\142

*Soil Water Balance in the Sudano-Sahelian Zone* (Proceedings of the Niamey Workshop, February 1991). IAHS Publ. no. 199, 1991.

# An evaluation of the SWATRER and CERES-Millet models for southwest Niger

J. FECHTER, B. E. ALLISON
*Institute for Crop Production in the Tropics and Subtropics, Hohenheim University, 7000 Stuttgart 70, Germany*

M. V. K. SIVAKUMAR
*ICRISAT Sahelian Center, BP 12404, Niamey, Niger*

R. R. VAN DER PLOEG & J. BLEY
*Institute of Soil Science, Hohenheim University, 7000 Stuttgart 70, Germany*

**Abstract** The SWATRER (Dierckx *et al.*, 1986) soil water and CERES-Millet (Godwin *et al.*, 1984; Jones *et al.* 1984) growth models were evaluated for millet (*Pennisetum americanum*) during the 1989 growing season at Tara, Niger (300 km, south of Niamey). The required minimum data sets for the plant and soil components of each model were either field determined or obtained from the literature. A field experiment was carried out in order to validate the soil water balance and plant growth subroutines. Soil water content, leaf area and dry matter (DM) were measured weekly. Good agreement between simulated and measured soil water content was obtained with SWATRER. The CERES-Millet model overestimated leaf area index (LAI), DM and yield by 46%, 40% and 101% respectively. The CERES-Millet model consistently overestimated soil water content by 5% throughout the growing season. The SWATRER model showed good promise for evaluating water/fertilizer management strategies. Once the CERES-Millet model is calibrated, it can be utilized to evaluate new production zones, new cultivars and numerous cultural practices.

## INTRODUCTION

The drylands are a collection of ecosystems that are an interaction of physical and biological processes coupled to social, political and institutional factors. They can be managed and modified within limits; and are able to support a sustainable yield without a system breakdown. As attention is focussed towards the drylands, specifically the Sahelian zone, it is evident that the ecosystems are not in a state of dynamic equilibrium. An overall decline in agricultural and pastoral output, not only for the Sahelian zone but also for the drylands in general, has occurred.

Stabilizing and improving agricultural production in the Sahel are possible if the interrelationships between environmental resources (especially water) and plant growth can be more thoroughly quantified. Dancette & Hall

(1979) analysed the water budget for millet in Senegal. They determined the cro water requirements for 75 day millet and developed a risk probability map. Ble (1990) used a calibrated soil water model (SWATRER) (Dierckx *et al.*, 1986) t identify potential millet zones from southern Mali to Niamey, Niger. The recen availability of the CERES-Millet model (Godwin *et al.*, 1984; Jones *et al.*, 1984 offers the opportunity to not only evaluate the soil water balance but also mille growth potential. A project was initiated in 1989 to evaluate the SWATRER an CERES-Millet models for southwest Niger. The objectives were:

(a) to characterize the physical and chemical composition of the soil a Tara, Niger,
(b) to validate the water balance model, SWATRER at Tara,
(c) to validate the CERES-Millet model at Tara.

## METHODS AND MATERIALS

Plant, soil and weather data for the two models were obtained from cropping system research project that was conducted at the INRAN Researc Substation at Tara, Niger (300 km southwest of Niamey) during the 198 growing season. The soil at the experimental site was classified as a luvi Arenosol (Bleich *et al.*, 1989). A summary of the laboratory determined so physical and chemical properties is given in Tables 1a and 1b. The long ter rainfall data were obtained from the nearest weather station, Gaya (30 k from Tara). The onset of the rainy season for this region is on or before June (80% probability). The average annual rainfall is 840 mm and is we.. distributed throughout a 126 day rainy season.

Millet (*Pennisetum americanum* L. cv CIVT) was planted on 25 June 1989 (day 175) in a randomized complete block design with six replications. The row spacing was 0.75 m and the millet spacing in the row was 0.8 m. Nitrogen fertilizer was applied at a rate of 40 kg $ha^{-1}$ as calcium ammonium nitrate 20 and 40 days after sowing and phosphorus fertilizer at a rate of 45 kg $ha^{-1}$ as $P_2O_5$ before sowing. The experimental area was weeded and sprayed for diseases as required.

