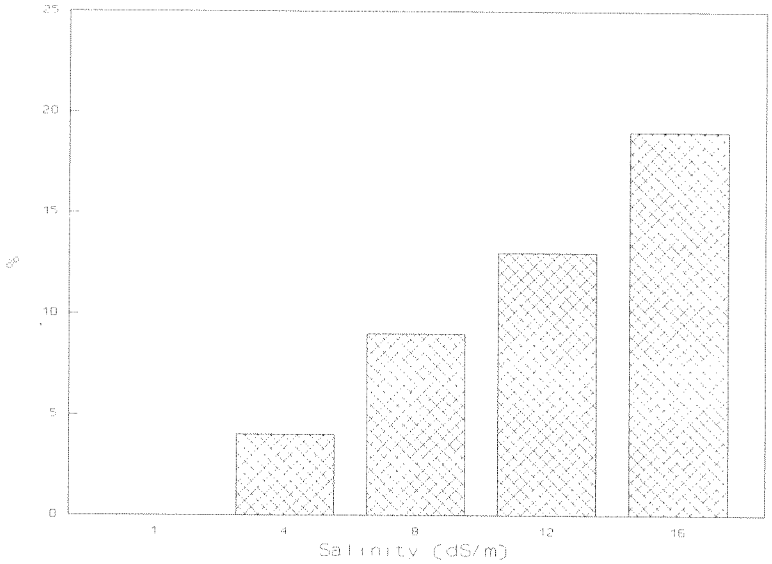
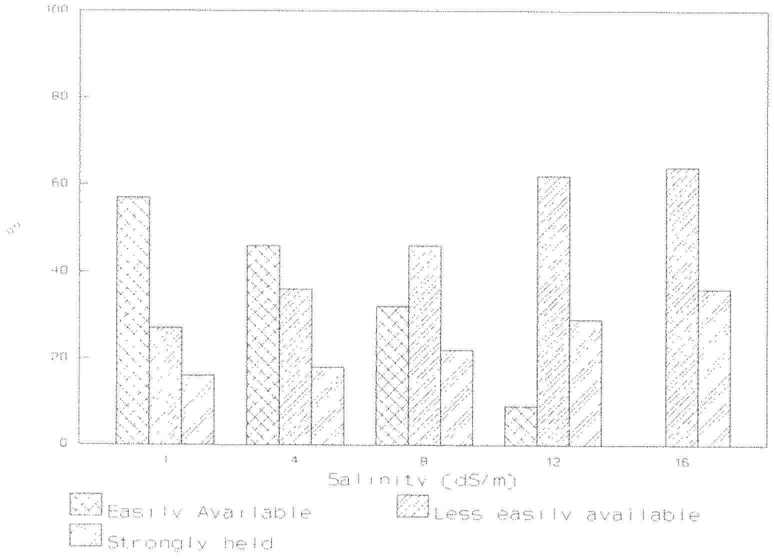


Figure 26

Distribution of Available Water in a Clay Loam Soil at different levels of Salinity



6.1.2 Model description

All crops do not respond to salinity in a similar way; some can produce acceptable yields at much greater soil salinity than others. This is because some are better able to make the needed osmotic adjustments enabling them to extract more water from a saline soil.

Maas and Hoffman (1977) and Maas (1984) propose numerical values for salt tolerance for a wide range of plants. The relative yield decrease (Ya/Ym) attributed to excess salt in a soil can be given by :

