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MODELLING SOIL–WATER–PLANT RELATIONSHIPS IN THE CERRADO SOILS OF BRAZIL: THE CASE OF MAIZE (*ZEA MAYS* L.)

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SUMMARY

A soil–water balance simulation model developed for the Cerrado soils of central Brazil is presented. The model calculates daily soil water evaporation, plant transpiration and soil–water balance for fourteen soil layers of 15 mm each. The model includes a subroutine to calculate capillary water movement. Computer simulations of daily soil water levels at five soil depths (15, 30, 45, 60 and 90 cm) for a field of maize are compared with actual field measurements over an 80-day period. Results indicated that the developed model can, in general, estimate the soil–water balance of the various depths within ±10% of actual measurements.

INTRODUCTION

The Cerrado of Brazil, occupying an area of approximately 1·5 million square kilometres, has long been considered a region of great agricultural potential by Brazilian planners. Until recently (the last 15–20 years), the limiting factor in its agricultural development was considered to be the lack of infrastructures such as roads and other means of communication. With the construction of the new federal capital of Brasilia in the centre of the Cerrado region, significant improvements have occurred in the basic infrastructure. As a result of this and other factors, the land use pattern is changing from one dominated by livestock grazing to greater field crop production.

One of the constraints to expanding field crop production in Cerrado soils is their high aluminium content. Among other things, the high levels of aluminium in the Cerrado soils cause plant root growth of many crops to be severely restricted. As a

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result of this restricted root growth, the plant is more subject to water stress which leads to reduced crop yields. This problem of water stress resulting from shallow root penetration is compounded by the relatively low water holding capacity of the Cerrado soils (40–45 mm of water per 50 cm of soil) and the occurrence of drought periods of 10–30 days during the growing period. To overcome this problem, several strategies are under consideration, such as supplemental irrigation, optimal dates of plantings, deep liming and earlier maturing varieties.

To evaluate fully the various alternatives for any crop requires significant knowledge of the complex soil–water–plant interactions that occur. In order to attempt to understand more fully the nature of the interactions occurring in the case of maize, the decision was made to utilise present research knowledge to develop a soil–water balance model for maize in the Cerrado soil. If the performance of the resulting model was judged satisfactory, it could then be used to assist in evaluating the alternative possibilities, as well as a tool to identify further research priorities. The emphasis in this paper is on model development and validation.

The development of crop–water use simulation models is a fairly recent phenomenon. However, there exists today a large number of crop and soil–water balance models varying widely in sophistication and use. Some models have been developed primarily to estimate water consumption (considered as soil water evaporation + plant transpiration) for use in scheduling crop irrigation. Other models, such as those developed by Ritchie (1972), Hill *et al.* (1974) and Flinn (1971), among others, can be used for irrigation scheduling but are also used to estimate plant yield by relating water stress at various growth stages in the plant's life cycle to dry matter or grain yield. Models such as the one developed by Arkin *et al.* (1976) attempt to estimate daily plant growth and calculate yield directly as a result of that growth. The model presented in this paper is basically a variation of the Ritchie–Hill–Flinn type.

MODEL SPECIFICATION AND DEVELOPMENT

The basic equation

The basic equation calculates the daily soil–water balance (SWB) for each of fifteen soil layers. Knowledge of the soil–water balance in individual layers was considered important due to the need to study root development restrictions in the soil caused by high levels of aluminium. The first fourteen layers have a depth of 75 mm each, reaching a depth of 1·05 m, while the fifteenth layer represents the remainder of the soil profile. (Maize roots generally do not penetrate to a depth of more than 450 mm in the Cerrado soils.)

The basic equation used to estimate the daily soil–water balance was the following:

$$SWB(i, t+1) = SWB(i, t) - AET(i, t) + EW(i, t) + DR(i, t) \qquad (1)$$

where:

$SWB(i, t+1)$ = the amount of water in layer i at the beginning of day $t+1$
$SWB(i, t)$ = the amount of water in layer i at the beginning of day t
$AET(i, t)$ = the amount of evapotranspiration from layer i during day t
$EW(i, t)$ = water from rainfall or irrigation entering layer i during day t
$DR(i, t)$ = net redistribution (gain or loss) of layer i during day t

The components AET, EW and DR are discussed individually in the following sections. All of the terms of the equation are expressed in millimetres of water. The values of $SWB(i, t)$ are limited to certain maximum and minimum values in each layer, as determined by water retention curves estimated by Wolfe (1975) and corresponding to field capacity and the permanent wilting point.

