ATLANTIC ZONE PROGRAMME

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APPLICATION OF **WOFOST**, **DUET** AND **QUEFTS** FOR MODELLING MAIZE AND GRASS PRODUCTION, USING DATA FROM THE ATLANTIC ZONE OF COSTA RICA

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FOREWORD

The work presented in this report was carried out within in the context of the Atlantic Zone Programme. Sustained land use in Costa Rica's planning region Huetar Atlántica is the central theme of this multidisciplinary research programme. A study of the region's soils and their potential for agricultural use forms an important aspect of the research. Information on this potential is essential for proper land use planning.

Results so far show that large areas of the region that have been deforested for agricultural purposes, could have been better left under natural vegetation, the soils being of such quality that they quickly deteriorate once the natural forest is removed. On the other hand, large tracts of land in the Atlantic Zone are underutilized, i.e., the soils are used below their potential.

The suitability of land units for different land use types may be assessed using the technique of land evaluation as described by FAO. This land evaluation is mainly qualitative. Recent developments include the introduction of quantitative aspects, using simulation models. In this way it is hoped to further refine the land capability appraisals.

The present report describes the application of three models to simulate the production of grass and maize using data from the Atlantic Zone. It is no more than a first reconnaissance. More information and work are required to validate these models.

The data for this report were collected whilst the author was in Costa Rica, from November 1986 to July 1987, carrying out a geomorphological and soils study in the northeastern part of the Atlantic Zone. The simulation was done at the Department of Soil Science of the Wageningen Agricultural University, the Netherlands.

The report was presented in partial fulfillment of the Masters Degree in Soil Science of the Wageningen Agricultural University.

The work was supervised by N. Konijn M.Sc. and Dr. J. Bouma of the Wageningen Agricultural University and by Dr. W.G. Wielemaker of the Programme.

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1 INTRODUCTION

More and more simulation of crop growth is used to study agricultural production. This enables the researcher to give a sound basis to physical land evaluation, in which the potentials of land for a specific use are expressed only in terms as good or bad. It also forces to study in more detail the basic processes which determine crop growth. By doing so, gaps in our knowledge are becoming more obvious, thus eventually indicating directions for additional research.

Various models have been developed in order to simulate plant growth. The WOFOST model used in this study has been developed by the Centre for World Food Studies (CWFS) (Van Keulen and Wolf, 1986). It predicts crop yields based on crop, climate and soil data. Processes are described by various relationships of theoretical or empirical nature. The calculation procedure comprehends three steps: first the production is predicted limited only by radiation and temperature, then in a second step water is introduced as a possible growth limiting factor and finally the nutrient limited yield is calculated. Unlike the first two steps, this last step is not a dynamic, time dependent calculation, in which for every timestep potential and water limited production is being calculated, but it is merely a simple calculation procedure which has to be carried out once for the whole growing cycle.

Waterbalance calculations in the WOFOST model are rather simple. The soil is considered homogeneous, that is, the root distribution and water extraction are supposed to be equal over the whole rooting depth and no soil layers are distinguished. This is rather a simplification of reality, and a reason why efforts have been taken to improve this part of the model.
Improvement has been found by removing the water balance calculations from WOFOST and replacing them by the SWATRER model (Dierckx, 1986), which has been turned into a subroutine. This combination of models has been called DUET (CWFS, 1986). In this study some calculations were carried out making use of DUET.

The used WOFOST version contains a subroutine to calculate the so-called nutrient limited production. In later versions this module is replaced by a more accurate working one, QUEFTS (Janssen et al, subm. for publication), which can also be used as a single model. Therfore the original subroutine was removed from WOFOST and the nutrient limited yield was calculated using QUEFTS.

Calculations were carried out using soil and climatological data collected in the northeast of the Atlantic Zone of Costa Rica. Since in this area cultivation of maize and cattle breeding at present are the economically most important agricultural activities, it was tried to simulate the growth of maize and grass. The used grass species was Ischaemum ciliare (Ratana), one of the most common grasses in the Atlantic Zone.

In most situations water shortage limits plant growth. However, growth might also be hampered by a lack of oxygen, which causes root activity and root growth to diminish or to stop. In the perudic soil moisture regime (Soil Survey Staff, 1975) of the Atlantic Zone it seems likely that high rainfall causes oxygen deficiency on some of the havier textured soils; therefore some emphasis was given to this subject.

Although results obtained by using simulation models often look accurate and promising, one has to realize that the outcome of the calculations is determined by the input of data and the used relations, and can be extremely sensitive to small changes in these; examples of this will be given in this report. Before using the obtained results the model has to be validated for the considered locations and crops; once the model shows to perform properly in a number of production environments it can be applied to produce results.

The report is structured as follows:
First a short description of the Atlantic Zone of Costa Rica is given. Next, attention is paid to the used models and the files which provide the basic information to them. Then the obtained results are discussed. Finally some conclusions and suggestions for further research are given. All figures mentioned in the text can be found in annex 4.

2 AGRICULTURE IN THE NORTHEASTERN PART OF THE ATLANTIC ZONE

About 20 years ago the northeastern part of the Atlantic Zone was completely covered by natural forest. Due to high pressure on the land elsewhere in the country settlers began to move in and started to clear the land, both government guided and spontaneous.

At present the natural forest can be found only in the extreme northeast, where very poor drainage conditions limit the possibilities of further clearing. Scattered over the area logged-out parts of the forest remain.

Roughly the soils of the area can be divided in three groups:

1 Deeply weathered, homogeneous, clayey, reddish brown soils, acid and poor in nutrients. These soils are mainly used for extensive cattle farming and are also known to be highly suitable for the cultivation of pineapple. Relatively large areas are still covered with primary or secundary forest.

2 Young, heterogeneous, moderately to well drained soils, generally fertile; young alluvial deposits. On these soils many crops can be grown due to the relatively high soil fertility. Economically important land use however is limited to maize, pasture and on a much smaller scale cash crops like cacao.

3 Young, heterogeneous, poorly to very poorly drained soils; young alluvial deposits and peats. If used at all, these soils are used for extensive cattle farming.

Usually maize is sown in December or January and harvested in April or May, after a period of a month (or more) of drying in which the stalks are doubled over in order to dry and to protect the ears from molds and diseases. All labour is done by hand, and on most farms no fertilizers are used. Herbicides are used frequently. To reduce planting time, plants grow in small clusters of 3 to 5 plants. On the better soils maize yields of approximately 2000 - 3000 kg grains/ha are obtained.

Cattle breeding is characterized by great differences in farm size and farm management. For example, some of the farms have several hundreds heads of cattle, while others have less than five.

Generally, the quality of the pastures and compaction of the top soil are considered to be constraining, and consequently many farmers try to improve their pastures by introducing better varieties. Not much can be done about soil compaction, and it can be questioned whether cattle breeding is an ecologically justified form of landuse in the prevailing climate or not, especially on the heavier textured soils.

3 THE MODELS

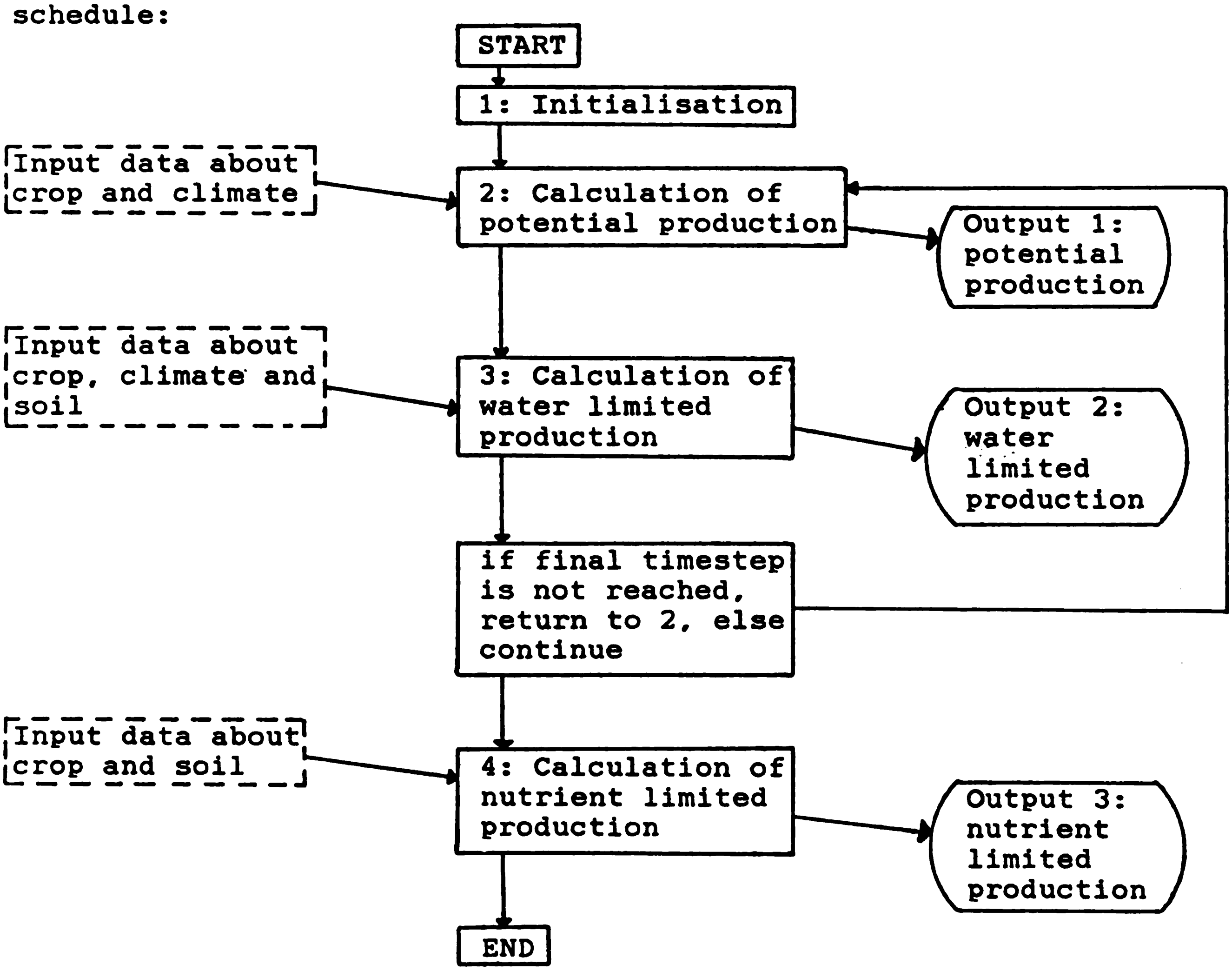
3.1 Introduction

In this chapter only short descriptions of the models are given. For detailed information is refered to the manuals (Rappoldt, 1986; Dierckx, 1986 and Janssen et al, subm for publ. for WOFOST, SWATRER and QUEFTS respectively).

Some of the crop variables and most soil data used in the models were collected on two experimental plots in the area. Both plots were situated in the same grazed Ischaemum ciliare pasture. On each plot a representative profile was described and sampled for chemical and physical analyses, and infiltration measurements were carried out. Grass production was measured and grass and top soil samples were taken and sent to Holland for chemical analyses to be used in the QUEFTS calculations. Profile descriptions, methods and results are given in annex 2 and 3.

3.2 WOFOST, version 3.1

The working of the model can be illustrated with the following schedule:



As a first step, the so called potential production for the crop and location under consideration is calculated, which is limited only by the amount of incoming radiation and the temperature. Thus it can be considered as the possible maximum production for the crop in that particular area.

A second step introduces water availability as a further growth limiting factor. If evapotranspiration demands are not fully met because of either water shortage or exess of water, growth is reduced. Water availability is determined by rainfall, irrigation, evapotranspiration and soil factors.

The third step, the calculation of the nutrient limited production, was omitted because in later WOFOST versions this part of the model has been replaced by a subroutine based on the QUEFTS system. Nutrient limited production was calculated by using QUEFTS. It has to be stressed that the nutrient limited production is calculated in one single calculation procedure for the whole growing cycle, while in step 1 and 2 growth is calculated for timesteps of one day.

Information about crop, climate and soil is provided to the model by 3 datafiles, which are discussed below. The meaning of the variables used in these files is given in annex 1.

3.2.1.The cropdata file

Since it was unknown which maize variety is grown in the study area, a CWFS crop data file was used.

No crop properties for Ratana (Ischaemum ciliare) are available. Since wheat in its vegetative development resembles grass growth, the grass crop file was composed by adopting the CWFS standard file of wheat with some modifications:

- It was assumed that the Ischaemum ciliare grass, like most tropical grasses, has a C-4 assimilation.
- Based on field observations in profile pits, the maximum rooting depth was set at 50 cm. and kept constant during the growing period. This does not mean that no roots can be found deeper than 50 cm, but efficient water extraction by roots is supposed to be limited to this depth.
- The lifespan of the leaves was set at 35 days, based on the field observations that after cutting the grass the first dead leaves appeared after about 5 weeks.
- Specific Leaf Area was measured, determining the dry weight (at 70°C) of about 80 Ischaemum leaves of different age classes (without sheaths), after measuring the fresh leaf surface.
- Specific Stem Area was tentatively set at 1m2/kg, since young leaf sheets contribute to the assimilation.
- Respiration was assumed to be the same as for wheat. This seemes to be a rather safe assumption, taken into account the small differences in respiration for the various crops as found by CWFS (Van Keulen and Wolf, 1986). On the other hand, continuesly high temperatures in the tropics might for instance cause a different respiratory activity.
- In a grass culture, it is difficult to work with the idea of development stage. One cannot consider grass growth in a grazed

pasture as a crop with a outspoken vegetative and generative fase, but has to remind that flowering may or may not occur during the year and that harvesting is a continuous process. Therefore the following was assumed: the Ratana grass needs 40 days to reach development stage 1, after which it starts to flower. However, this stage is never reached; after one month of growing the grass is supposed to be cut back to the begin dry weight (e.g. to development stage 0).

- Starting Leaf Area Index (LAI) was set at 0.5.
- Root mass and rooting depth are kept constant at 1200 kg/ha and 50 cm, resp., although replacement of roots takes place and thus assimilates are needed by the roots for both respiration and the production of new roots.
- To keep the root mass constant, the growth rate of the roots was set equal to the dying rate of the roots at 0.025 day-1.
- Distribution of assimilates over leaves and stems is assumed to be the same as for wheat during vegetative growth.

3.2.2.The climatological data file

Most meteorological stations in the Atlantic Zone were built recently and many of them are measuring only rainfall. Therefore data from 4 different stations were combined:

- The nearestby well equipped meteorological station is Guápiles, situated about 45 km south of the study area at an elevation of 250 metres. Used for air humidity and daily number of hours of sunshine.
- Wind speed was measured in Cobal-Guácimo, about 45 km to the southeast, at 15 metres above sea level.
- Rainfall is registered in Tortuguero, situated 20 km east of the area at sea level.
- Since april 1987, rainfall and temperature are being measured in the study area itself, at an elevation of about 25 metres.

Rainfall

Use was made of data from Tortuguero, were 8 years of daily rainfall data were available. A very dry year (1979 with 4108 mm) and a very wet year (1986 with 6637 mm) were selected for the simulations. Also calculations using the average monthly rainfall data were carried out. Comparing the average monthly rainfall in Tortuguero with data from Guápiles (see figure 1), yields that although the average annual amount is about a 1000 mm more in Tortuguero, the distribution over the year is the same.

Daily rainfall patterns were generated with the rainfall generator of WOFOST, using the mean monthly volume of rain and the mean monthly number of raindays as input. This is done using a random generator. In these simulations, a totally random distribution was generated. In later WOFOST versions the MARKOV parameter has been introduced, which enables to generate a more clustered rainfall pattern. Using this parameter would result in a more realistic rainfall pattern for the Atlantic Zone, where often rainy periods are followed by some dry days.

Rainfall is rather unpredictable, as can be concluded from figures 2 and 3, in which the rainfall distribution in the two selected years is shown.

Temperature

Since april 1987 temperatures are being registered in the south of the study area. It is tried to do this daily, but regularly days are missed.

The nearestby station where temperatures are adeqately registered is Guápiles. However, the elevation of 250 m causes a slightly lower average temperature. The available data suggest that especially night temperatures are about 2°C lower than in the study area. Therefore, in the simulations measurements of the temperature in the area itself were used, despite the fact that registrations only cover a period of one year.

One has to remind that the differences in temperature in the Atlantic Zone do not influence much the growth of plants, since they are within the optimum temperature range for C-4 plants. Higher temperatures only cause a slightly higher evapotranspiration and respiration.

Relative Air Humidity

The long term mean monthly values (1971 - 1983) of the relative air humidity in Guápiles were used, tentatively adding an extra 2% to the values. This was done since about 70% of the study area is still covered with forest and because of the occurence of vast marshy areas, which both add to the air humidity.

Wind Velocity

The mean monthly values of Cobal-Guácimo (1970 - 1976) were used.

Radiation

Mean monthly values of the numbers of hours of daily sunshine in Guápiles (1971 - 1984) were used, converting them to radiation by using the Angström formulae (see also figure 4):

$$R = Ra\ (a + b * n/N) \quad \text{where}$$

R = the radiation actually received in J/m2.day.
Ra = the Angot value, which is the radiation on the top of the atmosphere in J/m2.day. For the different latitudes and dates these values can be found in the Smithsonian Tables (List, 1971).
n = hours of actual bright sunshine.
N = number of hours of daylight.
a = empirical constants, in the humid tropical zones resp. 0.29
b = and 0.42 (Frère and Popov, 1979).

By using the mean monthly values of hours of daily sunshine in Guápiles an error might have been introduced, since despite the lower rainfall Guápiles probably has a more clouded climate than the study area. This is possibly due to the influence of the nearby volcanoes Turrialba and Irazú, which often cause cloudiness in the afternoon.

Evapotranspiration

Evaporation and evapotranspiration were calculated by a model which follows Penman's approach, using data about latitude and altitude of the location, minimum and maximum temperatures, daylength, relative humidity, global radiation and wind speed (in the later WOFOST versions these calculations have been included in the model).