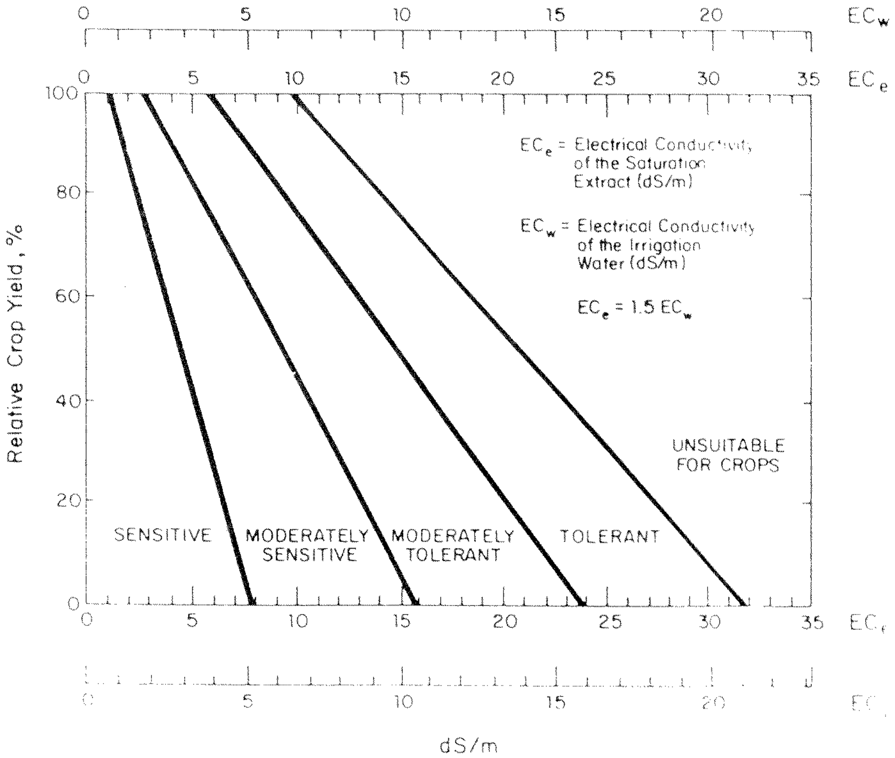
$$\frac{Y_a}{Y_m} = 1 - B_s(EC_e - A_s) \qquad \textbf{(45)}$$

where : A_s = salinity threshold of the crop in $dS.m^{-1}$
B_s = sensitivity of the crop to salinity above the threshold level in $m.dS^{-1}$
EC_e = electrical conductivity of the saturation extract in $dS.m^{-1}$

Equation (45) is illustrated for different crop sensitivity groups in Figure 27. Plant growth rate decreases linearly as salinity increases above the critical threshold. Deviations from this linear decrease can occur at production levels considerably less than 50% of the potential.

Figure 27

Salt Tolerance of different Crop Sensitivity Groups



Source: adapted from Maas (1984)

Additionally to the effect on soil water retention, certain salts may be specifically toxic to crops or may upset nutritional balance if they are present in excessive amounts. Two of these, sodium, and carbonates, are dealt with in the next sections.

6.1.3 Minimum Data Set

The minimum data required for the salinity model is the soil electrical conductivity, measured on the saturation extract[3], and the crop factors A_s and B_s, which describe the crop yield response to saline conditions (equation (45)).

CYSLAMB uses a weighted average EC_e value which reflects the greater relative importance of high salinity values in the topsoil layers. The weighting factors allocated to different 25 cm layers in the top 125 cm of soil are given in Table 6.1.

Table 6.1

EC_e weighting factors for soil layers

Number of layers	Correction factor for layer (depth in cm)					
	1 (0-25)	2 (25-50)	3 (50-75)	4 (75-100)	5 (100-125)	6 (125-150)
1	1.00					
2	0.65	0.35				
3	0.47	0.33	0.20			
4	0.38	0.29	0.19	0.14		
5	0.35	0.26	0.18	0.13	0.08	
6	0.33	0.25	0.17	0.13	0.08	0.04

The weighted average is obtained by multiplying the EC_e of each layer by the by the correction factor and by summing the results for the total number of layers in the soil effective rooting depth.

6.1.4 Testing and Validation

The salinity model has been validated internationally by Maas and co-workers (Maas, 1984; Maas and Hoffman, 1977). No validation was possible in Botswana due to a lack of trial sites on saline soils.