Evapotranspiration

The model divides evapotranspiration into its component parts—evaporation, which only occurs in the first soil layer, and transpiration, calculated only for those layers which have roots. Emergence is assumed to take 6 days, so the transpiration component of the model becomes operative 6 days after planting.

For ease of calculating evaporation and transpiration components, it is assumed that the seed is planted at a depth of 75 mm and that there are never roots in the first soil layer.

The determination of actual evapotranspiration within the model requires an estimate of potential evapotranspiration. In general, the potential evapotranspiration of a crop is a function of both climatic conditions and stage of plant development. The higher the temperature, solar radiation, and wind (among other climatic factors), the higher the potential evapotranspiration for a crop at a given stage of phenological development.

To express the relationship between potential evapotranspiration, climatic conditions and stage of plant development, the following equation, suggested by Penman (1948), was used:

$$PET = aE_0 \qquad (2)$$

where:

a = an empirical coefficient that depends upon the crop and stage of plant development
E_0 = daily Class A pan evaporation

The coefficient a has been estimated for various crops in different places. Table 1 presents the values of the coefficient a used in the model. For days intermediate between those given, the coefficient is estimated by linear interpolation.

The values in Table 1 were derived from data presented by Wolfe (1975) for maize planted in the Cerrado during the rainy season of 1974/75. Wolfe's data referred only to the period 40–110 days after planting; but since his estimates were similar to

TABLE 1
VALUES OF COEFFICIENT *a* FOR MAIZE

Days after planting	*Value of* a
1	0·37
6	0·37
15	0·40
30	0·50
45	0·68
60	0·80
75	0·80
90	0·75
105	0·62
120	0·37
150	0·37

those of Fritscher & Shaw (1961) for Ames, Iowa, USA, the information from the latter study was used to complete the Table.

Given the estimation of potential evapotranspiration (*PET*), the next step in the model is to divide the potential evapotranspiration estimate into an estimate of potential evaporation (*PE*) and an estimate of potential transpiration (*PT*). The division of *PET* into its two components was based upon the relationship between the net radiation reaching the soil surface and above the crop canopy. Chang (1968) states that when the soil is wet and advected energy negligible:

$$\frac{\text{Net solar radiation at the soil surface}}{\text{Net solar radiation above the crop canopy}} = \frac{\text{Soil evaporation}}{\text{Potential evapotranspiration}}$$

Hence, with knowledge of the ratio of solar radiation at the soil surface to that above the canopy, it would be possible to estimate the ratio of soil evaporation to potential evapotranspiration. Unfortunately, there were no estimates in Brazil of the ratio of solar radiation at the soil surface to that above the canopy. Ritchie (1972), however, presents evidence of a relationship between fractional net radiation at the soil surface and the leaf area index (*LAI*), and this allowed an indirect estimation of the components of evapotranspiration at different stages of crop development from data on *LAI*, as illustrated in Fig. 1.

The division of potential evapotranspiration into its two components is effected in the model as follows:

$$PE(M) = R(M)\,.\,PET \tag{3}$$

$$PT(M) = [1 - R(M)]\,.\,PET \tag{4}$$

where:

$PE(M)$ = Potential evaporation on the *M*th day after planting.
$R(M)$ = The ratio of potential soil evaporation to potential evapotranspiration on the *M*th day after planting.
PET = Potential evapotranspiration.
$PT(M)$ = Potential transpiration on the *M*th day after planting.