3.2.3.The soil data file

Two soils were selected for the simulations: "Suelo Cedral", a representative soil type for the deeply weathered, clayey soils and "Suelo Sardina", a moderately deep, loamy, young alluvial soil.

pF-Values and hydraulic conductivities were determined on the two experimental plots.

To study effects of top soil compaction, a strongly compacted and a slightly compacted surface layer of "Suelo Cedral" were distinguished, with different hydraulic conductivities and soil water retention curves.

3.2.4.Changes made in WOFOST

Hampering of crop growth caused by oxygen deficiency

Adequate soil oxygen is essential for normal growth for most plants. Decreasing the oxygen supply to the root system results in decreased respiratory activity, reduced water and nutrient absorption, and reduced rooting depth and growth of various plants (Patrick et al., 1973).

In a literature review by Russell (1952) the impact of a suboptimal oxygen supply to the water uptake is summarized. Probably of minor importance is the decrease of the root respiration, which is required for the active absorption of water by plant roots. Probably of greater significance is that high concentrations of carbon dioxide and low oxygen, connected with a lack of oxygen in the root zone, presumably reduce root permeability through the toxic action of carbon dioxide on the root cells.

In the WOFOST 3.1-version growth reduction by a suboptimally water supply is calculated by introducing T, the actual rate of crop transpiration. The crop grows optimally only when it can transpirate at a maximal rate Tmax. If not, growth is reduced by a factor T/Tmax.

T equals Tmax, only if the soil moisture content of the root zone is optimal. At high soil moisture contents, T is limited by:

T=Tmax*LIMIT(0.,1.,((SMO-0.05)-SM/0.05) in which:

SMO = saturated water content of the soil (ml/100 ml soil)
SM = actual water content of the soil (ml/100 ml soil)
LIMIT = the function LIMIT(P1,P2,X) limits the value of X to values in the range (P1,P2). If X is within the range nothing is done. If X is outside the range the value of P1 or P2 is given to X.

This means that the oxygen supply to plants is optimal when the root zone contains more than 0.10 cm3.cm-3 of air, is suboptimal when between 0.05 and 0.10 cm3.cm-3 and that root activity stops when less than 0.05 cm3.cm-3 of the root zone is filled with air.

However, there is no consensus on the minimum required amount of air in the rootzone. Very few quantitative data can be found in literature, and often values are given in oxygen concentration of soil air, which cannot be used in model calculations. In a literature review by Patrick et al. (1973) it is concluded that for every soil type there appears to be an optimum air-filled porosity. Values of the air-filled porosities at which optimal growth occurs range between 12% and 22%.

Also crops differ considerably in the effect of periods of poor aeration on their yield. An example is the difference between maize and sorghum, for sorghum yields are less effected than maize yields in wet seasons for reasons that are not yet known (Russell, 1973).

Driessen (1986) and Van Keulen and Wolf (1986) state that it would be better to assume oxygen deficiency when the soil air runs below a certain percentage of the total pore space in the root zone, instead of a fixed soil volume. Driessen suggests that when less than 8% of the total pore volume is filled with air, growth hampering occurs and in case less than 4% is filled, growth stops completely. Therefore T was changed to:

```
T=Tmax*LIMIT(0.,1.,(((SMO-(SMO*0.04))-SM))/((SMO*0.08)-
  (SMO*0.04)))
```

In this formulae growth decreases linear between an air-filled pore space of 8% and 4% and is nil when the total pore space contains less than 4 volume percent of air. One can wonder if, instead of linear, it would not be more realistic when the decrease between 8% and 4% would be non-linear.

<u>Hampering of crop growth in case of water shortage</u>

In case of a low soil moisture content, T is defined as follows:

```
T=Tmax*LIMIT(0.,1.,(SM-SMW)/(SMCR-SMW)
```

in which:

SMCR = The value of SM below which growth reduction due to moisture deficiency occurs. The value of SMCR is calculated as follows:

```
SMCR=(1-SWDEP)*(SMFCF-SMW)+SMW
```

where

SMW = moisture content of the soil at wilting point, e.g. at pF = 4.2
SWDEP = soil water depletion factor, a crop variable which is read from the cropdata file as a function of the maximum transpiration rate.
SMFCF = soil moisture content at field capacity.

The value of the field capacity is an initialisation variable in the model, and is set at a matrix suction h = -200cm (pF = 2.3). However, the value of field capacity varies with soil type. In the Atlantic Zone of Costa Rica the andic properties of most soils probably cause that the matrix suction at field capacity is higher than -200cm (Sanchez, 1976). Some pF-measurements in the field support this idea (pers.com.De Bruin). Therefore SMFCF was changed to: h = -50cm (pF = 1.7).

In the WOFOST model the amount of water in the soil at equilibrium determines the percolation to deeper soil layers. It is calculated as a function of SMFCF and therefore an increase in SMFCF will reduce percolation, which, in turn, causes a higher average moisture content of the soil and an earlier occurrence of oxygen deficiency. This effect is partly compensated for by a small increase of the actual soil evaporation rate, as a consequence of the higher soil moisture content.

Figures 5 to 10 show the effects on yield predictions for Suelo Cedral (compacted topsoil). As can be seen from figures 5 and 6, the change in the formulae to calculate oxygen deficiency results in a higher crop production, while a change in the value of SMFCF causes a decrease in the predicted production. However, combined they result in only a small change in the predicted yield level in most of the months (see also table 1).

Table 1: Effect of changes made in the optimal moisture content traject of WOFOST on yield predictions on Suelo Cedral (compact) in the relatively dry and relatively wet year.
Values are changes (in %) in the averages of 12 starting days throughout the year compared to the averages of the unchanged model.

	only oxygen formulae is changed	only value of SMFCF is changed	both are changed	
dry year	+5.0	-29.6	-8.2	
wet year	+9.5	-48.9	-12.9	

Infiltration capacity

Since the infiltration capacity of the top soil is important for the calculation of the soil water content some attention was paid to the part of the model which determines it.

When the amount of surface storage (SS) is less than 1 mm, no surface runoff is supposed to take place and the preliminary infiltration rate (RINPRE) is calculated as follows:

$$RINPRE=(1-NOTINF)*RAIN+RIRR+SS/DELT$$

NOTINF = the fraction of rain not infiltrating , mainly meant to account for a fraction of rain which evaporates before infiltration.
DELT = timestep
RAIN+RIRR = amount of rainfall+irrigation

However, this concept is difficult to handle in the situation in Costa Rica, were the sometimes huge amount of daily rainfall cannot infiltrate because the limited infiltration capacity, while the model proceeds as if it can infiltrate. Therefore this line was erased from the model, so RINPRE is in all situations (e.g. with and without surface storage) determined by:

```
RINPRE=AMIN1(SOPE*DELT,AVAIL)/DELT   in which
AVAIL=SS+(RAIN+RIRR-EL)*DELT
```

SOPE = saturated hydraulic conductivity of the wet soil
EL = evaporation rate from surface water layer

The non-infiltrating part of the rainfall is lost as surface runoff.

It has to be realised that this is rather a simplification of reality, which only holds when the top soil is saturated with water and when the amount of rainfall would be equally distributed over the day. The first assumption results in a overestimation of runoff because hardly ever a soil is saturated with water when it starts to rain; only when the model jumps from one rainy timestep to another this might be the case. The second assumption yields an underestimation of runoff, since rainfall is seldom equally distributed. On the contrary, often precipitation takes place in heavy rainstorms with intensities up to 100 mm/hour.

Grass growth

To simulate grass growth according to the assumption made in paragraph 3.1.1, the following changes were made.

1 At the end of development stage 1 growth was stopped.

2 The weight of living roots was made independent of development stage:

```
WRT=FR*TDWI was changed into WRT=1200   in which
```

WRT = dry weight of living roots (kg/ha)
FR = fraction of shoot dry matter increase partitioned to the roots (depends on development stage)
TDWI= total crop dry weight (kh/ha)

3 The growth rate of the roots was also changed to a constant value

```
GRRT=FR*DMI was changed into GRRT=0.025*WRT
```

GRRT = rate of increase in root dry matter (kg/ha.day)
DMI = rate of dry matter increase of the crop (kg/ha.day)

4 Death rate of roots (DRRT) in the model is set zero until development stage 1.5. It was changed into:

```
DRRT=PERRT*WRT  in which
```

DRRT = death rate of roots (kg/ha.day)
PERRT= relative death rate of roots (day-1), read from cropdata file

5 Gross photosynthesis rate

DMI=CVF*ASRC becomes DMI=(CVF*ASRC)-(WRT*0.025)

CVF = average efficiency of conversion of assimilates into plant dry matter (kg/kg)
ASRC= carbohydrates available for dry matter increase (kg/ha.day)

Further some small, more technical adjustments were made.

3.3.DUET

Duet is a combination of the models WOFOST (version 4.1) and SWATRER (Dierckx, 1986), a revised version of the SWATR model (Feddes, 1978).

Instead of using the WOFOST module to calculate a soil water-balance, for every simulated day a call is made to the subroutine which the SWATRER model has been turned into. Since SWATRER offers the opportunity to distinguish up to 5 different soil layers, has a more sophisticated water extraction model and is capable to simulate soil moisture flow, it is believed that using DUET results in a more accurate simulation, compared to WOFOST.

Climatological and crop data fed to the model are the same as used in WOFOST. However, more soil data are needed. Data files are turned into 'ready made' input table which are easy to fill in. Therefore no example and explanation is given in this report.

To simulate the unsaturated soil water flow, for every soil layer the θ - h and the θ - k relationships must be given. They were obtained by using the measured values of these relationships (see annex 2) and linearly interpolating in between them.

Instead of a waterfilled fraction of total pore space, a traject of the water potential has to be defined at which plants extract water optimally from the soil. If in a timestep root water extraction is limited by a suboptimal water potential, also transpiration is reduced, which, as in WOFOST, limits plant growth in that timestep.

For both soils the for plant growth optimal pressure head values were choosen as follows:

- optimal growth between a pressure head of -20 and -200 cm
- linearly decreasing growth between - 7 cm and -20 cm and between -200 cm and -2500 cm.

These values are supported by an investigation by Taylor (1949), who observed that oxygen diffusion in a loamy soil was small at tensions lower than 20 cm, and that there was little effect of moisture content on plant growth at tensions higher than 30 cm.

One should keep in mind however that every soil type has its own caracteristic values for these entities.

3.4QUEFTS

To predict the nutrient limited yield the QUEFTS system (Janssen et al, subm. for publ.) was used. It estimates the nutrient limited yield of a maize crop, on base of chemical analysis of the pH measured in water, organic carbon, phosphate according to Olsen and exchangeable potassium in the top 20 cm of an unfertilized soil. Because the system not yet has been validated thoroughly, chemical properties have to be within the following ranges:

- pH-H2O : between 4.5 and 7.0
- org. C : below 70 gram C/kg. soil
- P-Olsen : below 30 mg. P/kg. soil
- exch. K : below 30 mmol K/kg. soil

If available, analysis of total N and total P can provide the model with additional information about the supply of these nutrients. Else, nitrogen supply is estimated from the organic-C content of the soil, assuming a C/N ratio of 10. Phosphorus supply is estimated from the value of P-Olsen and the organic-C content, assuming a total-P (mg/kg)/organic-C (g/kg) ratio of 25.

The QUEFTS-system can be applied to well drained, deeply rootable soils.

Maize is used as a yardstick, because it is a nutrient demanding crop and is grown in a wide range of conditions. Plant density is assumed to be around 50,000 plants/ha.

Given the results of the analyses, the model first estimates the potential supply of the 3 nutrients considered, using empirically derived equations between chemical soil properties and maximum nutrient uptake. Next the actual uptake of each nutrient is calculated as a function of the supply, taking into account the supplies of the other nutrients. In a third step the yield ranges for each nutrient are established, based on empirical actual uptake - yield relationships. Finally the most likely yield level is calculated by combining the three yield ranges.

The empirical relationships used in the model are based on field trials carried out in Kenya and Surinam.

In this investigation, samples were collected as follows: on each of the experimental plots, 10 top soil samples (0 - 15 cm) were taken from at random choosen miniplots of 1 m2, using a small sample auger.

Grass samples were taken and analysed to see whether the mineral shoot composition was in accordance with the outcome of the QUEFTS predictions.

The results of the soil and grass analyses are given in annex 3.

Analyses were carried out in The Netherlands. For details about the methods, see Houba et al.(1985).

4 RESULTS

4.1 WOFOST

4.1.1 Potential production

Maize Figure 11 shows that in the average situation the highest yield can be obtained when sowing in January or February (by looking at the graphs one has to consider that the simulation starts at germination and does not include the days between sowing and germination). The second best sowing period would be June.

To show some of the variability between the years, simulations were also carried out for a year with a relatively low radiation (1974, average daily hours of of sunshine 3.8) and for a year with a relatively high radiation (1978, average daily hours of sunshine 4.6).

The curve for the 'low radiation' year fits in well with the one for the average year; the 'high radiation' year shows an additional optimum sowing period late October.

Grass As long as no more accurate crop data are available it is possible to predict almost any production. This is clearly shown in figures 12, 13 and 14. Potential production was calculated for 3 different rooting masses, keeping all other variables constant. In case of a high rooting mass most or all assimilates are used for respiration so no shoot growth occurs. Probably this is not a realistic situation, it seems more likely that a part of the roots quickly die so shoots can grow. In case of a low rooting mass growth seems to be unrealistic high.

Simular results can be obtained by changing, for example, the death rate of roots, respiratory activity of the various organs or the initial shoot dry matter.

The only conclusion which can be drawn from these calculations is that grass growth varies with the amount of incoming radiation.

The effect of a possibly lower radiation in Guápiles (mentioned in paragraph 3.2.2.) compared to the study area was studied by rising the mean monthly numbers of hours of sunshine with 10%. This resulted in an average 3.8% higher potential production for 24 different starting days throughout the year (range 2.4% - 5.2%), see figure 15. Especially during the more clouded months the relative production increase is large since respiration consumes a relatively large part of the dry matter production.

Using mean monthly values for temperatures and radiation instead of daily values most probably overestimate potential production. Days with a low temperature are usually cloudy days during which a large part of the assimilation products is used for respiration, so growth is limited.

During sunny days the relationship between the amount of incoming radiation and assimilation is no longer linear because light saturation occurs; also temperatures might rise over 30°C and cause a small growth reduction.

4.1.2 Water limited production

All calculations were carried out assuming that the soil was at field capacity at the starting day and surface storage never exeeded 5 mm.

Maize Ten rainfall patterns were generated, using the mean monthly amounts of rainfall and the mean monthly numbers of raindays. For the twelve starting days water limited production was predicted, using the generated rain patterns. The results of the ten runs were averaged over the starting days and are graphically presented in figure 16.

If annually only one crop is grown, best sowing day would be in February or March. An eventually second crop should be sown in September.

Traditionally, farmers plant their maize in December or January. However, this tradition originates from other parts of the country where the climate is different. The simulations suggest that higher yields might be obtained when sowing one or two months later. In that case harvest would be in the more rainy months of June and July. This does not have to be a problem, since all labour is done by hand. Should machinery be used, the wetter soil conditions might form a serious constraint to a later sowing date.

If a second crop is grown, it is sown in August or September, which corresponds with the outcome of the simulations.

For 24 starting days, calculations were also carried out for the relatively dry and the relatively wet year, using measured daily rainfall data as input.

The outcome of these calculations gives a good example of the variability in the predictions, see figures 17 and 18. In the relatively dry year growth is only seriously hampered when sowing takes place in June and November, while in the relatively wet year serious production losses occur when the crop is sown anywhere in the period early June - late December.

Unfortunately, rainfall data of only 8 years were available, so nothing can be said about the frequency of occurence of a dry or a wet year.

The three soils differ very little in their behaviour; the growth curves are equally shaped, only the magnitude of the growth reduction varies. This is not a very realistic result, due to fact that the optimal water-filled pore space traject was defined equally for both soils.

Grass production is less effected by oxygen deficiency then maize production. Consequenty, compared to maize the production curves (see figures 19 and 20) show only a small reduction for most starting days of the relatively dry year and a moderate growth reduction for the starting days of the relatively wet year.

In the model, plants are most sensitive to oxygen deficiency when the rooting zone is shallow. In case of a shower, a shallow rooting zone is filled with water much sooner dan a deep one.

This is clearly shown in figures 21 and 22, which show the effect of the rooting depth on the water limited grass yield. A relatively small difference in rooting depth already causes big differences in production losses due to oxygen deficiency. This is not a realistic situation since distribution of roots is not equal over the whole rooting depth, as WOFOST assumes. In case of grass, most roots are situated in the upper 20 cm. Root activity is therefore probably seriously effected when a heavy rain fills up the upper 20 cm, no matter if the maximum rooting depth is 40 or 60 cm.

No calculations were carried out using generated rainfall patterns, nor for Suelo Cedral with a less compacted top soil.

4.2 DUET

Not many calculations were carried out using the DUET model, because it was felt that for proper use of the model too many data were lacking.

Plant growth was simulated for Suelo Cedral (compacted topsoil) and Suelo Sardina for 24 starting days. Water limited productions were calculated using only the real rain data from the relatively dry and relatively wet year. The only crop used was maize; initial moisture content was set at field capacity.

Although certainly a better simulation of the water balance and thus of crop growth can be obtained, DUET requires a much more detailed soil data set which is not easy to obtain.

In this investigation much information about the lower boundary condition and the pressure head traject at which plants are able to extract water optimally from the soil was missing; besides more accurate θ - h and θ - k curves are necessary.

Nevertheless, the results of the simulations are interesting and will be discussed below.

The outcome of the simulations for Suelo Cedral is very simular to the WOFOST results, which are shown in figures 23 and 24. This soil is homogeneous and therefore the difference in waterbalance calculations between the two models is small.

Simulations on Suelo Sardina on the other hand give very different results, see figures 25 and 26. Almost no growth reduction occurs as a consequence of oxygen deficiency, but crop growth is seriously hampered by water shortage. Consequently, simulation yields a higher production in the wet year than in the dry year and highest productions are obtained when sowing is followed by a rainy period (compare figures 25 and 26 with the distribution of rainfall, figures 2 and 3).