Leaf area and dry matter were measured weekly by sampling a 7 $m^2$ area in each treatment. A 5000 $cm^2$ subsample was used for the leaf area determination. Leaf area was measured with a leaf area meter (Li-Cor). The plants were separated into stems, leaves and heads and dried at 70xC for 48 h for the dry matter determination. Soil water content was measured weekly throughout the growing season from 30 to 180 cm with a neutron probe (Troxler). The surface horizon (0 to 20 cm) soil water content was determined gravimetrically. Weather data required for the simulation models were collected hourly with an automatic weather station (Campbell Scientific) close to the experimental area. Millet was harvested on 5 October 1989.

### Model description

**SWATRER** The simulation of the soil water balance is divided into the three routines: ETREF, ETSPLIT, and SWATRER (Fig. 1). ETREF calculates

*Table 1a Some soil physical properties for the Tara experimental research site*

| Depth (cm) | Volumetric water content: Upper limit ($cm^3\ cm^{-3}$) | Lower limit ($cm^3\ cm^{-3}$) | Bulk density ($g\ cm^{-3}$) | Hydraulic conductivity ($m\ day^{-1}$) | Sand (%) | Silt (%) | Clay (%) |
|---|---|---|---|---|---|---|---|
| 00-10 | 15.8 | 2.6 | 1.58 | 2.86 | 82.8 | 11.3 | 6.7 |
| 10-20 | 18.2 | 5.6 | 1.65 | 3.25 | 81.8 | 8.6 | 9.6 |
| 20-40 | 15.9 | 5.5 | 1.50 | 4.50 | 79.0 | 10.9 | 10.0 |
| 40-60 | 18.8 | 6.7 | 1.53 | - | 78.6 | 9.9 | 12.0 |
| 60-80 | 19.4 | 6.9 | 1.53 | - | 78.8 | 8.5 | 12.9 |
| 80-100 | 19.4 | 6.9 | 1.50 | - | 78.8 | 8.3 | 12.9 |
| 120-140 | 17.8 | 7.0 | 1.54 | - | 78.4 | 7.0 | 14.6 |
| 140-160 | - | - | - | - | 74.2 | 11.6 | 14.1 |
| 160-180 | - | - | - | - | 73.3 | 12.8 | 13.9 |

*Table 1b Some soil chemical properties for the Tara experimental research site*

| Depth (cm) | pH(KCL) | Bray-P (ppm) | C (%) | N (%) | C/N Ratio |
|---|---|---|---|---|---|
| 00-10 | 3.7 | 5.88 | 0.23 | 0.018 | 12.8 |
| 10-20 | 3.7 | 3.21 | 0.18 | 0.014 | 12.5 |
| 20-40 | 3.9 | 2.76 | 0.15 | 0.011 | 13.6 |
| 40-60 | 4.0 | 1.53 | 0.12 | 0.011 | 10.9 |
| 60-80 | 4.0 | 0.98 | 0.09 | <0.010 | - |
| 80-100 | 4.0 | 0.60 | 0.08 | <0.010 | - |
| 100-120 | 4.0 | 0.58 | 0.05 | <0.010 | - |
| 120-140 | 4.1 | 0.80 | <0.05 | <0.010 | - |
| 140-160 | 4.0 | 0.40 | <0.05 | <0.010 | - |
| 160-180 | 4.0 | 0.40 | <0.05 | <0.010 | - |

the potential evapotranspiration ($ET_o$) based on a reference crop evapotranspiration ($ET_0$) using a modified Penman equation (Doorenbos & Pruitt, 1977).

ETSPLIT separates $ET_o$ into potential transpiration ($T_p$) and potential evaporation ($E_p$). The estimate of $E_p$ is obtained from:

$$E_p = f\, e^{-c\ LAI}\, ET_{cropm} \tag{1}$$

where $f$ and $c$ are regression coefficients 1 and 0.6 respectively, $ET_{cropm}$ is the potential crop evapotranspiration and is calculated by multiplying $ET_o$ by a crop coefficient $K_c$ (Doorenbos & Pruitt, 1977) and LAI is the leaf area index. $T_p$ is calculated as the difference between $ET_{cropm}$ and $E_p$.