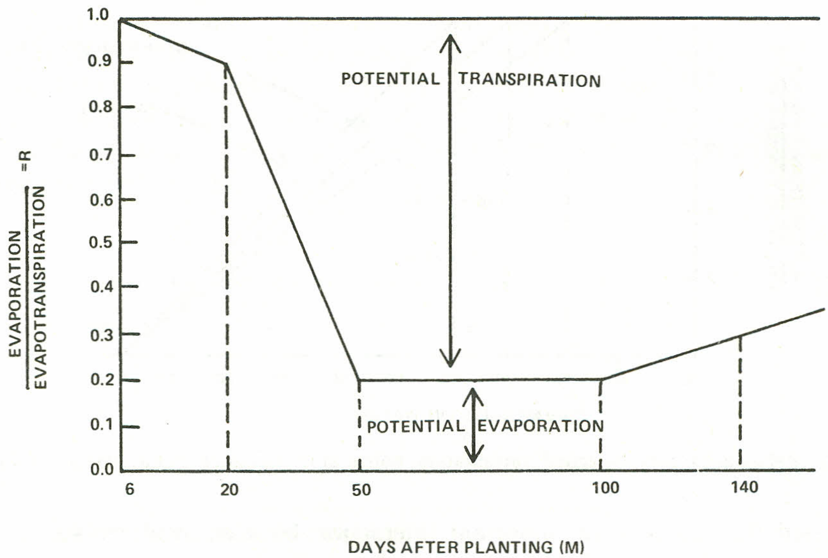

Fig. 1. Assumed allocation of potential evapotranspiration between potential evaporation and potential transpiration.

Values of R for values of M are presented in Fig. 1. It should be noted that this relationship is for a given pattern of LAI development during the life of the crop. If the pattern of LAI development changes, so does the relationship.

Soil evaporation

Actual soil evaporation (AE) was first estimated by the following formulae:

$$AE = PET \qquad \text{up to 6 days after planting}$$

$$AE = PE(M) \qquad \text{for } M > 6 \tag{5}$$

If, on any given day, AE is greater than the amount of water available in the first layer, then this last quantity is taken as the true value of AE.

Transpiration

The definition of actual transpiration by the plant depends on two factors: (1) potential transpiration and (2) the water supply function to the plant, which depends upon the water content of the soil and the volume of soil being exploited by the crop root system. If the amount of water available in that exploited volume of soil is less than the plant demand, actual transpiration will diverge from its potential.

This expression of divergence between actual and potential transpiration in the model was drawn from the results of Denmead & Shaw (1962). Their research with maize in Iowa, USA, suggested that actual transpiration diverged from potential transpiration long before 15 bars of pressure under certain conditions. Their results

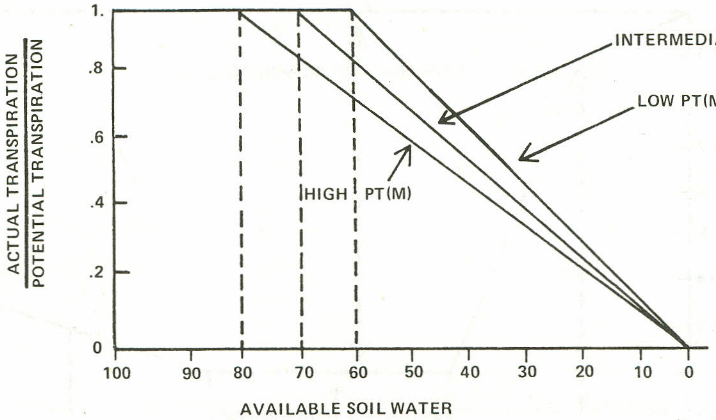

Fig. 2. Relationship between actual transpiration, potential transpiration and available soil water.

suggested that there is an important interaction between available soil water, potential transpiration and atmospheric conditions that must be taken into account to determine actual transpiration. The curves in Fig. 2 are adapted from their results and are taken to represent the relationship between actual and potential transpiration as influenced by climatic conditions (as shown by the various rates of potential transpiration) and water available in the soil.

Equation (6) describes the relationship depicted in Fig. 2:

$$IAT(M) = bPT(M) \tag{6}$$

where b is a number between 0 and 1 and is a function of the level of $PT(M)$ and the water available in the soil.