Except for the fact that the pressure head value at which plants experience water stress might be set too high, which resulted in growth reduction, some points are worth to be considered.

Suelo Sardina has a very high infiltration and drainage capacity compared to Suelo Cedral. Oxygen deficiency to the extent of Suelo Cedral seems therefore unlikely, but is nevertheless predicted by WOFOST.

The sandy layer from 40 to 70 cm causes a fast drainage of the top soil and holds less water at the same matrix suction than the top soil. If during a period of drought the available water is extracted from the top soil and the matrix suction reaches its critical value, the subsoil cannot provide enough water to the crop to maintain maximal growth because its moisture content already is very low.

Despite the fact that yield predictions by DUET are rather unreliable due to lack of reliable data, they indicate that WOFOST's water balance module indeed is too simple to simulate accurately water balances for heterogeneous soils like Suelo Sardina and that the DUET model might give better results. It has to be realised however that combining of two complex models is a risky undertaking and that therefore results can be used only after proper validation.

Also the attention is focused on the fact that in spite of the very high rainfall crops growing on some soils might experience water shortage during short dry periods, a feature also mentioned by Sanchez (1976).

4.3 QUEFTS

For the twenty topsoil samples, yields were first estimated using only the 4 necessary chemical parameters pH-H2O, organic C, P Olsen and exchangeable K. The results of these calculations, see table 2, did not correspond with the actual field situation. According to farmers, yields of about 2000 - 3000 kg grains/ha can be obtained on Suelo Sardina, while almost no maize is grown on Suelo Cedral due to the low fertility. It was noted that on the very few places where maize was grown on this soil, germination was poor and plants stayed small.

Table 2: Average nutrient limited yield prediction in kg grains/ha (with 95% confidence interval). Results are averages of runs for ten different top soil samples per soil type.

Suelo	predicted yield	idem, including total-N and -P analyses	idem, including bulk density
Cedral	3342±1023	2374±667	1515±450
Sardina	5121±516	5594±471	3816±325

It was tried to get a better correlation with the actual field situation by analysing also the total-N and total-P contents of the samples. For the two soils, C/N and Total-P/Org.C ratios are given in table 3.

Table 3: Actual C/N and Total-P/Org.C ratios

ratio	Suelo Cedral		Suelo Sardina	
	range	average	range	average
C/N	10.0 - 13.7	11.3	8.9 - 11.2	10.1
Total P/Org.C	10.7 - 16.7	13.7	46.0 - 70.7	53.3

This table shows clearly the difference between the actual measured C/N and Total-P/Org.C ratios and the values assumed for them by the model.

Not surprisingly, the yield predictions are strongly influenced. The average yield prediction for Suelo Cedral goes down by almost 29 % from 3.3 tons/ha to 2.4 tons/ha, while on Suelo Sardina the average yield prediction rises by more than 9 %, from 5.1 tons/ha to 5.6 tons/ha.

These results indicate that, when applying the QUEFTS system to Costarican soils, the total-N and total-P analyses should be carried out.

In both cases the difference in the predictions is mainly caused by the changed estimation of the phosphorus supply. Often soils with andic properties (see Soil Survey Staff, 1970) have a very high phosphate retention, which might cause phosphorus deficiency, despite the high total-P contents of these soils

(according to Fassbender (1969) between 1000 and 3000 ppm).
Phosphorus retention on Suelo Sardina varies between 60 and 90%; on the experimental plot its value is about 78 % (pers. com. Stoorvogel), which can be considered as rather low for a soil with andic properties.
Together with the high total-P content, which lies within the range given by Fassbender, this might explain the high phosphorus supply on Suelo Sardina.
No phosphate retention was measured on Suelo Cedral. However, the very low total P content indicates that availability of phosphate probably is low.

Due to the low bulk density of the investigated soils, the potential supply of nutrients to the crop is overestimated, since nutrient levels are expressed in mmol/kg instead of mmol/m3. The soils in Kenya and Surinam for which the model has been developed, have a bulk density of about 1.2 g/cm3. Assuming that the rooted soil volume is the same, the calculated supply of nutrients in the soil with a different bulk density should be devided by 1.2/actual bulk density. The average bulk density of the top soil of Suelo Cedral is 0.80 g/cm3 (n = 78) (De Wolff, pers. com), of Suelo Sardina 0.83 g/cm3 (n = 39). Yield predictions using these values (see table) show a decrease by 36 % and 32 %, respectively.
These ultimate yield predictions can be seen as the best possible predictions for the nutrient limited production.
The Quefts system was adapted to include bulk density in the calculations by multiplying the calculated supply by: actual bulk density/1.2.
The yield predictions for each of the soil samples are given in annex 3.

Although the last predictions already give a much better fit with reality, there are still many points which influence the predictions but are not, or cannot be quantified.

1 Only the three elements N, P and K are considered in the model, based on the experience that in many cases these elements are the most yield limiting ones. Of course it is very well possible that deficiency of other elements hampers plant growth. For example, Ca levels of the grass samples (see table 4) are rather low, compared to the values given as normal by Chapman (1966).
Possible deficiencies of nutrients other than N,P and K are not included in the model, and possibly the nutrient limited yield is overestimated. Magnesium levels on the other hand are very high.

Table 4: Nutrientlevels in grass samples from Suelo Sardina and Suelo Cedral, compared with figures from literature.

	nutrient levels in % of total dry weight			
	Suelo Cedral (range)	Suelo Sardina (range)	Chapman (range)	Andrew et al. (range)
N	1.55-1.88	1.49-1.90	1.85-3.15	not given
P	0.16-0.24	0.24-0.38	0.27	0.16-0.25
K	2.51-3.46	2.70-3.73	0.43-2.70	not given
Ca	0.28-0.53	0.32-0.58	0.57-1.75	not given
Mg	0.21-0.34	0.18-0.29	0.09-0.21	not given
Zn(ppm)	31-51	24-51	not given	not given

Both Van Diest (1988) and Sanchez (1976) mention the possibility of sulfur deficiency in tropical soils, the last author especially in soils with andic properties. Unfortunately, no sulfur analysis were carried out.

2 Only the top 15 cm of the soil have been sampled and analysed, while the models is based on analysis of the top 20 cm. Generally the levels of nutrients, especially of N and P, are lower in the lower soil compartments. Thus the possible supply of the nutrients might be slightly overestimated.

3 Other pH-H2O measurements in suelo Cedral suggest that the measured pH values on the experimental plot are relatively high and that a value of 4.5 or 4.6 is more in accordance with the general situation. Especially in the low pH ranges the estimated yield is extremely sensitive to a change in the value of the pH, see figures 27, 28 and 29, in which respectively potential supply of the three nutrients and the predicted yield for sample no. H1 (see annex 3) are given as a function of pH (all other parameters were kept constant).

To illustrate the effect of the pH in the lower pH range, also the average productions for both soils were calculated, raising and lowering the pH-H2O values by 0.1 and 0.2 units and keeping all other parameters constant. The predicted yields on suelo Cedral are strongly influenced by these small changes, while on Suelo Sardina there is no change in the yield predictions, see figure 30.

It can be questioned whether a rather fluctuating variable as pH-H2O should be used in the model, considering the impact of pH values on the yield predictions. pH-H2O values are known to vary tenths of units due to the weather conditions, to crop varieties and crop development stage or to treatment of the samples. Because of their less fluctuating character, the author feels that it should be tried to replace pH-H2O by pH-KCl or pH-CaCl2. In about 70 top soil samples on Suelo Cedral pH-KCl was found to vary only 0.1 unit (pers.com. De Wolff).
Another possibility to adapt the model would be to narrow the pH range for which predictions are carried out, by limiting the pH-H_2O range in which predictions are carried out to 5.0 - 7.0.

4 In a perhumid climate as prevailing in Costa Rica, leaching and surface runoff losses of mobile nutrients are likely to occur and lead to a lower potential supply of nutrients and thus lower yields. Since high temperatures and humidity cause a continuous high activity of microorganisms, the supply of nutrients is also continuously high. Especially during germination and the beginning of the vegetative growth and during ripening, leaching of mobile nutrients might occur. The high porosity of the soils facilitates this process (Sanchez,1976).

5 Plant density is unknown.

6 The high organic matter content in soils with andic properties is associated with amorphous allophane. Allophane reacts with organic radicals to form very stable aggregates that remain relatively resistant to mineralisation (Sanchez, 1976). The reasons of this resistance are not very clear. A physical blocking of the organic particles by allophane (or other minerals, see also Janssen, 1983) may render the organic materials partly inaccessible to microorganisms. Munevar and Wollum (1976) found that the very low phosphate availability in many Andepts hampers the growth of microorganisms and thus the mineralisation of organic matter.

Nitrogen supply in the QUEFTS model is determined by the organic-C content of the soil, which is mineralised at a certain, pH dependent rate. It seems likely that in the investigated soils the mineralisation rate is less than the assumed one, due to the andic properties of the soils, and thus nitrogen supply is overestimated.

On the other hand, the high temperature and humidity in the study area probably cause the activity of microorganisms to be higher than in Kenya, so mineralisation rate might be higher than assumed in the model. Adding the average temperature as a factor determining Nitrogen supply maybe results in more accurate predictions.

5 CONCLUSIONS AND SUGGESTIONS FOR FURTHER RESEARCH

As in many places in the humid tropics nutrient availability in the Atlantic Zone of Costa Rica is more limiting to crop growth than water supply, assuming that planting is done at the right time.

Calculations by both WOFOST and DUET suggest that no water shortage occurs in Suelo Cedral; growth reduction in the water limited yield calculations occurs only as a consequence of a lack of oxygen.

The two models give different results for Suelo Sardina: WOFOST predicts growth reduction by a lack of oxygen while DUET calculations result in a serious hampering of growth caused by drought. Although some field observations on grass indicate that drought stress might occur, the question which of the two models gives the best fit with reality remains unsolved until validation will be carried out.

Best sowing date for maize would be in February, which is one or two month later than actually happens. Again, this can only be stated with certainty after a validation of the models has been carried out.

When the QUEFTS system is applied in the Atlantic Zone, total-N, total-P and bulk density should be determined and used in the calculations.

Large differences exist between actual yield level and calculated water limited production. Nutrient limited yields as calculated with the QUEFTS system are more in accordance with reality, although calculated yield levels are still too high.

The need for more reliable and extended data was clearly felt during this investigation.

Long term meteorological data from the Atlantic Zone are scarse and many existing data seem rather unreliable. Therefore the program should start soon with the measuring of climate characteristics, that is, if quantitative land evaluation becomes one of the research topics.

As pointed out in paragraph 4.1.1. measuring of actual radiation is probably most rewarding, especially in combination with daily temperatures. Although wind speed is not very important since it is often virtually absent, very few reliable data exist so registration should be encouraged.

Although for many crops, among which maize, complete data sets are available, it should be tried to collect as many as possible data about the locally sown varieties.

Trying to simulate growth of a crop for which no data are avialable (like for instance grass), requires a comprehensive investigation, not only to measure and collect the necessary parameters, but also to check and where necessary adjust the used relationships in the model.

The approach followed to simulate grass growth was not realistic. It might be a better idea to simulate grass growth in a grazed pasture as follows:

Total dry matter of a grazed pasture has to be determined. If all necessary crop parameters like respiratory activity etc. are known, for every timestep grass growth of this pasture can be calculated. By introducing a "harvest subroutine", in which the grass consumption by animals can be calculated per timestep, the optimum number of animals/ha in every timestep can be determined. Information about grass consumption by animals can be found in literature.

Since for heterogeneous soils DUET probably results in a better simulation than WOFOST, it should be strived to use DUET; consequently the necessary soil data have to be collected. This includes measuring comprehensive θ - h and θ - k relationships, determining drainage conditions and establishing a optimal soil moisture traject. It should be tried to do this as part of the routine analyses which are carried out for all important soil types of the Atlantic Zone, but also field and pot experiments on the reaction of crops to soil water content will be useful.

Actual pF measurements in the field at various dephts and under various weather conditions probably will give valuable information to validate the results.

Large parts of the Atlantic Zone of Costa Rica were colonized only recently. Present day landuse seems to be not yet fully adapted to the prevailing physical condition of the land, since it originates to a large extent from other parts of the country. This implies that farmers might have problems in adapting the use of their land to the new environment. An example of these problems is the cultivation of beans in the study area. Beans are planted at the same date as in the dryer western parts of the country, but due to the much higher rainfall, the crop is lost in many years in a very rainy period during ripening.

Under these cicumstances, properly validated crop growth models can be valuable to study some of the possibilities and contraints of new and existing forms of landuse.

Therefore, in a short term it is necessary to concentrate on validating the existing models, so the results of the simulations can be used by field workers in the Atlantic Zone, like for instance extension field workers.

In the long run however, the search for new, better approaches for modelling landuse in Costa Rica should continue. Although the models used in this investigation are rather sophisticated, does that not mean that new models are a luxury. With new technical possibilities it should be possible to built models which are much easier to adapt and to use by less well trained people.

6 LITERATURE

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SUMMARY

This report should be seen as a first reconnaisance of the possibilities and constraints of the use of simulation models, e.g. quantitative landevaluation, in the northeast of the Atlantic Zone of Costa Rica.

Two soil were selected for the simulations:

- Suelo Cedral, a deeply weathered, homogeneous clayey soil and
- Suelo Sardina, a layered, young aluvial soil with a texture ranging from sandy loam to silt loam.

The dynamic crop growth simulation models WOFOST and DUET were used to predict yield levels of maize for two production situations.

In the first production situation the so-called potential production was calculated, which is only limited by the amount of incoming radiation and the temperature. Under the prevailing climatological conditions predicted maize yields ranged from 7500 kg grains/ha to 5500 kg grains/ha, depending on the sowing date. Highest yields can be obtained when sowing in February, lowest when sowing in October. When actual weather data from a single year are used to calculate the potential production, results might differ considerably from the abovementioned findings.

It was also tried to simulate grass growth, but the obtained results are highly unreliable and are therefore not summarized.

The second production situation introduces water availability as a further plant-growth limiting factor. Both models predict growth reduction on Suelo Cedral only by air shortage. The amount and distribution of the rainfall during the growing period determines the magnitude of the growth reduction. Yields may be reduced to only 30% of potential production.

Under average weather conditions sowing best takes place in February/March. However, rainfall distribution and thus predicted water limited production is highly variable from year to year.

On Suelo Sardina WOFOST predicts more or less the same growth reduction as on Suelo Cedral, while the DUET simulations result in growth reduction mainly by water shortage.

Yield levels of maize limited by the available amount of the nutrients Nitrogen, Phosphorus and Potassium were calculated using the QUEFTS system. The calculated average production on Suelo Cedral was 1500 kg grains/ha, on Suelo Sardina 3800 kg grains/ha.

It is concluded that the used models and data have to be validated before the results of the simulations can be applied in practise.

ANNEX 1

INFORMATION ON DATA FILES

A: PLANTDAT.DAT

The file plantdat.dat is composed of numbers. For maize, their meaning is explained in the following (see Rappoldt, page 10 - 12):

1	crop type, in this case it means that maize is a C4 crop
0	indicates that the pre-anthesis development rate is independent of daylength and depends on temperature
0	indicates that the crop has no airducts
60	life span of leaves in days under optimum temperature
135	maximum rooting depth in cm.
1.0	
0.0	daylength optima, not used for maize or grass
20.0	initial total dry weigth in kg/ha.
10.0	initial rooting depth in cm.
0.0357	maximum developement rate in the pre-anthesis stage in days-1
0.0385	idem in the post-anthesis stage
1.2	rate at which the rooting depth increases until maximum depth is reached in cm/day
0.700	extinction coefficient for total radiation
0.720	efficiency of the conversion of assimilates into leaf dry matter in kg/kg.
0.730	idem into storage organ dry matter
0.720	idem into root dry matter
0.690	idem into stem dry matter
0.0000	specific pod area in ha/kg.
0.0000	specific stem area in ha/kg.
2.0	factor by which the relative maintenance respiration increases per 10 degrees increase of temperature
0.030	relative maintenance respiration rate of leaves in days-1
0.010	idem of storage organs
0.010	idem of roots
0.015	idem of stems
0.030	maximum relative death rate of leaves due to water stress in days-1
0.020	relative death rate of roots in days-1
0.020	idem, of stems
0.0100	
0.0040	
0.0011	minimum nutrient concentrations in various organs, not
0.0005	used in the calculations

24 24 24 6 12 6 18	numbers indicating the length of the following AFGEN tables (see Rappoldt I.4)
table 1	fraction of the total dry matter increase partitioned to the roots as a function of development stage
table 2	fraction of the total above ground dry matter increase partitioned to the leaves as a function of development stage
table 3	idem to the stems
table 4	idem to the storage organs
table 5	specific leaf area in ha/kg as a fuction of development stage

table 6	reduction factor for the development rate as a function of temperature in °C
table 7	soil water depletion factor as a function of potential transpiration rate in cm/day

B: SOILDAT.DAT

The soil data file is composed of three numbers and two AFGEN tables which have the following meaning (see also Rappoldt, p.9):

4.80	saturated conductivity of the soil (SOPE) in cm/day, limiting the infiltration rate of water, and, in calculation without groundwater, also the downward transport of water.
6.15	variable not used in this WOFOST version
18.12	conductivity used in calculations without groundwater to limit the loss of water to deeper soil layers. Normally it is set equal to SOPE, but it can also be used to simulate an impermeable soil layer.

Next two AFGEN tables are given:
table 1: table representing the water retention curve: pF-values (log waterpressure in cm) are the X-, and the soil moisture content the Y-values.
table 2: with pF-values as X and the 10-logarithm of the conductivity (in cm/day) as Y. Only used in simulations with groundwater.