The SWATRER routine calculates changes in the soil water storage (δW) as:

$$\delta W = (P + U) - (R + F + T + E + D) \tag{2}$$

where $P$ is precipitation, $U$ the upward capillary flow, $R$ the surface runoff loss, $F$ the water fraction intercepted by the leaves, $T$ the actual transpiration,

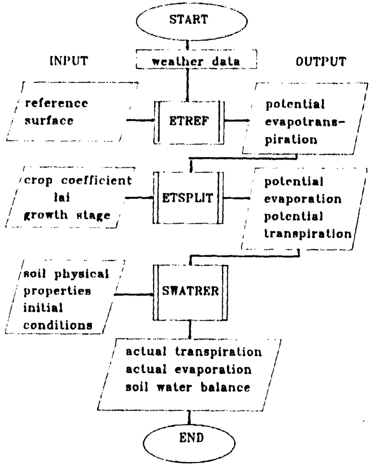


*Fig. 1 Flow chart for the SWATRER model.*

$E$ the actual evaporation and $D$ the soil drainage.

The soil moisture flow is calculated using the Richards equation (Dierckx *et al.*, 1986). The actual transpiration ($Ta$) is calculated using a sink variable given by the integrated root water uptake, which is a function of the soil water pressure potential. The calculation of the actual evaporation ($E_a$) is based on the Ritchie method (Ritchie, 1972). Dierckx *et al.* (1986) provide a detailed description of the model and the required inputs. The SWATRER model was calibrated for the soil and weather conditions at the ICRISAT Sahelian Center, Sadoré, Niger, during the 1986, 1987 and 1988 growing seasons (Bley, 1990).

**CERES-Millet** CERES-Millet simulates the soil water balance (WATBAL), the nitrogen balance (NTANS), the phenological stages (PHENOL) and the biomass development (GROSUB) (Fig. 2). Soil water balance components ($T_a$ and $E_a$, soil profile water content and plant extractable water) are calculated daily. The nitrogen balance component of CERES describes leaching, upward flow, mineralization, humus decay, nitrification, crop demand and crop uptake. Cumulative water and nitrogen stress indices for photosynthesis and leaf expansion are calculated for five growth periods.

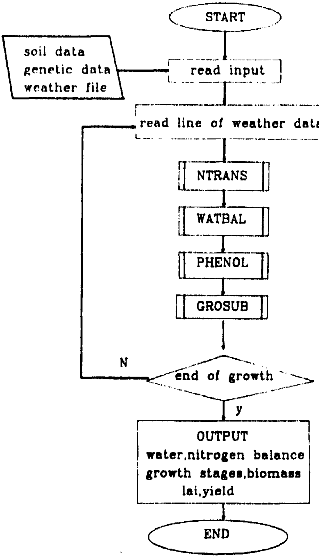


*Fig. 2 Flow chart for the CERES-Millet model.*

The development of the plant is calculated by using the intercepted PAR as the driving force for the potential increase in dry matter. The potential dry matter is calculated as:

$$Cp = (5\ PAR/NP)\ (1 - e^{-0.85\ LAI}) \qquad (3)$$

where $Cp$ is the dry matter gain, NP is the plant density, LAI is the leaf area index and PAR is the incident photosynthetically active radiation.

$Cp$ is reduced by a temperature index, a water index, and a nitrogen index. The estimation of phenological stages is driven by daily thermal time (DTT) using a base temperature of 8°C during the germination stage and 10°C during the other growth stages. The phenological development of the millet plant depends on the variety. The model requires genetic coefficient inputs that define the DTT during the juvenile phase and the grain filling phase. Additional genetic input parameters are coefficients for photoperiodism and kernal number. Godwin *et al.* (1984) and Jones *et al.* (1984) provide a model description.