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[3] If EC data is only available for a 1:2.5 or 1:5 soil:water suspension, correction factors are available to derive EC_e values. Landon (1991) suggests $EC_{suspension}$ should be multiplied by factors of 2.2 or 6.4 to derive EC_e for 1:1 suspensions and 1:5 suspensions respectively. Actual correction factors will vary with soil texture.

6.2 Sodicity

6.2.1 Introduction

The sodicity of a soil is expressed by the *exchangeable sodium percentage* (ESP). The ESP is the degree of saturation of the soil exchange complex with sodium, and may be calculated by:

$$ESP = \frac{Na}{CEC} \times 100 \qquad \textbf{(46)}$$

where: Na = Exchangeable sodium (meq/100g soil)
CEC = Cation Exchange Capacity (meq/100g soil)

Sodicity has two distinct effects on crop production. Firstly there is the direct toxicity of the sodium ion. Typical sodium toxicity symptoms are leaf burn, scorch and dead tissue along the outside edges of leaves. At this moment however it is not clear whether direct sodium toxicity or the induced calcium deficiency through cation imbalance is responsible for these symptoms.

Secondly the ESP considerably influences soil structure. High ESP values give rise to massive or coarse columnar soil structure, associated with lower infiltration rate, lower permeability and higher susceptibility to erosion.

6.2.2 Model description

The influence of ESP on crop yields is much less documented than the salinity effect. Lunt (1963) prepared a summary literature of crop yield reduction due to different ESP levels. Based on this review , Sys (1985) proposed ESP ratings for different crops. In general, the relative yield decrease (Y_a/Y_m) attributed to high ESP values in a soil can be given by :

$$\frac{Y_a}{Y_m} = 1 - B_a(ESP - A_a) \qquad \textbf{(47)}$$

for $ESP > A_a$

where: A_a = ESP threshold of the crop
B_a = sensitivity of the crop to sodicity above the threshold level
ESP = exchangeable sodium percentage of the soil

This equation is similar to equation (45), which expresses the relative yield decrease due to excessive salt content of the soil.

6.2.3 Minimum Data Set

The minimum data required for the sodicity model is the soil exchangeable sodium percentage, determined from measured CEC and exchangeable sodium using Equation (45), and the crop factors A_a and B_a, which describe the crop yield response to sodic conditions (equation (46)).

For layered soil profiles, ESP is calculated as a weighted average using the same correction factors as those for salinity in Table 6.1.

6.2.4 Testing and Validation

The crop response factors (A_a and A_b) for sodicity have been derived from international research and field observations. Due to the lack of field trials on sodic soils in Botswana, no local validation of this model is possible.

6.3 High pH and Carbonates

6.3.1 Introduction

Soils of high pH are frequently associated with the sodic or saline conditions described in the previous sections. However, high pH soils also occur which are unaffected by soluble salts or exchangeable sodium. In Botswana, these soils are usually associated with high levels of calcium carbonate.

Apart from the obvious effect of a cemented calcareous layer in limiting crop rooting depth, dispersed carbonate particles also adversely affect soil moisture characteristics and provide a less fertile environment for crop roots (FAO, 1979). High pH also affects availability of phosphorus and of micronutrients such as iron and zinc.

6.3.2 Model Description

As relatively few soils in Botswana have been analysed for calcium carbonate, the model assesses the impact of high pH on crop yield using a relationship of the form:

$$Y_a = kp \times Y_m \tag{48}$$

where: Y_a = Predicted yield, after correction for high pH
kp = Crop response factor based on sensitivity to high pH
Y_m = Potential yield when high pH is not limiting.

Crops are assigned to groups according to their sensitivity to high pH (Table 6.2) and a series of crop response factors are tentatively proposed in Table 6.3.