C: CLIMEAN.DAT

This file provides WOFOST with data about climate and geographical position (see also Rappoldt, p.12 - 13):

On the first line the name of the station and its geographical position in degrees are given.
For the 12 months of the year the lines 2 to 13 contain:
mean temperature (°C), average rainfall (cm/month), potential evapotranspiration (cm/day), potential soil evaporation (cm/day), potential gross CO2 assimilation rate of a closed C4 crop (kg/ha.day), idem for a C3 crop, effective irrigation (cm/month) and the mean number of rainy days.
The potential gross CO2 assimilation had to be calculated using a model which in later WOFOST versions is incorporated.

ANNEX 2

INFORMATION ON SOILS

In order to carry out measurements, two plots were selected in the same grazed 10 year old pasture and fenced. The plots were situated on different soil types: Suelo Sardina and Suelo Cedral.

Profiles were described according to the FAO guidelines (1977) and samples for chemical and physical analyses were taken. Analyses were carried out by the laboratory of the Costarican Ministry of Agriculture in Guádeloupe, San José. Unfortunately, some of the samples for the determining of the watercontent at higher suction values were lost.

Suelo Cedral

Classification (tentatively): Typic Hydrandept (Soil Taxonomy)
date: 16-05-1987
author: André Nieuwenhuyse
geographical position: approximately 10°32'N 83°44'E
location: approximately 15 km north of Cariari, Limón, Costa Rica; about 100 metres northwest of Río Penitencia.
elevation: about 25 metres
landform: remain of dissected Pleistocene terrace
slope on which the profile is situated: about 5%
land use: pasture
parent material: riversediments of unknown texture
drainage: well drained
moisture conditions of the profile: moist throughout
depth of groundwater: more than 2 metres
presence of surface stones and rock outcrop: nil
evidence of erosion: none detected
soil animals: some earthworms, ants
evidence of human influence: compaction by cattle

Description of the horizons (colours are described according to Japanese Munsell Colour Card):

0 - 6 cm	Brown (7.5 YR 4/3) when moist, many fine, distinct, clear, red and gray mottles; clay; moderate, very small angular blocky; slightly sticky, slightly plastic; firm when moist; no pores; abundant very fine and many fine roots; not thixotropic; clear smooth boundary to:
6 - 14 cm	Dull brown (7.5 YR 5/4) when moist, few to common fine, faint, clear red mottles; clay; moderate, small and medium angular blocky; slighly sticky, slightly plastic; firm when moist; broken, thin cutans on ped faces, possibly of clay minerals; few very fine pores; abundant very fine and many fine roots; not thixotropic; clear smooth boundary to:
14 - >95 cm	Yellowish brown (10 YR 5/8) when moist, some very coarse (>4cm) faint, sharp, orange and gray mottles in upper 45 cm; clay; moderate to weak, very small and small, angular and subangular blocky, which

easily can be broken into smaller peds; slightly sticky, slightly plastic; friable when moist; broken, thin cutans on ped faces, possibly of clay minerals; many very fine pores and few fine pores; many fine roots at a depth of 15 cm, decreasing to none at about 70 cm.

results of chemical analyses:

depth	pH H2O	Al	Ca	Mg	K	P	Zn	Mn	Cu	Fe
		(in me/100ml)				(ppm)				
0 - 14 cm	5.5	1.70	2.5	1.2	0.50	5	2.0	8	10	196
14 - 70 cm	5.3	2.80	2.0	0.9	0.37	3	1.8	3	5	40

water content at different pF values and bulk density

(values are averages of 3 samples)
water contents in mg/100 ml, bulk density in g/cm3

sample depth	pF=0	pF=1.7	pF=2.0	pF=2.3	pF=2.7	bulk density
4 - 9 cm c	74.2	59.5	57.2	51.7	50.9	0.77
4 - 9 cm nc	69.5	65.3	63.9	59.8	58.0	0.73
30 - 35 cm	70.0	57.7	55.7	49.4	47.1	0.68

c = compacted top soil
nc = not compacted top soil

The clasification of this soil depends on the presence of an argilic horizon; in the abovementioned clasification is assumed that there is no such horizon. In case there would be an argilic horizon, tentatively the soil would be clasified as a Palehumult or Paleudult, depending on the organic matter content.

Suelo Sardina

Clasification: Entic Udic Eutrandept (Soil Taxonomy)
date: 16-05-1987
author: André Nieuwenhuyse
geographical position: approximately 10°32'N 83°44'E
location: approximately 15 km north of Cariari, Limón, Costa Rica, about 200 metres northeast of Río Penitencia
elevation: 20 metres
landform: young aluvial plain
slope on which the profile is situated: about 1%
land use: pasture
parent material: sandy river sediments
drainage: moderately well drained
moisture conditions of the profile: moist throughout
presence of surface stones and rock outcrop: nil
evidence of erosion: none detected
soil animals: many earthworms

evidence of human influence: compaction by cattle

Description of the horizons (colours are described according to Japanese Munsell Colour Card):

0 - 5 cm	Brownish black (10 YR 3/2) when moist, common, fine, distinct, clear red mottles; loam; weak fine and medium angular blocky, with a tendency to massive; slightly sticky, slightly plastic; firm when moist; very few fine pores; many very fine and fine roots; slightly thixotropic; clear, wavy boundary to:
5 - 40 cm	Yellowish brown (10 YR 5/6) when moist; silt loam; partly strong medium and fine crumb, partly moderate, very fine angular and subangular blocky; slightly sticky, slightly plastic; friable when moist; many very fine and few medium pores; many very fine and fine roots; thixotropic; clear, smooth boundary to:
40 - 50 cm	Dull yellowish brown (10 YR 5/3) when moist; sandy loam; structureless: massive with pores; non sticky, non plastic; very friable when moist; many very fine and few medium and coarse pores; common very fine roots; not thixotropic; clear smooth boundary to:
50 - 70 cm	Brown (10 YR 4/6) when moist, common medium, distinct, clear brownish mottles due to mixing with overlying horizon; silt loam; partly structureless: massive with pores (about 65 %), partly moderate, fine and medium crumb (about 35%); slightly sticky, slightly plastic; very friable when moist; many very fine pores, common fine and medium and few coarse pores; few very fine roots; very thixotropic; gradual, smooth boundary to:
70 - >110 cm	Yellowish brown (10 YR 5/6) when moist, many, medium, distinct, clear orange and gray mottles; silt loam; partly (80%) moderate very fine angular and subangular blocky, partly (20%) moderate fine and medium crumb; slightly sticky, slightly plastic; friable when moist; many very fine pores, common fine and medium, and few coarse pores; very few fine roots; very thixotropic

results of the chemical analyses:

depth	pH H2O	Al	Ca	Mg	K	P	Zn	Mn	Cu	Fe
		(in me/100ml)				(ppm)				
0 - 5 cm	5.4	0.25	13.5	4.0	0.42	29	4.0	16	9	200+
5 - 40 cm	5.8	0.10	9.5	3.1	0.62	16	3.4	4	10	140
40 - 50 cm	6.0	0.10	6.0	2.0	0.27	16	2.2	2	4	68
50 - 70 cm	6.1	0.10	8.0	2.7	0.26	22	1.8	2	5	74
70 -110 cm	6.2	0.10	11.0	4.0	0.27	29	2.6	2	10	120

depth	Ca	Mg	K	CEC	sand	silt	clay	OM	PR
	(me/100g)				(%)				
0 - 5 cm	17.50	5.00	0.93	28.60	28	50	22	12.86	90.3
5 - 40 cm	12.50	4.25	1.16	23.92	26	56	18	3.48	68.3
40 - 50 cm	5.44	1.20	0.45	17.68	60	30	10	1.07	70.4
50 - 70 cm	8.75	2.63	0.45	17.68	34	52	14	0.80	71.4
70 -110 cm	12.50	4.50	0.58	31.20	16	66	18	1.07	75.1

OM = Organic Material
PR = Phophate Retention (measurements carried out by J. Stoorvogel).

<u>water content at different pF values and bulk density:</u>

(values are averages of 3 samples)
water contents in mg/100 ml, bulk density in g/cm3

sample depth	pF=0	pF=1.7	pF=2.0	pF=2.3	pF=2.7	pF=4.2	b.d
7 - 12 cm	67.1	61.2	60.5	53.2	51.0	30.7	0.89
22 - 27 cm	65.9	50.3	48.6	41.2	39.0	27.7	0.77
45 - 50 cm	55.6	30.3	26.0	18.9	16.9	12.0	0.96
80 - 85 cm	67.5	53.2	51.4	40.8	38.1	35.3	0.74

Hydraulic conductivities
Unsaturated and saturated hydraulic conductivities were measured using the crust method. Instead of gypsum, cement was used to make the crusts. For further details about this method is refered to Bouma (1983)
Results of the measurements are:

<u>Suelo Cedral</u>

infiltration in cm/day

	crust2	h (cm)	crust3	h (cm)	without	h (cm)
topsoil 1	nm	nm	4.6	-3	4.8	-2
topsoil 2	nm	nm	16.3	-6	10.7	-5
subsoil	1.5	-14	nm	nm	18.2	0

Suelo Sardina

infiltration in cm/day

	crust1	h (cm)	crust2	h (cm)	crust3	h (cm)	without	h (cm)
topsoil 1	nm	nm	1.2	-12	3.2	-7	89	-2
topsoil 2	1.8	-16	4.8	-5	nm	nm	78	0
subsoil	nm	nm	2.7 4.7	-41 -31	5.2 12.6	-29 -22	306	0

explanation:
nm = not measured or failure
crust1 = 1 part of cement, 3 parts of sand
crust2 = 1 part of cement, 5 parts of sand
crust3 = 1 part of cement, 8 parts of sand
without = using no crust

No real differences in infiltration capacity were found between the two topsoils on Suelo Sardina. Therefore a compacted and less compacted topsoil were only distinguished on Suelo Cedral.

ANNEX 3

RESULTS OF SOIL ANALYSES USED IN QUEFTS CALCULATIONS

A: Results of soil analyses

Soil 1: Suelo Cedral

sample nr	pH-H2O	K-HCl mmol/kg	P-Olsen mg P/kg	C-Kurmies g C/kg	N-tot g N/kg	P-tot mg P/kg
H1	4.6	7.6	2.9	57	5.70	712
H2	4.8	8.2	2.7	53	4.70	698
H3	4.9	5.2	2.0	43	3.90	672
H4	5.0	6.1	2.5	48	4.20	705
H5	4.9	7.3	2.1	38	3.30	633
H6	4.8	9.5	3.2	45	3.90	638
H7	4.8	4.6	3.1	61	5.90	777
H8	4.9	10.3	3.5	62	5.60	805
H9	5.1	8.0	2.1	63	4.60	674
H10	4.9	5.9	2.8	50	4.40	699
Soil 2: Suelo Sardina						
V1	5.1	7.4	17.1	27	3.00	1910
V2	5.0	8.2	20.1	32	2.90	1711
V3	5.2	8.2	24.7	38	3.40	1824
V4	5.5	8.7	14.7	39	3.70	1801
V5	5.8	8.2	15.2	37	3.80	1752
V6	5.7	6.9	14.7	37	3.60	1876
V7	5.9	6.9	19.2	41	3.80	1886
V8	5.7	5.6	9.1	30	3.10	1700
V9	5.6	5.5	10.2	31	3.50	1959
V10	5.6	5.6	15.1	35	3.60	1752

B: Results of grass analyses

Soil 1: Suelo Cedral

sample nr	N %	P %	K %	Ca %	Mg %	Zn ppm	Yield gr.DM/m2
H1	1.77	0.20	3.39	0.41	0.34	49	202
H2	1.71	0.17	2.96	0.36	0.28	31	231
H3	1.63	0.22	3.03	0.43	0.28	43	195
H4	1.84	0.23	3.37	0.40	0.31	43	143
H5	1.86	0.21	3.46	0.34	0.32	40	174
H6	1.67	0.24	3.08	0.33	0.34	39	180
H7	1.57	0.23	2.71	0.46	0.34	51	203
H8	1.55	0.20	2.51	0.53	0.29	43	144
H9	1.88	0.16	3.39	0.38	0.29	44	236
H10	1.64	0.16	3.16	0.28	0.21	36	172
Soil 2: Suelo Sardina							
V1	1.66	0.24	3.04	0.32	0.19	24	180
V2	nd	nd	nd	nd	nd	nd	194
V3	1.90	0.26	3.73	0.42	0.20	28	207
V4	1.64	0.36	3.01	0.44	0.29	41	236
V5	1.85	0.35	2.95	0.46	0.26	39	165
V6	1.49	0.27	2.74	0.38	0.20	34	241
V7	1.62	0.36	2.70	0.41	0.28	41	180
V8	1.49	0.30	3.00	0.52	0.18	36	169
V9	1.58	0.32	3.05	0.58	0.20	43	160
V10	1.79	0.38	3.13	0.54	0.22	51	131

QUEFTS: PREDICTED YIELDS
in kg grains/ha

Soil 1: Suelo Cedral

sample	(1)	(2)	(3)	most limiting element
H1	869	750	420	P
H2	3259	2115	1338	P
H3	3171	2329	1489	P
H4	4024	2949	1906	P (K)
H5	3122	2348	1498	P
H6	3107	2168	1372	P
H7	2895	2155	1371	P (K)
H8	4710	3169	2047	P
H9	4593	3175	2057	P (K)
H10	3667	2578	1656	P (K)
Soil 2: Suelo Sardina				
V1	4664	5645	3852	N and K
V2	5120	5232	3558	N and K
V3	5930	6130	4182	K (P,N)
V4	5899	6375	4356	K (P)
V5	5699	6233	4262	K
V6	5188	5613	3825	K
V7	4893	5038	3435	K
V8	4575	5250	3577	K
V9	4577	5391	3672	K
V10	4667	5037	3439	K

standard prediction (1)
prediction using total N/total P (2)
prediction using also bulk density (3)