## RESULTS AND DISCUSSION

The SWATRER model simulates a crop water balance with input weather, soil and LAI data. Measured and simulated (SWATRER and CERES) growing season soil water content in millet is presented in Fig. 3. The simulated soil water content (SWATRER) showed good agreement with the measured data throughout most of the growing season. The SWATRER model appears to be sensitive to rainfall, soil surface evaporation and plant water uptake. There was also a good agreement between simulated and measured soil water content at other soil depths. The individual components of the millet water balance are summarized in Table 2. Based on the results of Bley (1990), simulated values for cumulative $T_a$ and $E_a$ and deep percolation at Tara, Niger are assumed to be reasonable. Even though the growing season rainfall was only 65% of normal, crop water requirements appeared to be met during 1989 at Tara, Niger ($T_a/T_p$ = 0.92).

The CERES model is a dynamic crop growth model simulating both soil water balance and plant growth components. Table 3 summarizes simulated and observed phenological, growth and yield data. The CERES-Millet model overestimated maximum LAI, DM and grain yield by 46%, 40% and 101% respectively. An accurate simulation of LAI is important since canopy photosynthesis and subsequent above-ground dry biomass are strongly dependent on leaf area development. Better estimates of the genetic inputs

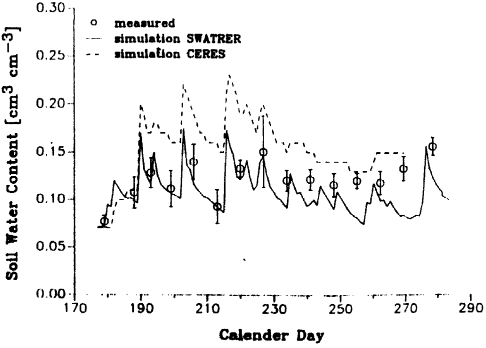


*Fig. 3 Simulated and measured soil water content (0–30 cm depth) in millet at Tara, Niger, 1989.*

*Table 2 Simulated (SWATRER) water balance components for millet at Tara, Niger during 1989*

| | *SWATRER* |
|---|---|
| *Cumulative precipitation (mm)* | *493* |
| *Cumulative $T_p$ (mm)* | *165* |
| *Cumulative $T_a$ (mm)* | *151* |
| *Cumulative $E_p$ (mm)* | *358* |
| *Cumulative $E_a$ (mm)* | *168* |
| *Deep percolation (mm)* | *94* |
| *Change in soil moisture storage (mm)* | *80* |

*Table 3 Simulated (CERES-Millet) and observed millet yield components and growth stages*

| | *Predicted* | *Observed* |
|---|---|---|
| *Anthesis (Julian day)* | *225* | *233* |
| *Maturity date (Julian day)* | *262* | *278* |
| *Grain yield (kg $ha^{-1}$)* | *2585* | *1240* |
| *Kernel weight (g)* | *0.028* | *0.011* |
| *Grains $m^{-2}$* | *9194* | *11272* |
| *Grains $panicle^{-1}$* | *2760* | *2167* |
| *Max. LAI* | *2.1* | *1.44* |
| *Biomass (kg $ha^{-1}$)* | *6141* | *4390* |

will be made during the 1990 growing season in order to improve the crop phenology and the growth simulation subroutines. Additionally, the relationship between light interception and leaf area will be examined.

Soil water content simulated by the CERES model is presented in Fig. 3. The CERES model consistently overestimated the soil water content by 0.05 $cm^3$ $cm^{-3}$. Critical to the simulation of the soil water content is the determination of the drained upper limit (DUL) and lower limit (LL). These site specific soil properties were estimated from laboratory determined soil retention curves. A better understanding of the soil water balance component of the CERES model will be possible after the DUL and LL are field determined and the plant growth and the phenology subroutines are modified (after completion of the 1990 growing season).