The three curves refer to the following levels of potential transpiration for a given day:

1. Low: $PT(M) < 4{\cdot}1$ mm/day
2. Intermediate: $4{\cdot}1 \leq PT(M) \leq 6{\cdot}4$ mm/day
3. High: $PT(M) > 6{\cdot}4$ mm/day

Equation (6) provides a preliminary value for actual transpiration. Whether actual transpiration will reach that value depends upon the available soil moisture in all layers with root penetration.

A basic assumption of the model is that the water uptake in each layer should be proportional to the root density. As the value of IAT is divided among the various layers, there is the possibility that there will not be enough water in some layers to satisfy the water uptake calculated to come from them. In this case, the deficit from that layer will be reallocated to the other layers with roots in order to approach the value $IAT(M)$.

The pattern of root distribution with time is based on research results of Espinoza (unpublished) at the Cerrado Research Center and is presented in Table 2. The red latosol soil has a high level of exchangeable aluminium, and maize roots rarely penetrate below 450 mm. Past 80 days, root growth was assumed to cease. For days intermediate between those in the Table, linear interpolation is used to find the root penetration and density.

TABLE 2

ROOT DEPTH AND DENSITY (%) BY SOIL LAYER AND DAYS AFTER PLANTING

Soil layer	*Days after planting*					
	5	*20*	*40*	*50*	*60*	*80*
2	100	75	60	45	30	10
3	—	25	30	30	30	15
4	—	—	10	15	15	25
5	—	—	—	10	15	30
6	—	—	—	—	10	20

Source: Information of the authors.

Exogenous water

The model component designated $EW(i, t)$ represents the quantity of water entering layer i on day t as a result of rainfall or irrigation.

The model does not take into account the duration of intensity of the water input. This implies that the water application is instantaneous, and it is also assumed that no surface runoff occurs. The infiltration process from the surface to succeeding layers is as follows: the first layer retains all of the water it receives until it reaches field capacity; if there is any remaining, it infiltrates to the second layer and the process is repeated. Finally, after saturating the first fourteen layers, any excess is assumed lost to the system as drainage.

Redistribution of water within the profile

The basic equation for the study of redistribution corresponding to the model component $DR(i, t)$ is Darcy's formula:

$$DR(i, t) = K(H) \cdot \frac{T(i, t) - T(i+1, t)}{75} \qquad (7)$$

where:

$T(i, t)$ = soil moisture tension (mm of water) of soil layer i

75 = the distance between the centres of the two layers

$K(H)$ = the capillary conductivity (in millimetres of water per day)

H = the average of the moisture levels (% volume) of soil layers (i) and $(i + 1)$

TABLE 3
ESTIMATED VALUE OF THE CONSTANTS USED TO CALCULATE CAPILLARITY CONDUCTIVITY

Depth (mm)	*A*	*B*	R^2
0–225	−64·117	18·93	0·90
225–450	−42·963	13·126	0·77
450–750	−24·593	7·812	0·62
750–1050	−49·931	15·464	0·86

Source: Wolfe (1975).

The term $K(H)$ is calculated by the following formula:

$$K(H) = e^{A} H^{B} \tag{8}$$

where H is as defined above and A and B are constants estimated by Wolfe in 1975 at the Cerrado Research Center (Table 3).

To calculate the values of the tension (T) in the different layers the following formula was used:

$$T = (H/\mathrm{K})^{1/\mathrm{C}} \tag{9}$$

where:

T = soil water tension in a particular zone
H = soil water content of the zone
K = a constant
C = a constant

The values of the constants K and C were estimated by Wolfe using the formula $H = \mathrm{K}T^{\mathrm{C}}$ and are shown in Table 4. In the estimating formula T is in centimetres of water, but for the model the value obtained must be multiplied by 10 to get millimetres of water.

As can be seen, $DR(i, t)$ estimates the daily water movement between two adjacent layers. If $DR(i, t)$ is positive the water rises, if $DR(i, t)$ is negative, it descends.