ANNEX 4

FIGURES

figure 1A

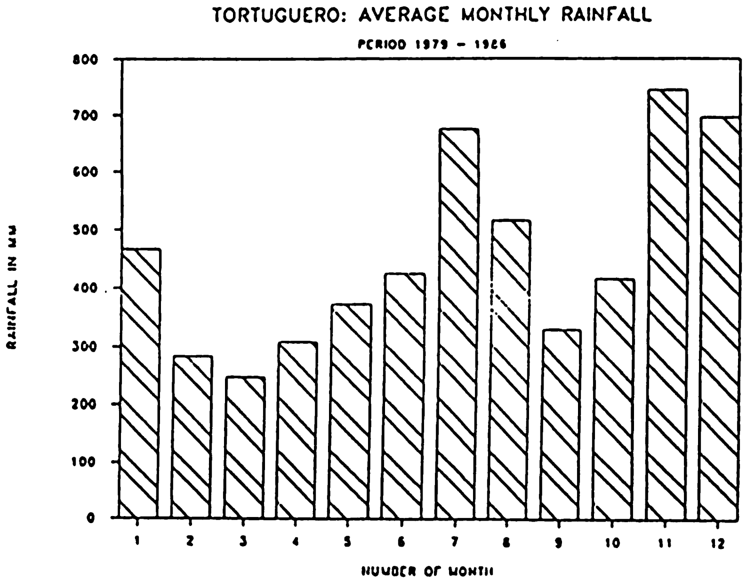


figure 1B

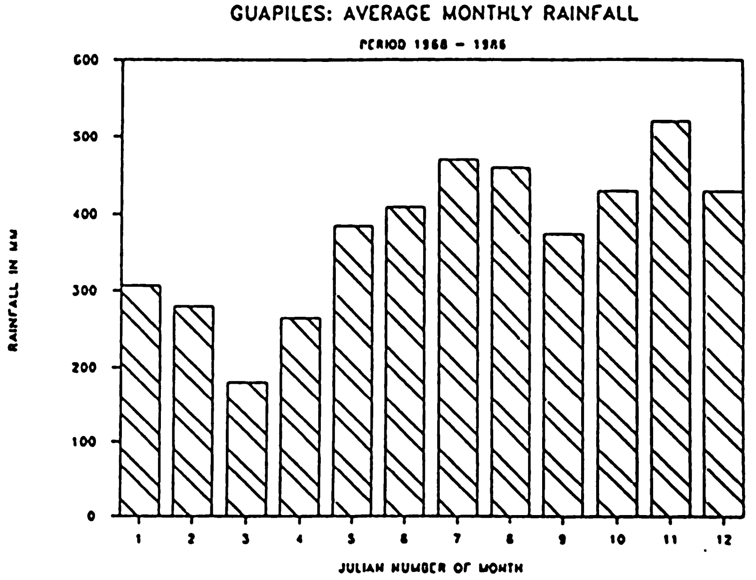


figure 4

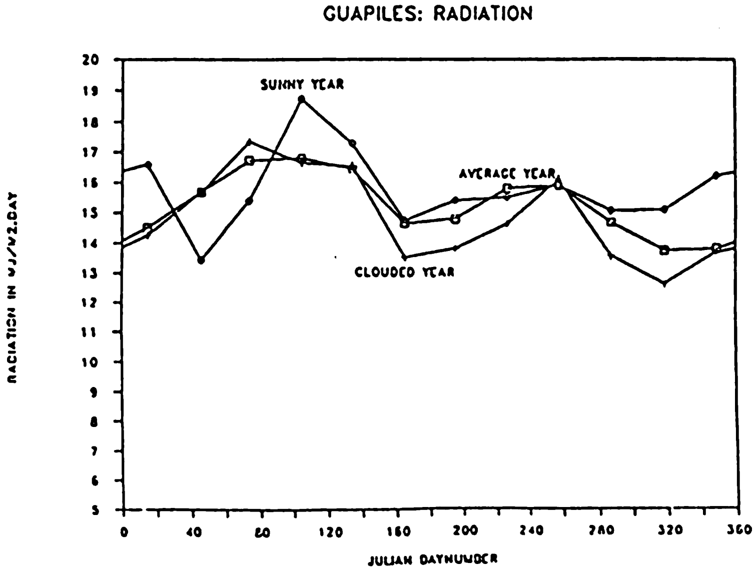


figure 2

RAINFALL IN A RELATIVELY DRY YEAR

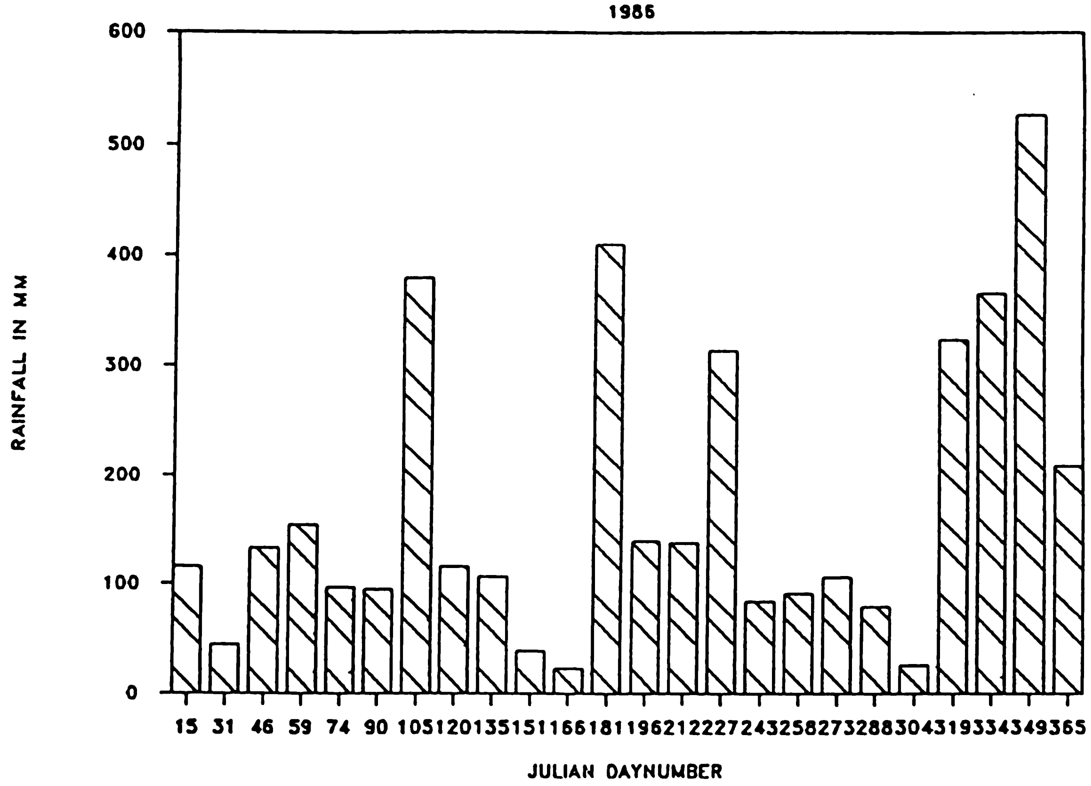


figure 3

RAINFALL IN A RELATIVELY WET YEAR

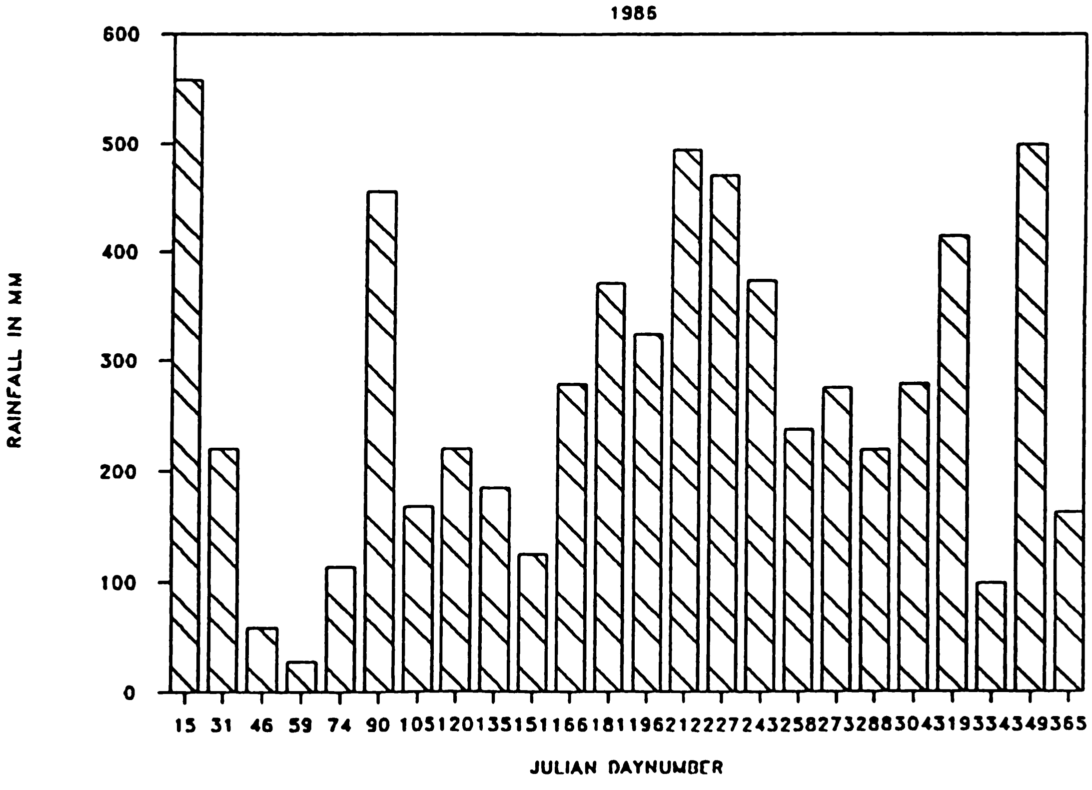


figure 5

YIELD RESPONSE TO A CHANGE IN O2 SUPPLY

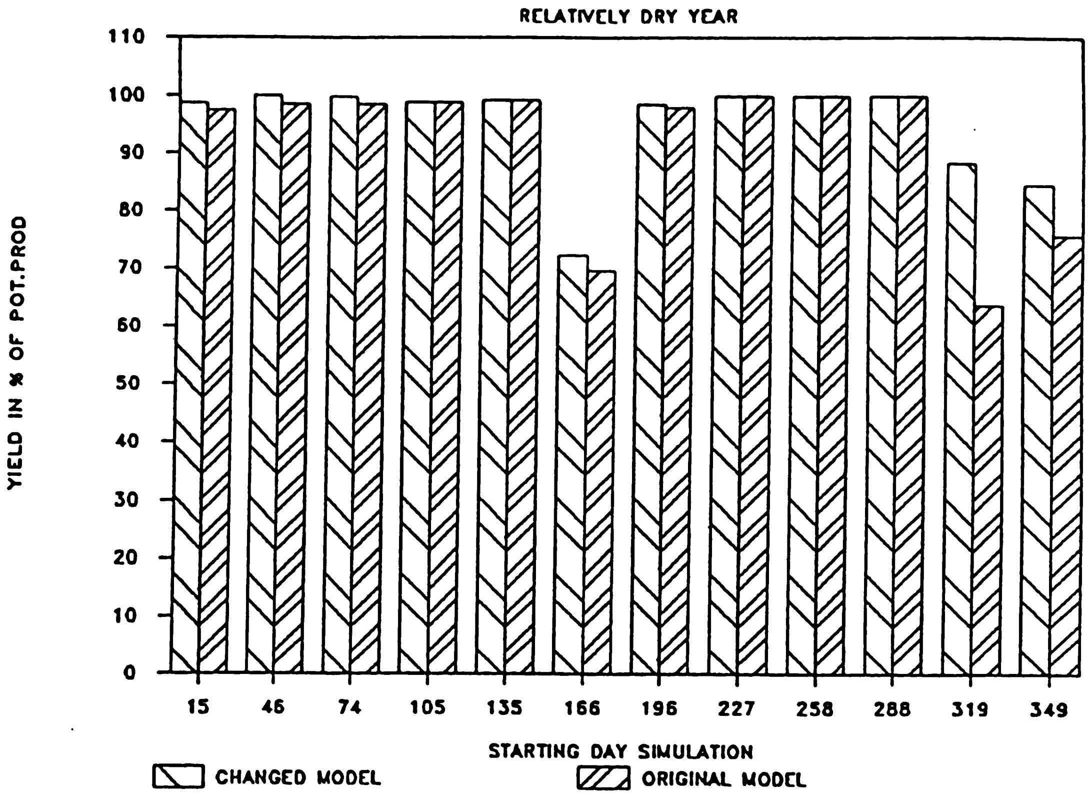


figure 6

YIELD RESPONSE TO A CHANGE IN O2 SUPPLY

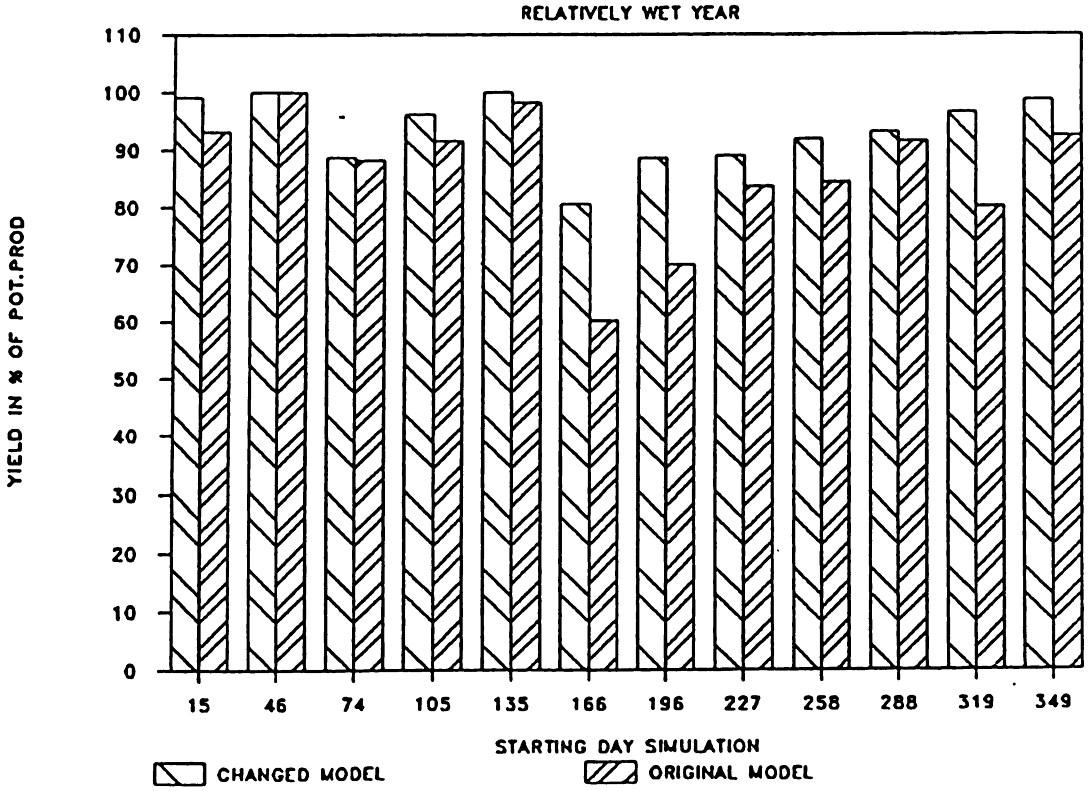


figure 7

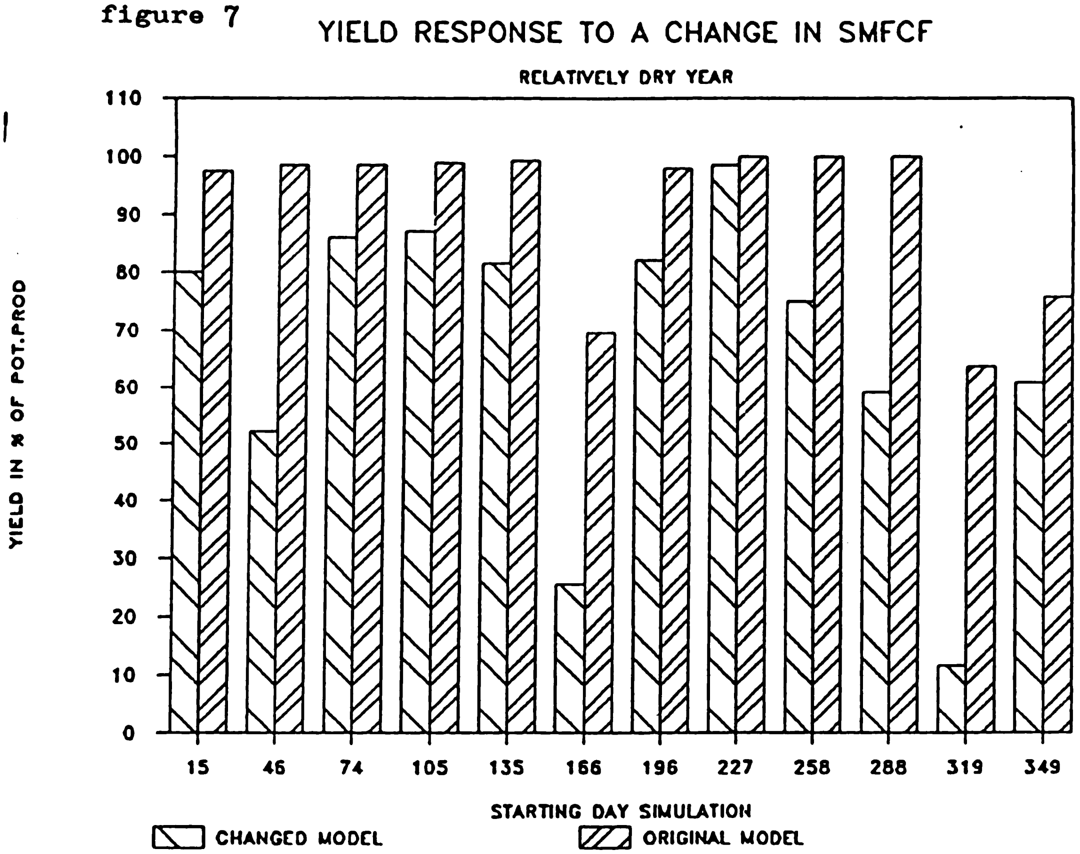


figure 8

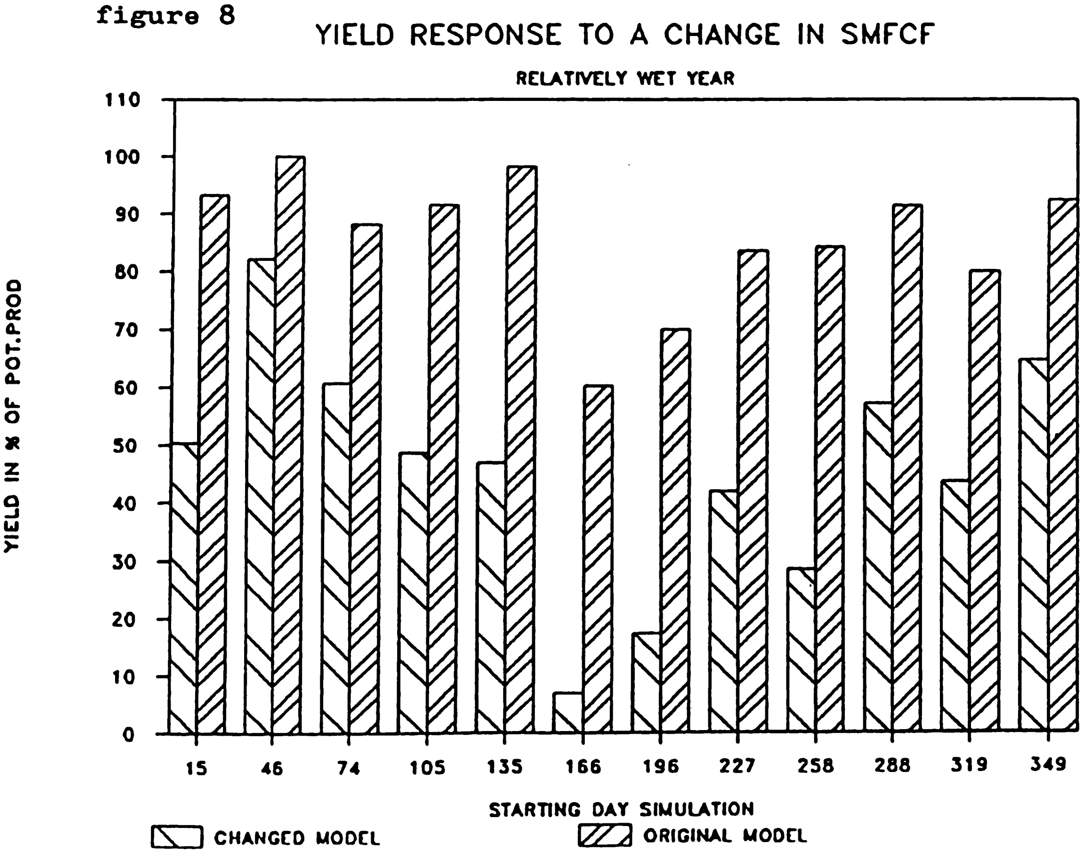


figure 9

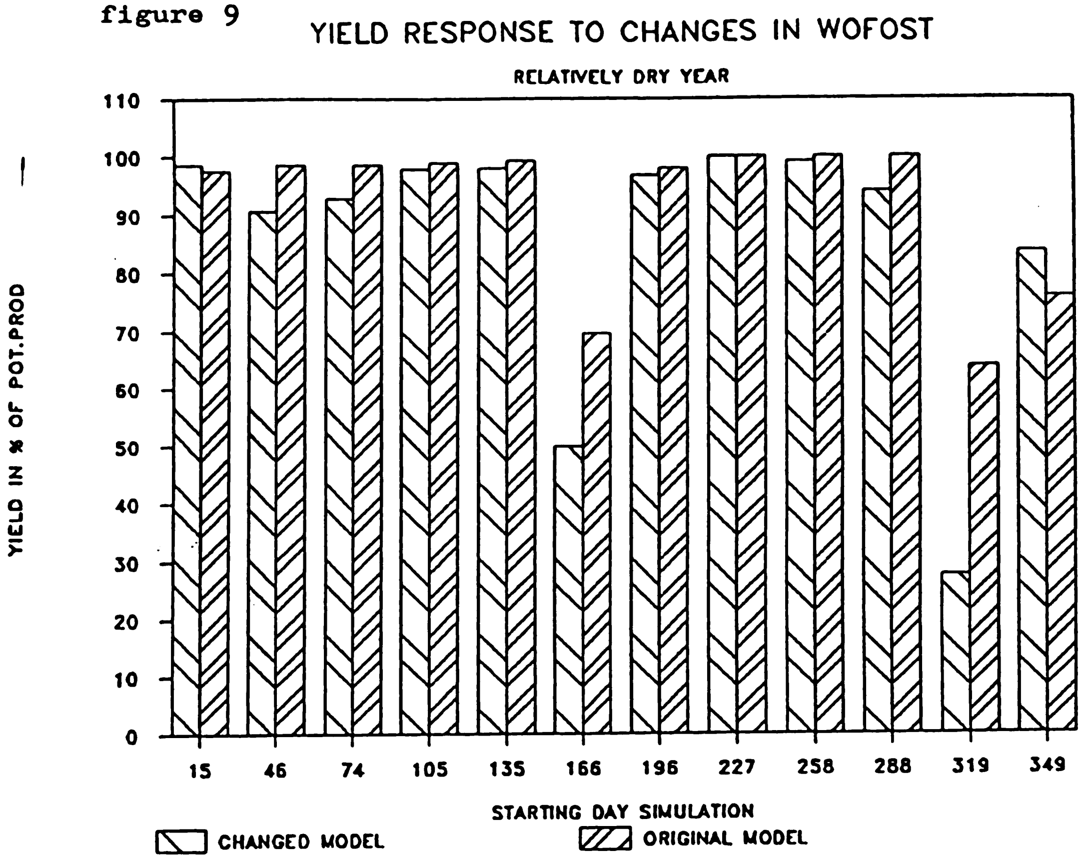


figure 10

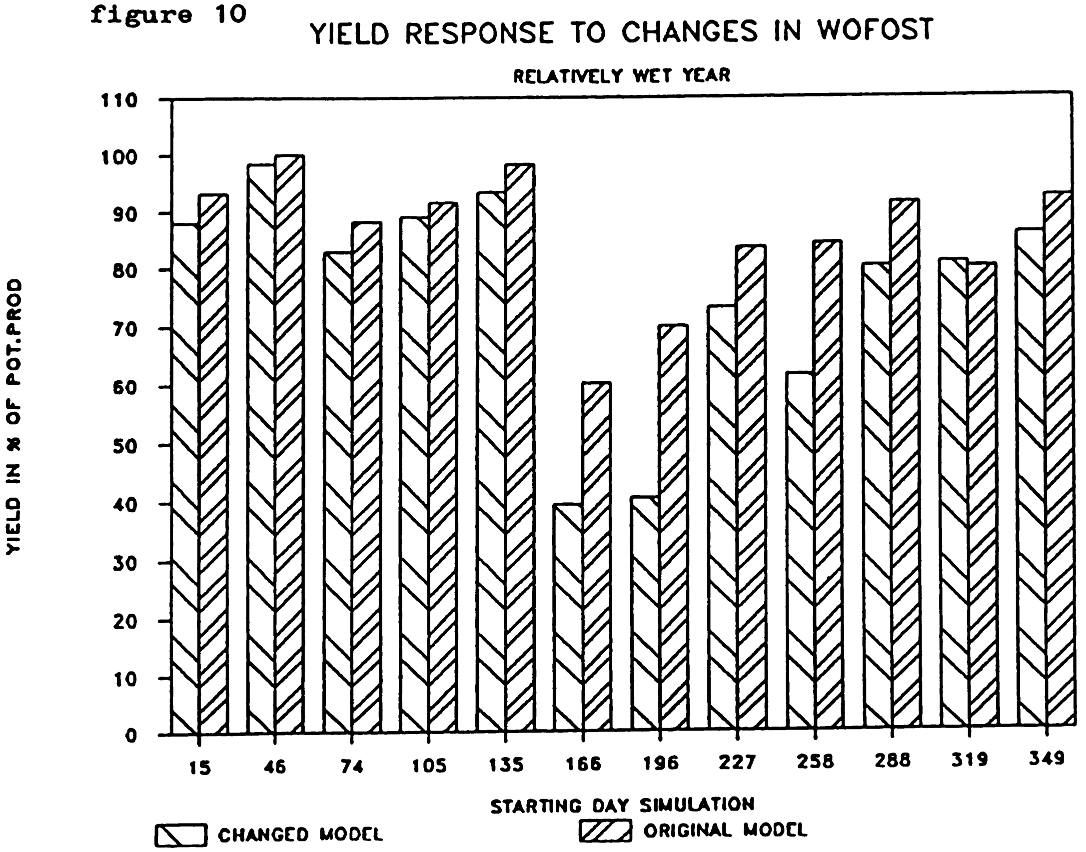