Based on threshold levels, water and nitrogen stress indices for photosynthesis and leaf expansion are calculated in CERES. The stress indices are summarized in Table 4. It is evident that there was little to no water stress present during 1989, which supports the SWATRER simulation results summarized in Table 2. The CERES model predicted an intermediate level of nitrogen stress during panicle initiation through to the end of vegetative

*Table 4 Nitrogen and water stress indices for leaf expansion and photosynthesis during five growth periods for millet*

| *Stage of growth* | *Water stress index:* | | *Nitrogen stress index:* | |
|---|---|---|---|---|
| | *Photosynthesis* | *Leaf expansion* | *Photosynthesis* | *Leaf expansion* |
| *Emergence - end juvenile* | *0.00* | *0.00* | *0.07* | *0.07* |
| *End juvenile - panicle initiation* | *0.00* | *0.02* | *0.04* | *0.04* |
| *Panicle initiation - end leaf growth* | *0.00* | *0.27* | *0.63* | *0.63* |
| *End leaf growth - endgrowth* | *0.00* | *0.00* | *0.16* | *0.16* |
| *End panicle growth - maturity* | *0.00* | *0.00* | *0.03* | *0.03* |

*In the above table, 0.0 represents minimum stress and 1.0 represents maximum stress.*

growth, however laboratory plant analyses indicated that there were normal levels of plant nitrogen present. Soil analysis indicated that the test soil was very acid and low in organic matter (Table 1b), therefore additional plant nutrients were possibly deficient which affected both simulated and actual root density; and element availability. Insufficient soil fertility and plant nutrition data make it difficult to explain the differences in the nitrogen stress index and the plant analysis data.

## CONCLUDING REMARKS

The SWATRER and CERES models can be used to evaluate production strategies. Good soil water balance estimates were obtained with the SWATRER model and it can be coupled to the recently available general growth model, SUCROS. The forthcoming changes in the CERES model should improve not only the soil water balance but also millet growth subroutines. Using long-term weather data together with site specific soil properties and millet variety characteristics, a calibrated CERES-Millet model can be used to evaluate planting date, N fertilizer programmes, plant population, row spacing and long or short season varieties.

## REFERENCES

Bleich, K. E., Bley, J. & Hebel, A. (1990) Erlaeuterung zu den Landschaftsformen, Böden und Standorteigenschaften auf den Versuchsflaechen der INRAN-Station Tara, Südniger. Unpublished Data, Institute für Bodenkunde und Standortlehre Universitaet Hohenheim 7000, Stuttgart 70.

Bley, J. (1990) Experimentelle und modellanalytische Untersuchungen zum Wasser- und Naehrstoffhaushalt von Perlhirse (*Pennisetum americanum* L.) im Südwest-Niger. Unpublished PhD Thesis, University of Hohenheim, Stuttgart, Germany.

Dancette, C. & Hall, A. E. (1979) Agroclimatology applied to water management in the Sudanian and Sahelian zones of Africa. In: *Agriculture in Semi-Arid Environments*, 98-117. Springer Verlag, Berlin.

Dierckx, J., Belmans, C. & Pauwels, P. (1986) *SWATRER. A Computer Package for Modelling the Field Water Balance.* Laboratory of Soil and Water Engineering, K. U. Leuven, Leuvan, B-3030 Leuven (Heverlee), Belgium.

Doorenbos, J. & Pruitt, W. O. (1977) Crop water requirements. *FAO Irrigation and Drainage Paper no. 24* FAO, Rome.

Godwin, D. C., Jones, C. A., Ritchie, J. T., Vlek, P. L. G. & Youngdahl, L. J. (1984) The water and nitrogen components of the CERES models. In: *Proceedings of the International Symposium on Minimum Data Set for Agrotechnology Transfer* (ICRISAT, March 1983), 101-106. ICRISAT Center, Patancheru, AP 502324, India.

Jones, C. A., Ritchie, J. T., Kiniry, J. R., Godwin, D. C. & Otter, S. I. (1984) The CERES wheat and maize models. In: *Proceedings of the International Symposium on Minimum Data Set for Agrotechnology Transfer* (ICRISAT, March 1983), 95-100. ICRISAT Center, Patancheru, AP 502324, India.

Ritchie, J. T. (1972) Model for predicting evaporation from a row crop with incomplete cover. *Wat. Resour. Res.* **8**, 1204-1213.