In the first versions of the model, the drainage $DR(i, t)$ was calculated based on only one pass, moving from layers 14–15 up to layers 1–2. This calculated *DR*

TABLE 4
CONSTANTS TO CALCULATE SOIL WATER TENSION AS A FUNCTION OF MOISTURE AVAILABILITY

Depth	*Tension range ($cm\ H_2O$)*	*K*	*C*	R^2
0–450	0–500	64·5733	−0·1716	0·892
0–450	500–15000	37·1185	−0·0753	0·987
450–1050	0–500	56·7986	−0·1626	0·729
450–1050	500–15000	31·2057	−0·0581	0·991

Source: Wolfe (1975).

between layers 14–15. Making the transfer of water indicated by the value of *DR*, one now had a new water level in layer 14 (layer 15 was no longer used for that day). The process was then repeated to calculate *DR* between layers 13 and 14, with the procedure repeated until the estimate was made for layers 1 and 2. This procedure, however, produced large differences in the water content of successive layers. To overcome this problem, the following procedure was adopted:

(1) Divide *DR* by 24, thus estimating the drainage on an hourly basis.
(2) Make 24 passes as described above to approximate the drainage for a 24-h period.

As a result of the above smoothing procedure, the behaviour of the model improved substantially, producing estimates of redistribution between layers that were less extreme in layers 1–14 (for layer 15 the water content was always assumed to be at −15 bars of tension at the beginning of each of the 24 interactions).

MODEL VALIDATION

A computer program was written for the above model in the FORTRAN IV language, and then a first validation study was made. Following the suggestions of Meier *et al.* (1969) (pp. 294–5), validation was interpreted as a two-stage process. For the first stage, logical and programming consistency was studied through a series of planned experimental runs. In that phase several sensitivity analyses were carried out. The model did not show excessive sensitivity to any one parameter.

The second stage of the validation process is the comparison of simulation results with data collected in the field. Espinoza (unpublished) conducted an experiment to examine the response of three maize varieties, planted at four population levels, to water stress at the Cerrado Research Center near Brasilia. Soil moisture measurements were made at 15, 30, 45, 60 and 90 cm depths using tensiometers in the plots which receive supplemental irrigation. The tensiometer data from the plots with 60,000 plants/ha were used in the validation process. It would have been desirable to compare the simulated results with the non-irrigated plot results, but this was not possible. Tensiometers only function at soil moisture tensions between −0·1 and −1·0 bars. The non-irrigated plots were usually outside of that range and thus data were not available.

The simulation period began on the 8th of September, 1976, with the first rain ending the dry season. The model begins with the assumption that the beginning soil moisture tension is at −15 bars. Planting took place on the 19th of November, 1976, and harvest on the 31st of March, 1977.

A comparison of model to actual results began 35 days after planting, ending at maturity, 116 days after planting. The results are shown in Figs. 3 and 4. The following points can be noted.