figure 11

POTENTIAL MAIZE PRODUCTION

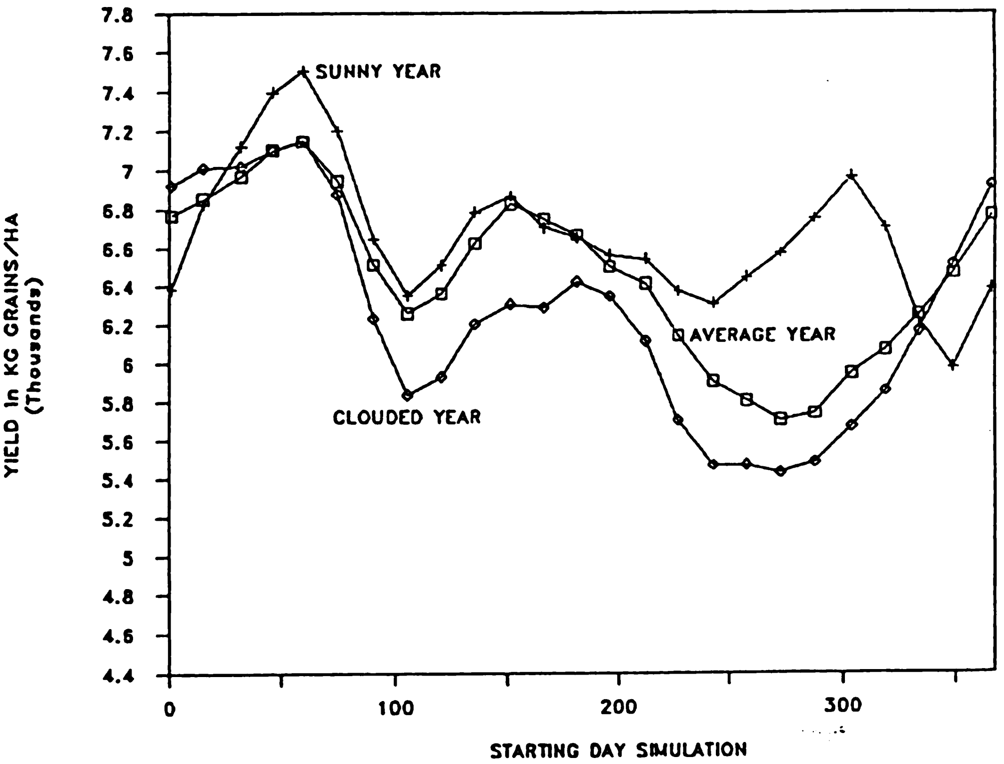


figure 15

EFFECT OF INCREASE IN DAILY SUNSHINE

ON POTENTIAL MAIZE YIELD

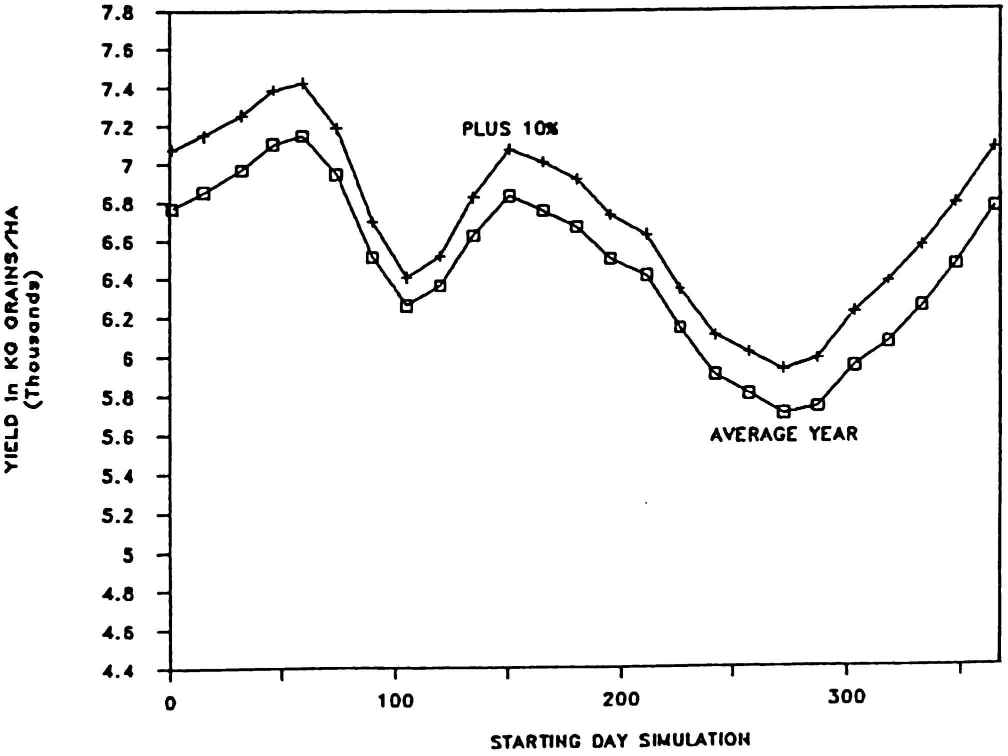


figure 12

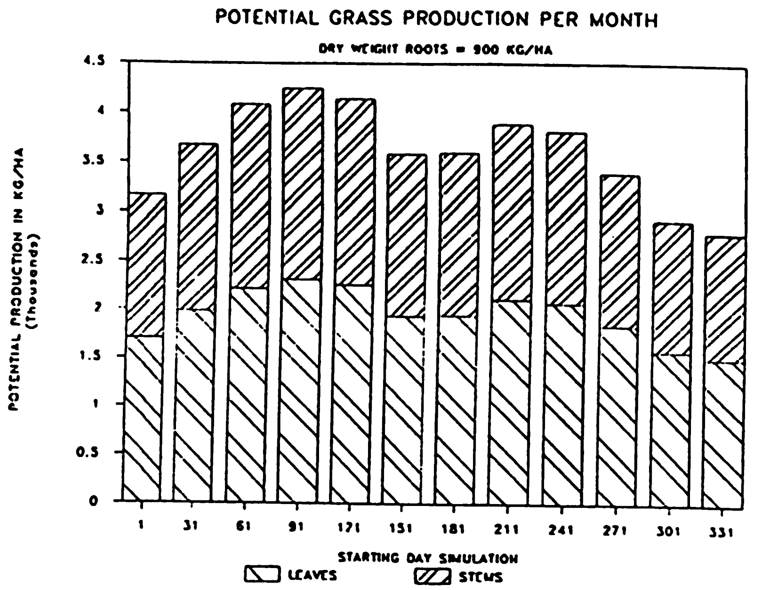


figure 13

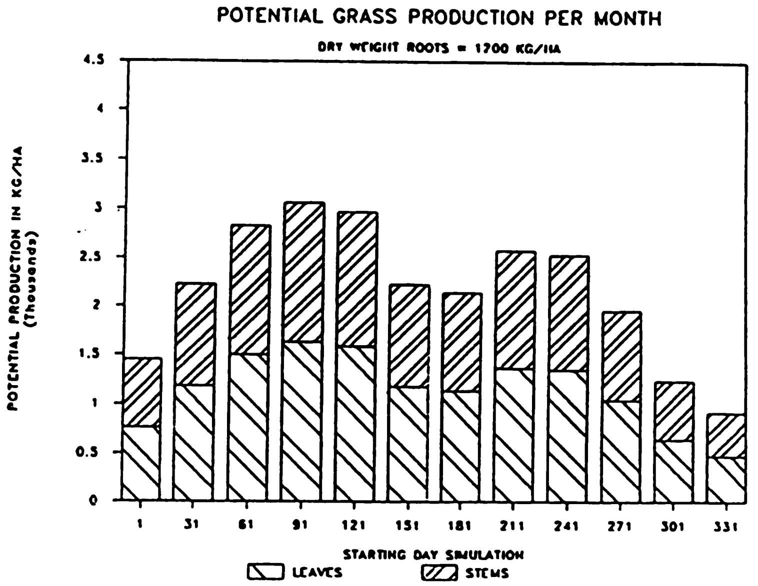


figure 14

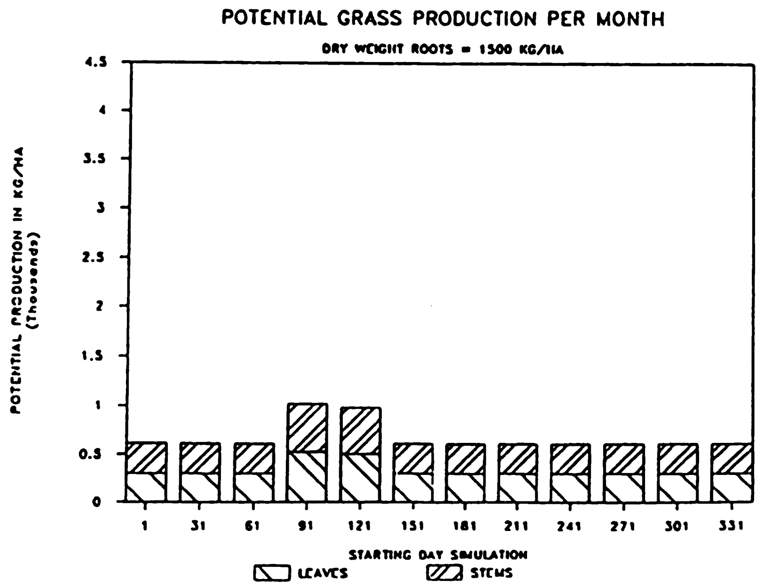


figure 16

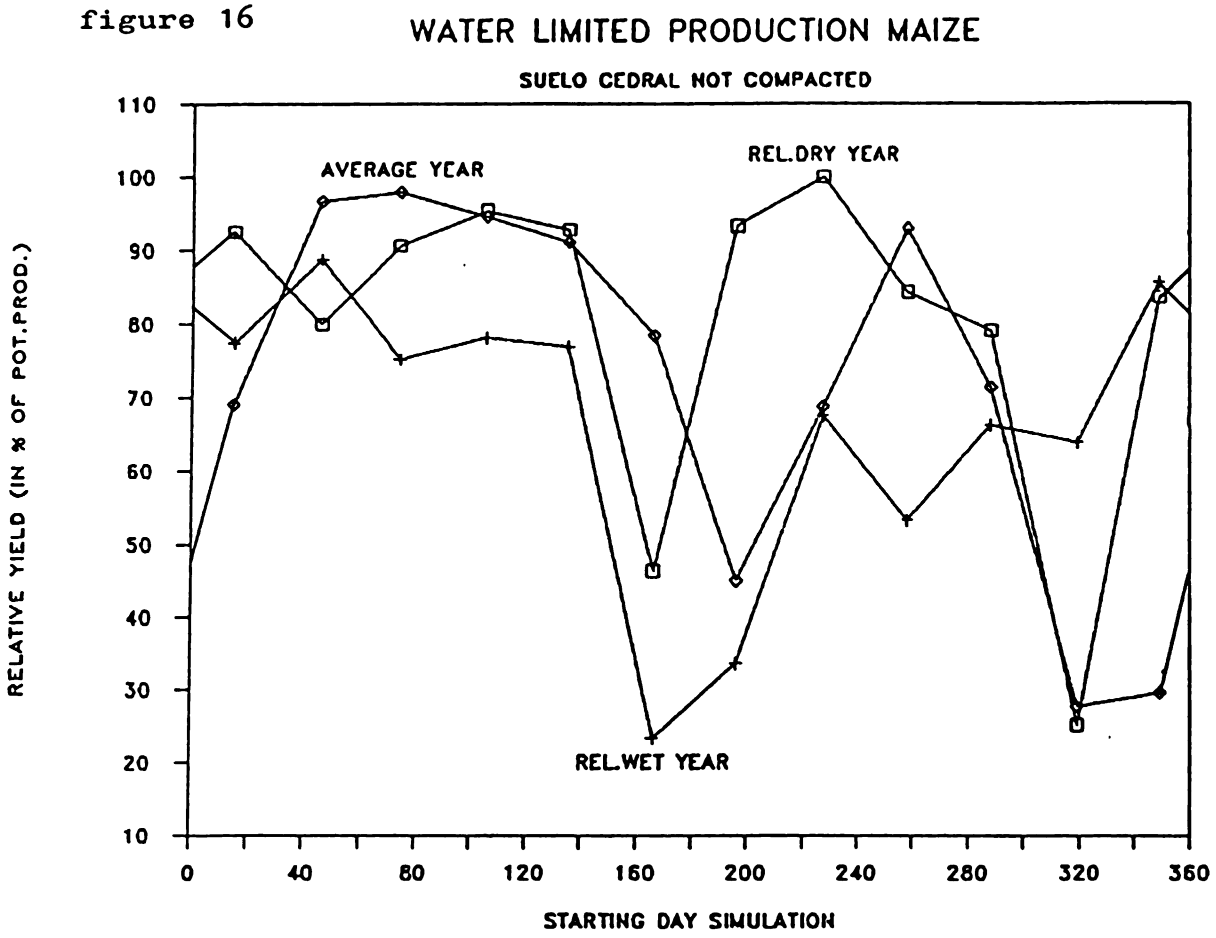
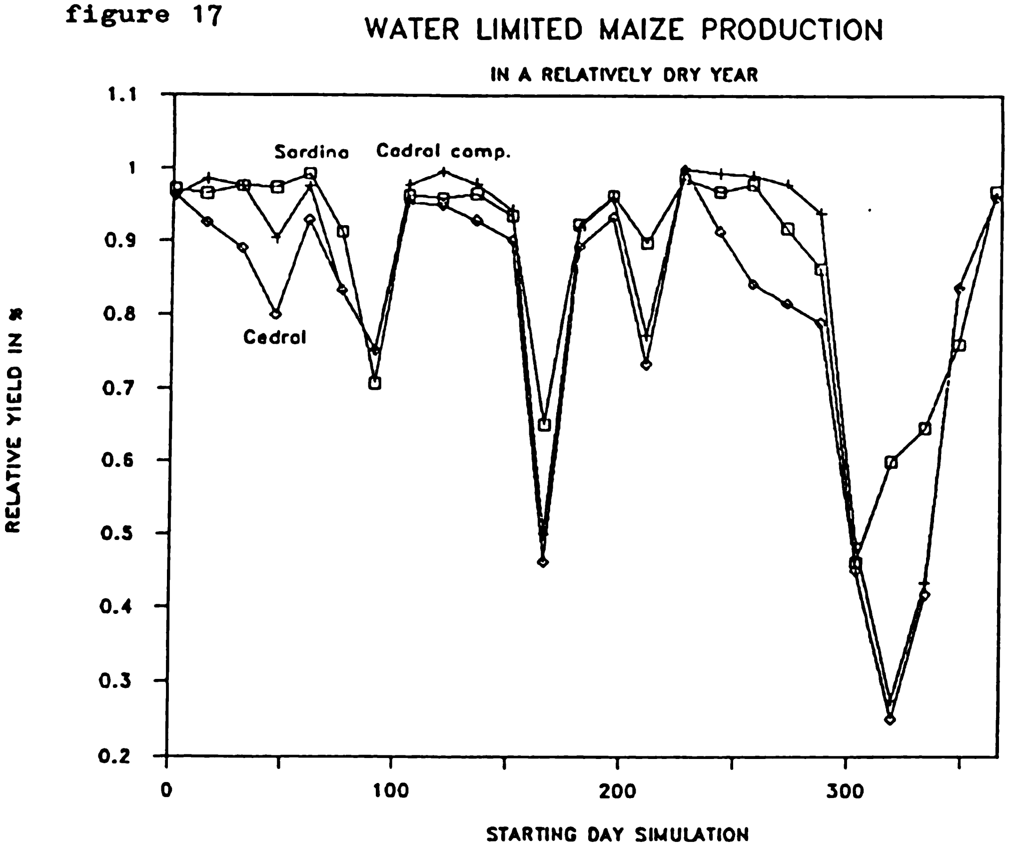
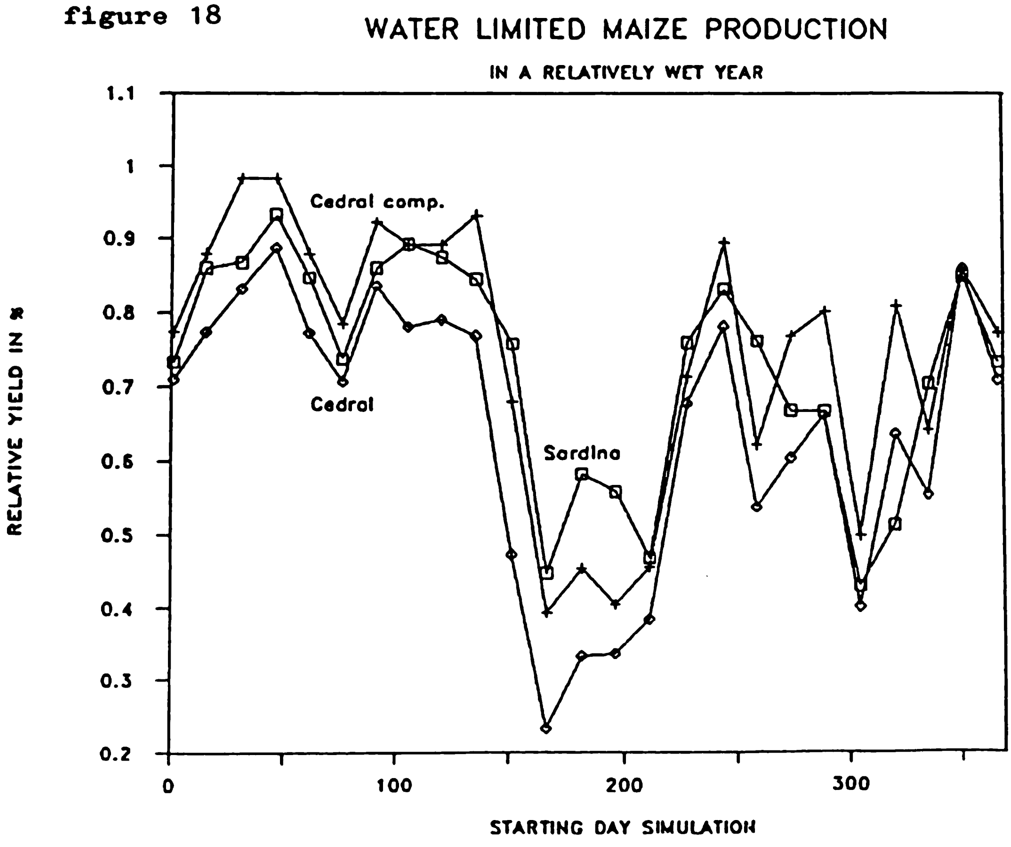

WATER LIMITED PRODUCTION MAIZE
SUELO CEDRAL NOT COMPACTED
AVERAGE YEAR
REL.DRY YEAR
REL.WET YEAR
RELATIVE YIELD (IN % OF POT.PROD.)
110
100
90
80
70
60
50
40
30
20
10
0
40
80
120
160
200
240
280
320
360
STARTING DAY SIMULATION