6.3.3 Minimum Data Set

The minimum data required for this model is the soil pH, measured in aqueous paste, and the crop sensitivity group. pH is calculated as a weighted average for the top 125 cm of soil using the same weighting factors as those for salinity and sodicity (section 6.1.3). The crop sensitivity group can be interpreted from Table 6.2.

6.3.4 Testing and validation

Lack of field trials on highly calcareous soils have prevented any local validation of the model. Field observations of crop performance on these soils should be used to check the validity of the response factors listed in Table 6.3.

Table 6.2

Crop Groups based on sensitivity to high pH

Sensitive	Moderately sensitive	Moderately tolerant	Tolerant
Carrot	Alfalfa	Bean	Cowpea
Peppers	Cabbage	Cassava	Date palm
Lettuce	Castor	Cotton	Olive
Pumpkin	Citrus	Maize	
Sisal	Groundnut	Millet	
	Lablab	Potato	
	Mango	Rice	
	Onion	Sesame	
	Pawpaw	Sorghum	
	Pea	Soybean	
	Sweet potato	Sugarcane	
	Sunflower		
	Tomato		

Table 6.3

Crop Response Factors to High pH

pH range	Crop response factor (kp) for crop groups:			
	Sensitive	Moderately sensitive	Moderately tolerant	Tolerant
< 7.5	1.0	1.0	1.0	1.0
7.5 - 8.0	0.5	1.0	1.0	1.0
8.0 - 8.5	0.5	0.8	1.0	1.0
8.5 - 9.0	0.2	0.5	0.8	1.0
9.0 - 9.5	0.0	0.2	0.5	0.8
>9.5	0.0	0.0	0.2	0.5

7. TESTING AND VALIDATION OF THE OVERALL YIELD

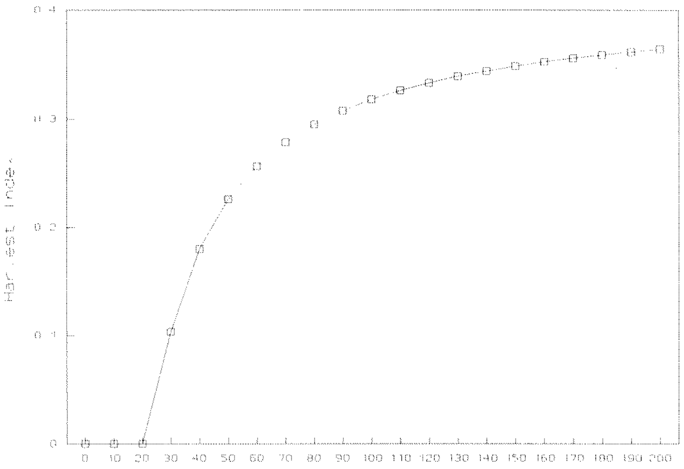
7.1 Validation of Simulated Yields

As mentioned in the previous chapters, the radiation and temperature limited yield model, the moisture limited yield model and the nutrient limited yield model have been tested separately. Yield reductions due to drainage conditions, excess of salts/sodium and pH could not be tested at this stage due to the lack of available data.

The biomass yield, calculated from sequential application of the previously described modules, is converted to the yield of economic product by the *harvest index*. Although the harvest index can be applied to any of the intermediate biomass yields calculated by the model, for routine purposes it should be used to to correct the final biomass after all limitations have been accounted for. This is because the harvest index is not constant, but falls exponentially at low levels of biomass production as shown in Figure 28, which is derived from actual measurements for sorghum.

Figure 28

Harvest Index and Plant Weight for Sorghum



Adapted from De Wit (1991)

The trial data previously used to test the moisture limited yield and nutrient limited yield modules is combined in the validation of the the entire model. Table 7.1 gives an overview of the statistics of the testing for all crops together, and for each individual crop separately.