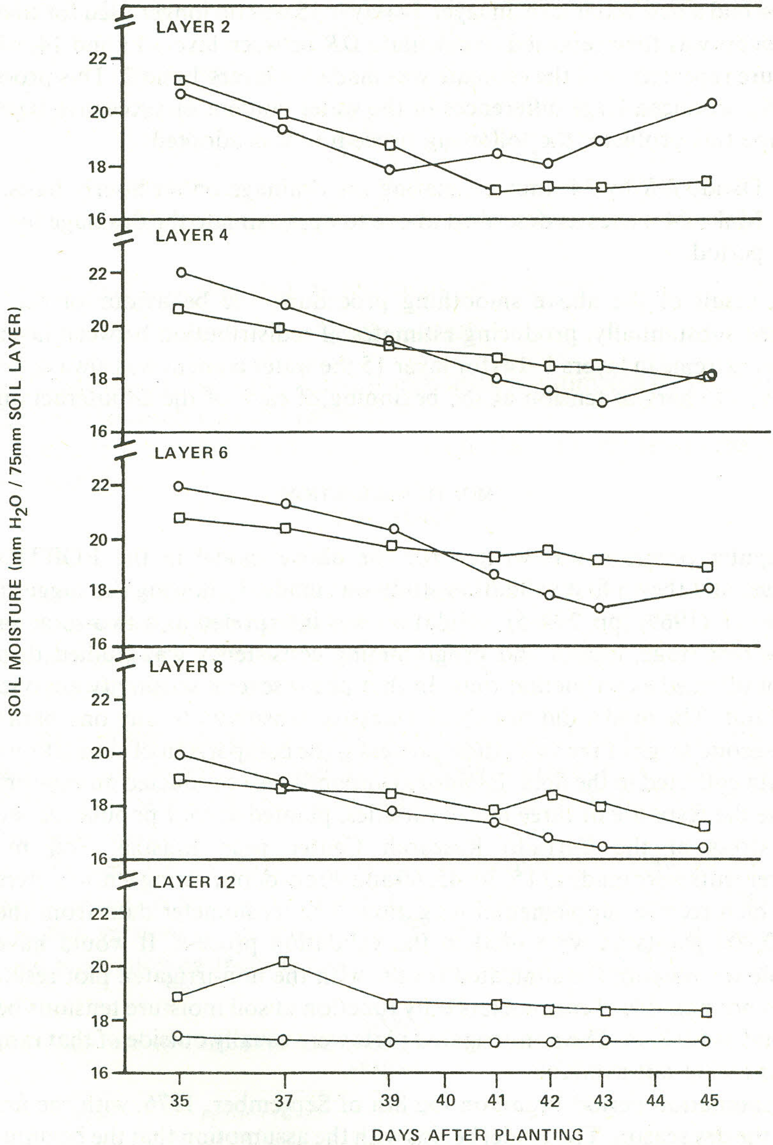

Fig. 3. Measured (□) and simulated (○) daily soil moisture levels for five soil layers from 35 to 45 days after planting.