figure 17


WATER LIMITED MAIZE PRODUCTION

IN A RELATIVELY DRY YEAR

figure 18


WATER LIMITED MAIZE PRODUCTION

IN A RELATIVELY WET YEAR

figure 19

WATER LIMITED GRASS YIELD

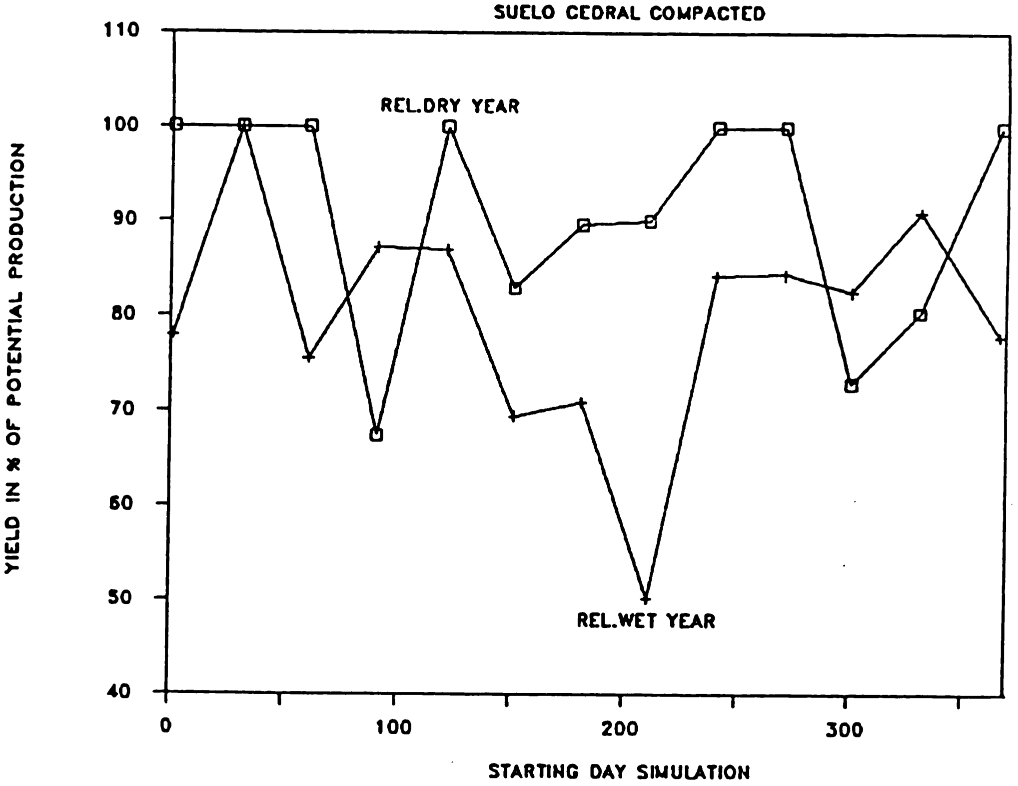


figure 20

WATER LIMITED GRASS YIELD

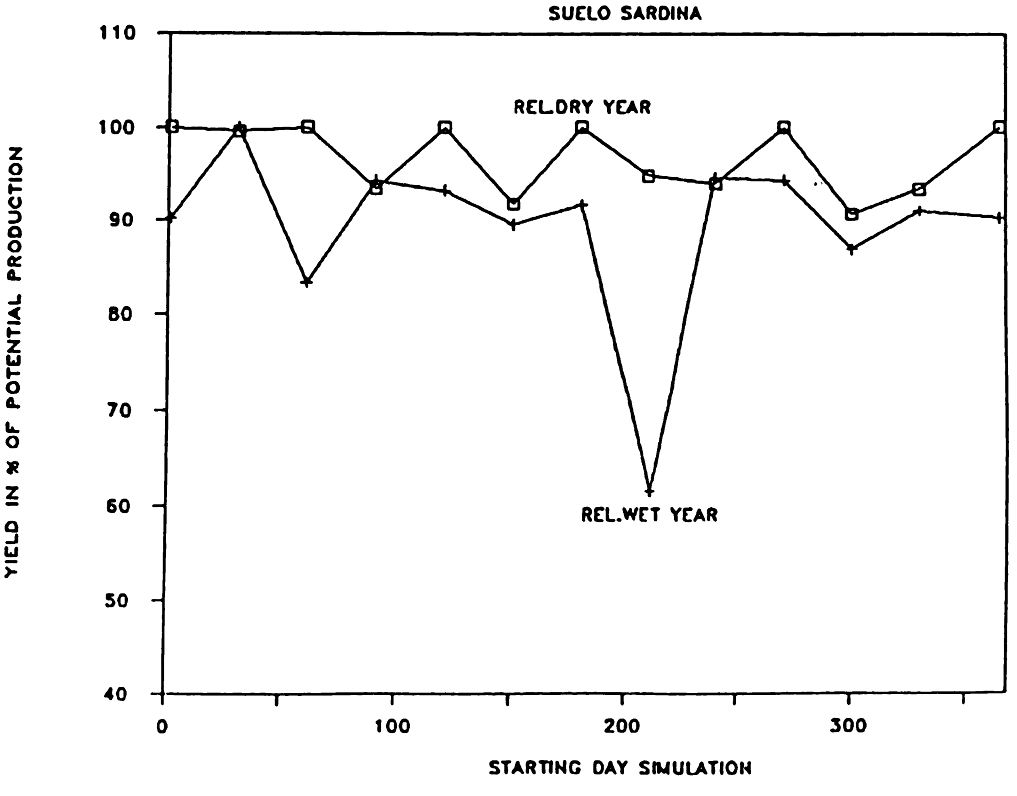


figure 21

EFFECTS OF DIFFERENT ROOTING DEPTHS

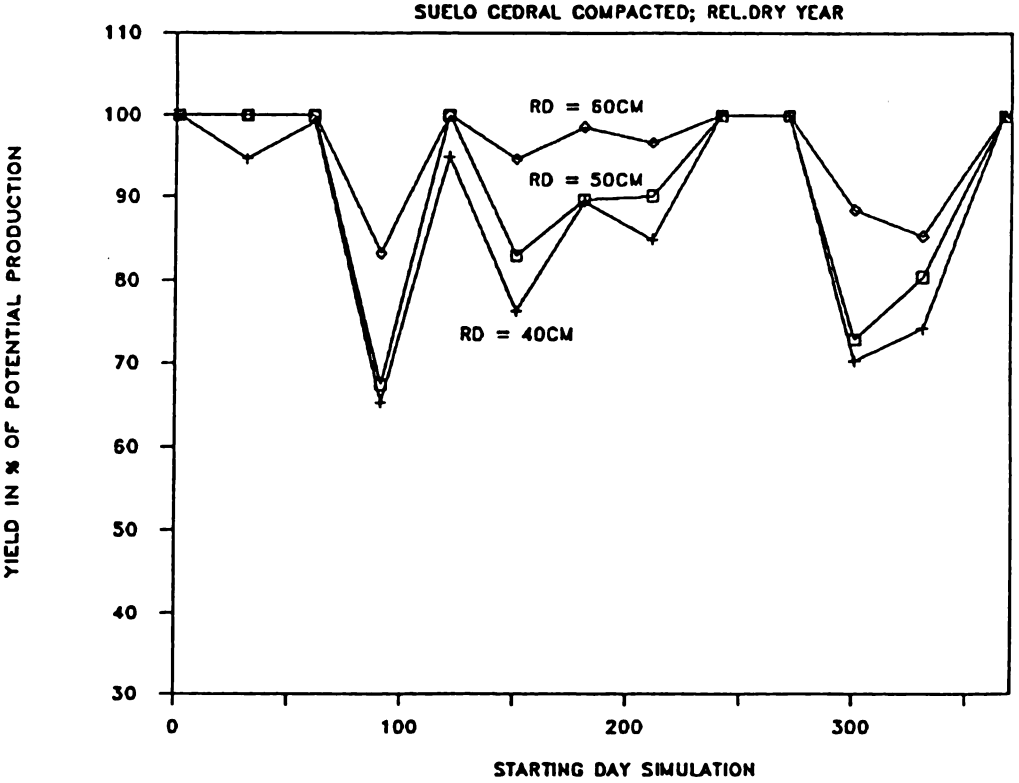


figure 22

EFFECTS OF DIFFERENT ROOTING DEPTHS

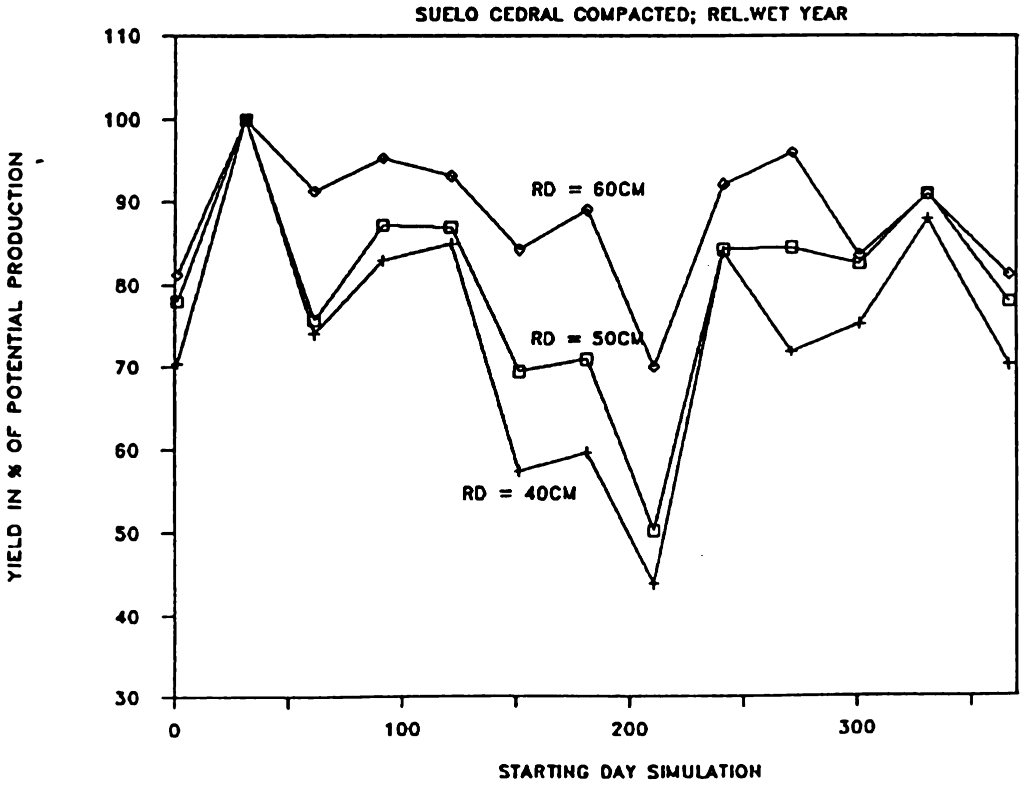
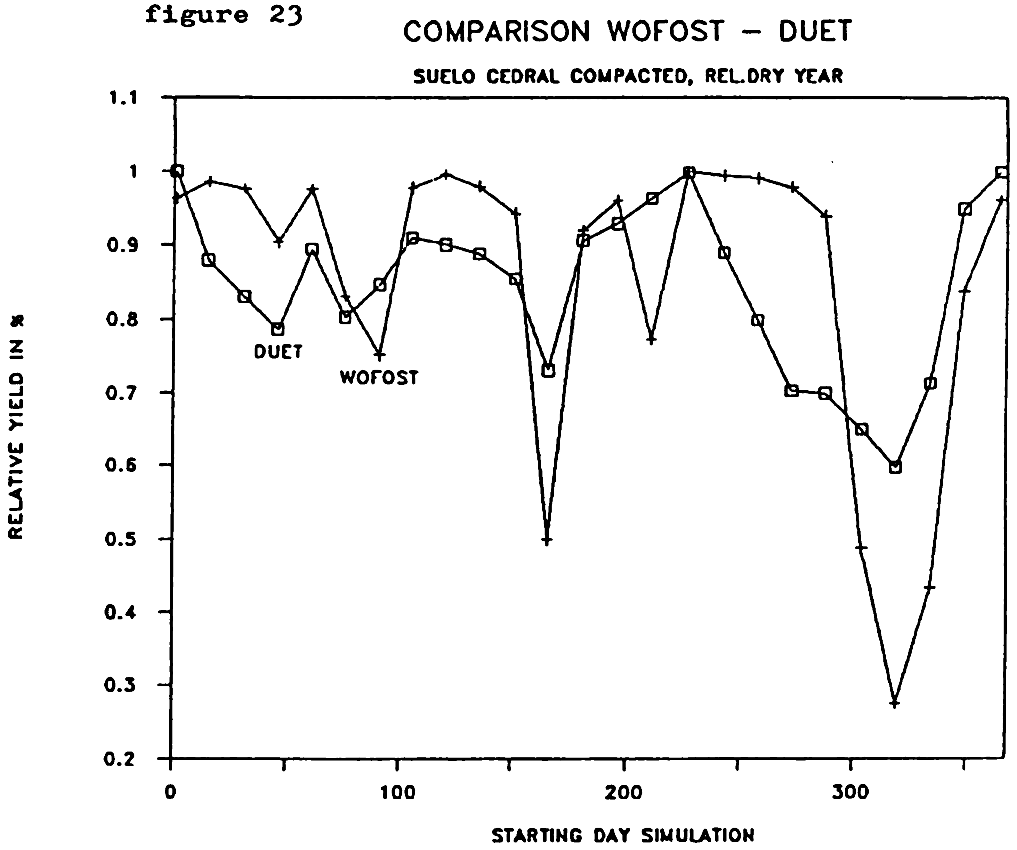
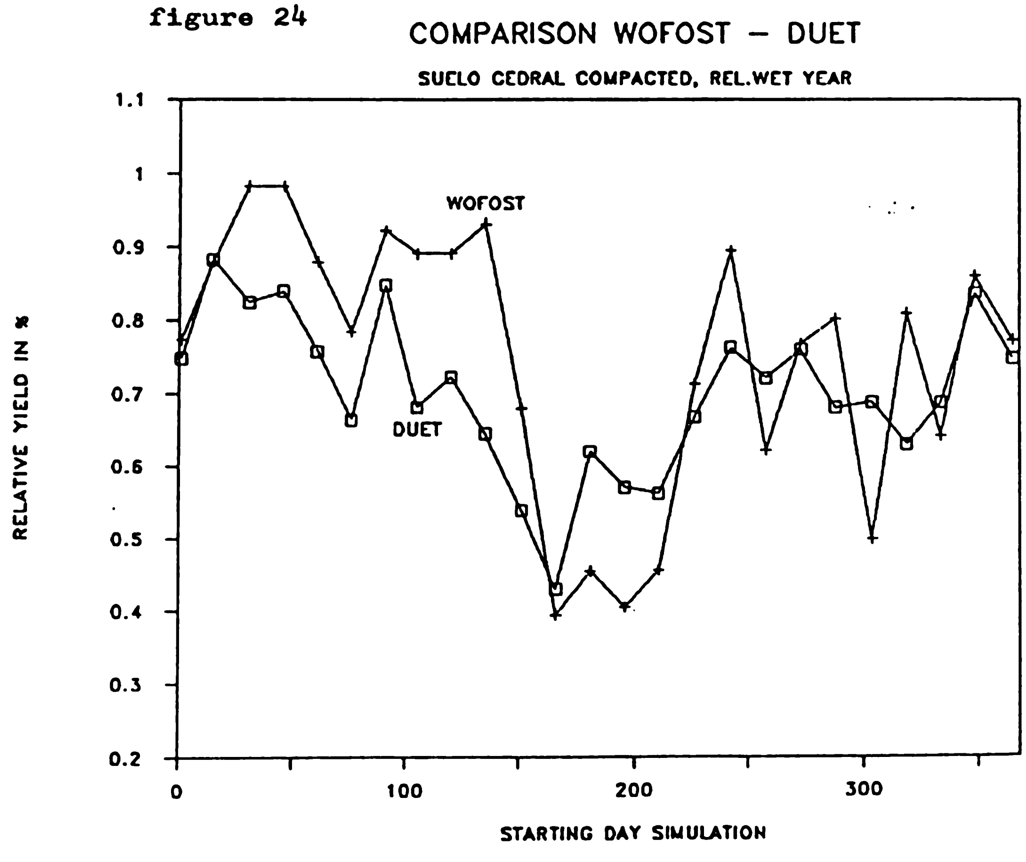


figure 23


COMPARISON WOFOST - DUET