Table 7.1

Statistics of Measured Yields versus Yields Simulated by CYSLAMB

Statistic	All crops	Sorghum	Maize	Cowpea
n	27	14	9	4
r^2	0.94	0.94	0.85	0.97
S.E (kg/ha)	n.a	162	494	115
R.E (%)	n.a	11	15	14

where:
n : number of observations
r^2 : coefficient of determination
S.E. : standard error of estimate of simulated on measured yields
R.E. : relative error of estimate of simulated on measured yields

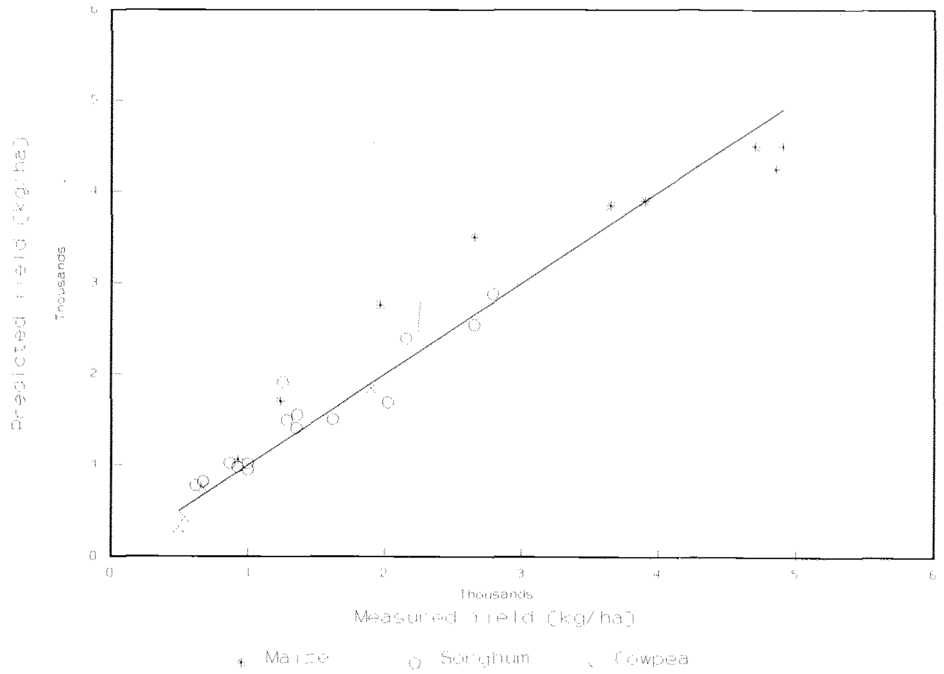
In addition to the standard error of estimate, a relative error of estimate of simulated on measured yields is calculated. The latter compares the standard error of estimate with the average value of the yields. It reveals that the a maximum error of estimate for the three validated crops of 15%.

7.2 Discussion of CYSLAMB Validation

One of the principal advantages of a quantitative land evaluation methodology expressing the results as crop yields is that it is capable of validation. Assuming the yield dataset used for validation is representative of the area in which the program is applied, confidence limits can be set on the accuracy of predicted yields. The results illustrated in Figure 29 are very satisfactory as the standard error indicated is not much greater than that expected due to within plot variation in trial sites. Caution should be used in interpreting yield data at the lower end of the scale. If the indicated yield is less than the standard error of the estimate (Table 7.1), a crop failure, rather than a low yield, may be indicated. However, provided data on the physical environment and the production system are correctly specified, the land evaluator can use CYSLAMB with confidence in Botswana.

Figure 29

Validation of CYSLAMB Model



The logical methodology of CYSLAMB, and the prominant role of moisture stress in determining yield, make it appropriate for use in other semi-arid regions. Before CYSLAMB is routinely applied in countries other than Botswana, the crop input parameters should be adjusted according to the characteristics of local varieties, and a validation, similar to the one described above, should be carried out using data from crop trials on experimental stations and on farmer's fields.

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