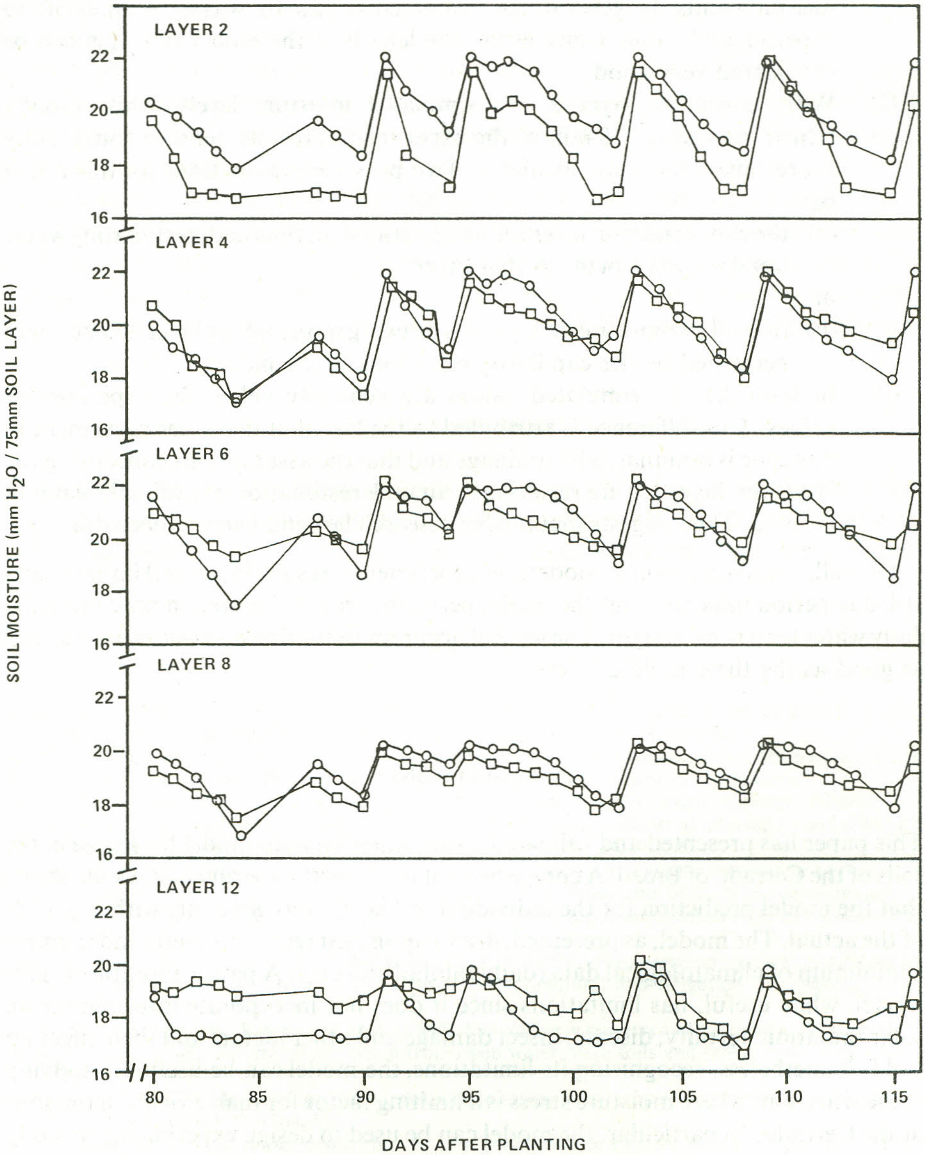

Fig. 4. Measured (□) and simulated (○) daily soil moisture levels for five soil layers from 80 to 116 days after planting.

(1) The model results for layers 4, 6 and 8 are exceptionally close to the actual measurements. In general, the simulated values are within ± 1 mm of the experimental value. Considering the length of the model run, this can be considered very good.

(2) With respect to layer 2, the simulated moisture levels, while usually remaining within 1–2 mm of the experimental results, tend to consistently overestimate the water available. Two possible explanations for this might be:

   (a) the root density in layer 2 is underestimated, thus underestimating water uptake by the plant in that layer

   or:

   (b) the soil evaporation in layer 1 is drawing moisture for layer 2 faster than permitted by the capillarity equations in the model.

(3) In layer 12, the simulated values are generally below the experimental values. This difference is attributed to the fact that the water movement in this zone is dominated by drainage and that the assumptions concerning the last layer (layer 15) are resulting in an underestimation of available water in layer 12. This suggests that further research be conducted on deep drainage.

Overall, the comparison of model and experimental results in five soil layers over a 101-day period indicates that the model performs reasonably well in predicting the daily water level in each layer. The level of accuracy in the first and last zones was not as good as the three middle layers.

CONCLUSIONS

This paper has presented and validated a soil–water balance model for maize in the soils of the Cerrado of Brazil. A comparison of model with experimental results shows that the model prediction for the individual soil layers was generally within $\pm 10\%$ of the actual. The model, as presented, draws upon past research results and requires a minimum of climatological data (daily rainfall and class A pan evaporation). This model, while useful, has limitations since it does not incorporate information on solar radiation, fertility, disease, insect damage and other factors and their effect on yield. Nonetheless, recognising its limitations, the model can be useful in studying those situations where moisture stress is a limiting factor for maize yields in the soils of the Cerrado. In particular, the model can be used to design experiments to study the relationship between moisture stress and plant yield. As is well known, in the case of maize, the relationship between moisture stress and yield reduction is complicated by such factors as the intensity and timing of stress. In order to attempt to statistically estimate a yield equation relating yield to level of stress, one must design an experiment that provides for a sufficient level and intensity of stress at various phenological growth stages. As it is possible in Brazil to undertake dry season irrigated experiments, the present model can be used to simulate alternative irrigation applications to give the desired stress patterns.

With greater knowledge of the relationship between corn yield and water availability, it would be possible to use the present model (or one similar) to simulate the moisture-related effects of soil management alternatives, differing planting dates and alternative moisture levels.

The present model, however, does not represent an end—but rather a beginning—of crop modelling in Brazil. Already, variations of the present model are being considered that will permit the analysis of alternative aspects of crop growth. Also, research is under way to develop similar models for alternative crops such as rice, wheat and soybeans, even as work continues on modelling of maize in the Cerrado.

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