SUELO CEDRAL COMPACTED, REL.DRY YEAR

figure 24


COMPARISON WOFOST - DUET

SUELO CEDRAL COMPACTED, REL.WET YEAR

figure 25

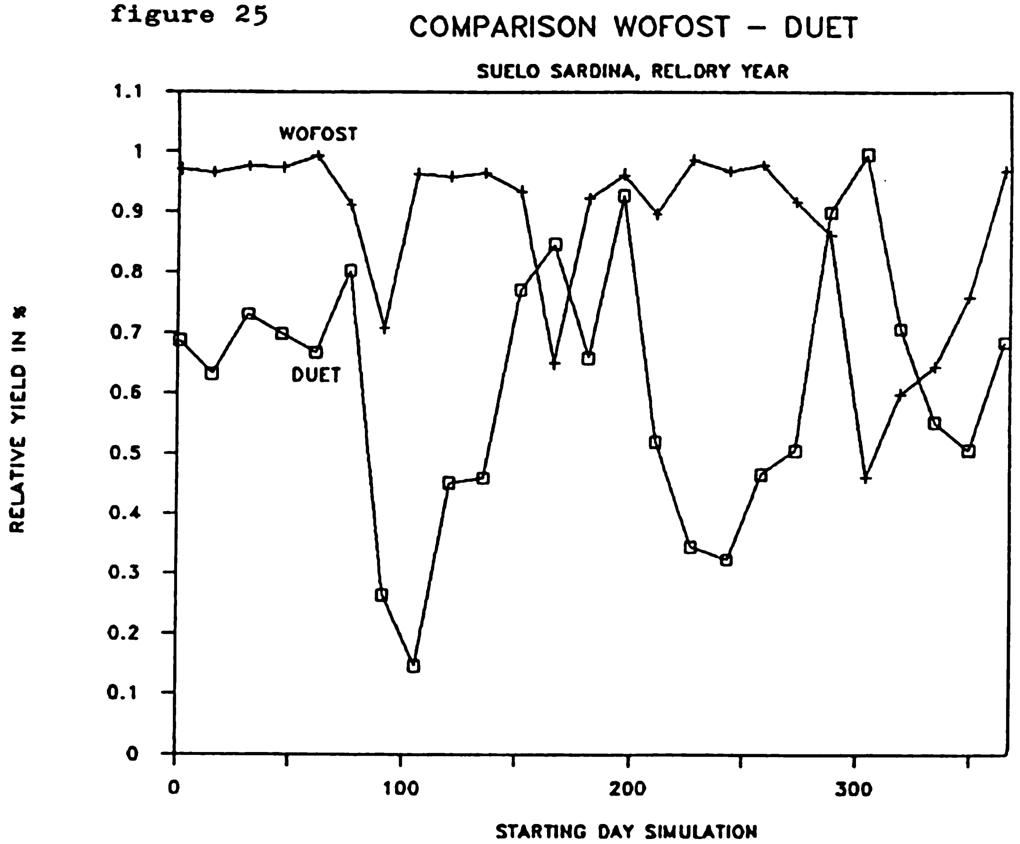


figure 26

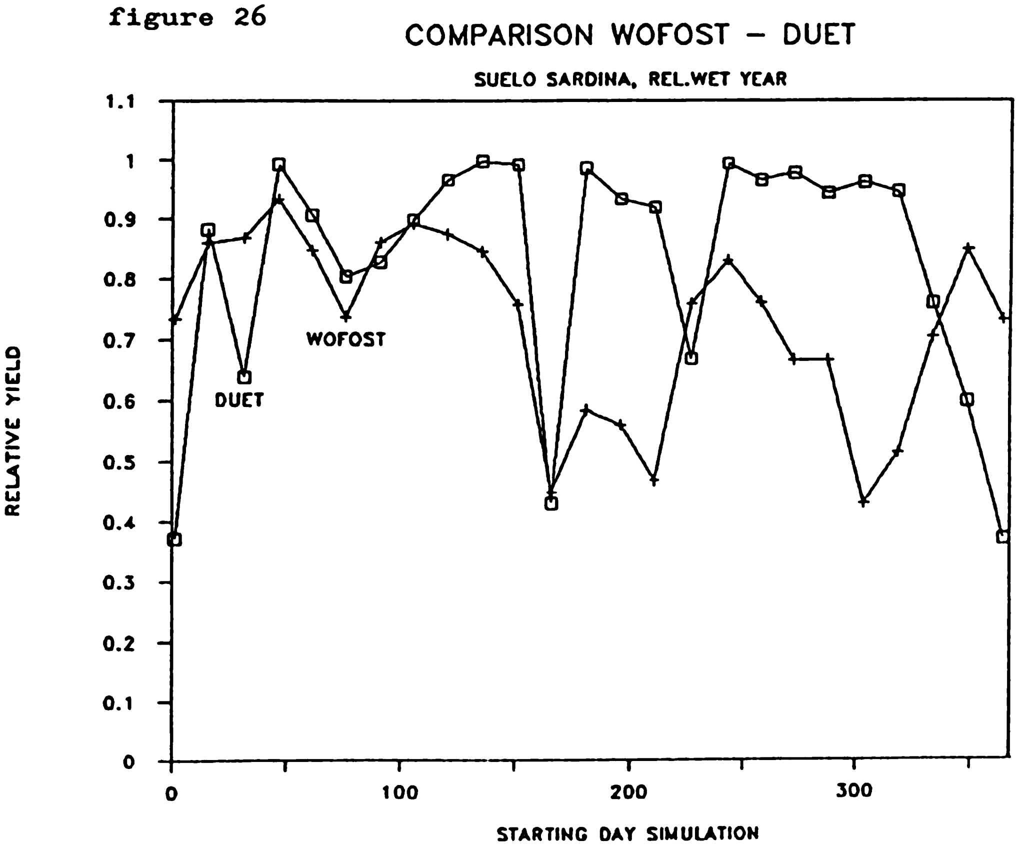


figure 27

PH RELATED POTENTIAL N AND K SUPPLY

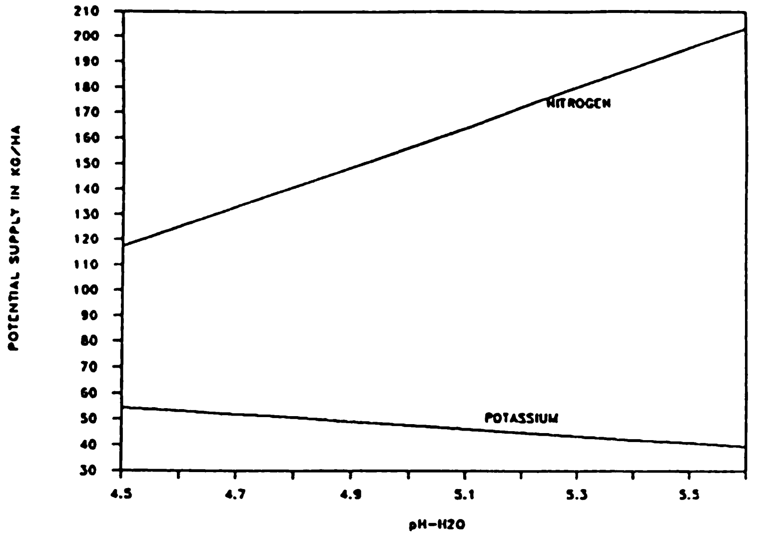


figure 28

PH RELATED POTENTIAL PHOSPHORUS SUPPLY

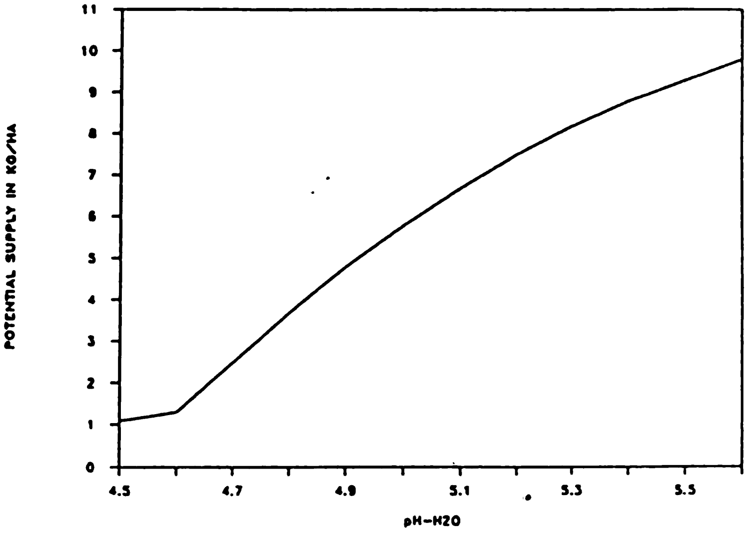


figure 29

QUEFTS: PH RELATED YIELD PREDICTION

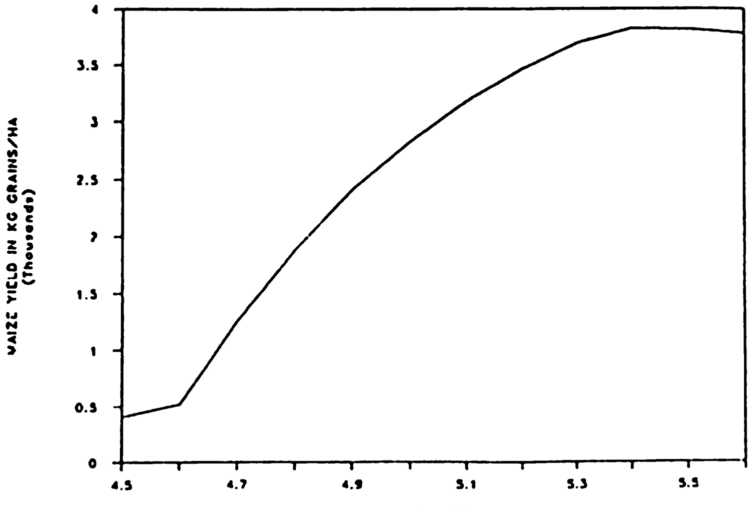
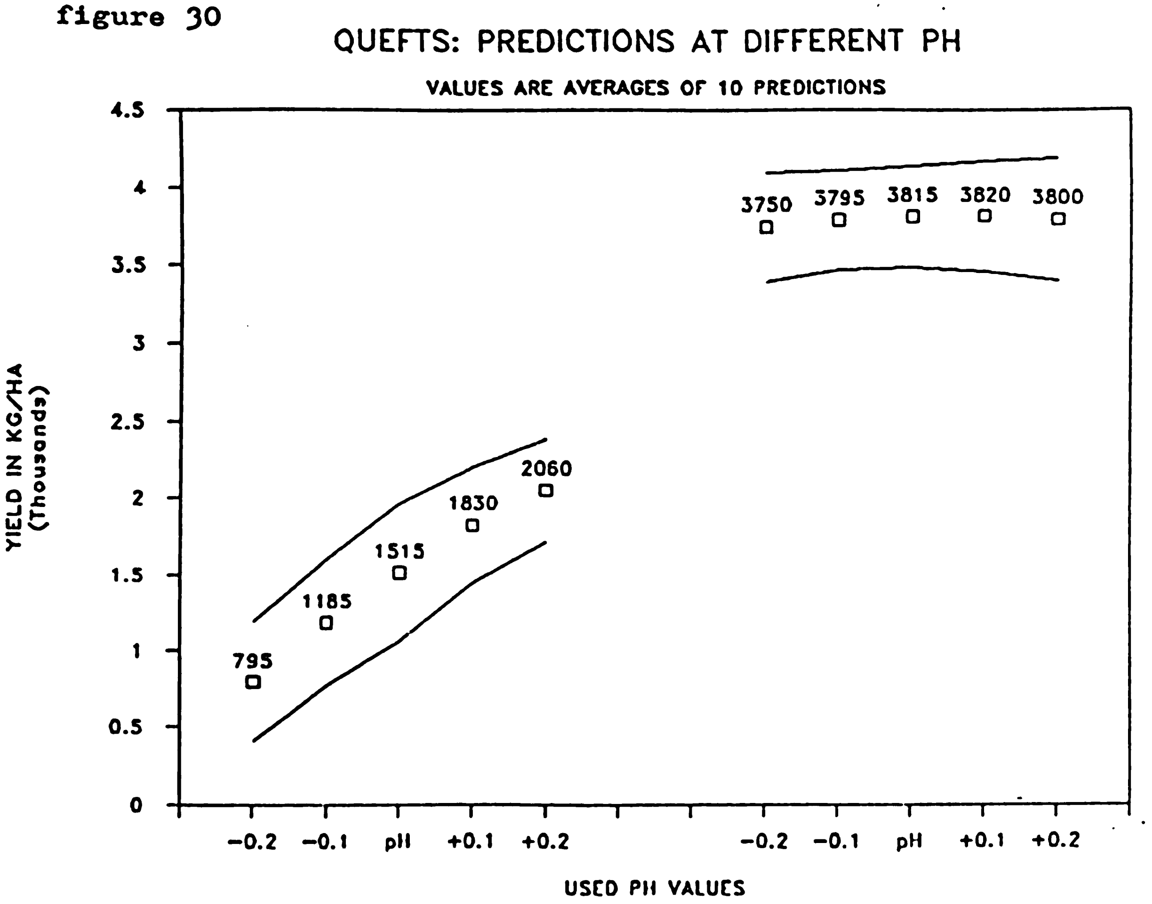


figure 30



QUEFTS: PREDICTIONS AT DIFFERENT PH

VALUES ARE AVERAGES OF 10 PREDICTIONS