Simulation of biomass production and soil water dynamics on highly weathered, acidic Acrisols with the EPICSEAR model

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1 Abstract

The EPICSEAR model is a newly developed version of the EPIC model for simulating crop production and nutrient uptake on highly wheatered, acidic soils. It has been used to simulate soil water dynamics and biomass production of a Maize/Cowpea intercrop with and without fertilization on an Alumi-Haplic Acrisol with high aluminium saturation. The simulation results were used to appreciate the effect of fertilization on water use efficiency in rainfed agriculture on similar sites. The simulation results where checked against soil water and biomass measurements of a field trial in the semiarid Northeast of Brazil. The field had been previously used for Maize/Cowpea mixed cropping and the effect of complete fertilization (C) on soil water changes, nutrient uptake and biomass development was tested in a randomized complete block design with four repetitions against the control treatment (CR) without fertilizer application. Depending on the parametrization of soil hydrological properties, the average total dry matter production of both treatments (C and CR) was reasonably well represented by the model. The absolute soil water content was better represented when field capacity and wilting point were calculated from pedotransferfunctions other than the EPIC defaults. The coefficients of transpiration in the treatment with complete fertilization were ranged on average between 576 and 653 l kg^{-1} dry matter depending on the calculation method for crop transpiration, whereas those in the control were between 1265 and 1528 l kg^{-1}. The results demonstrate the extremely high coefficients of transpiration of a maize/cowpea intercrop under semi-arid tropical conditions and the increase of efficiency of transpiration by more than 100% when mineral fertilizer is applied.

2 Background and Objectives

Crop production in the semiarid Northeast of Brazil is characterized by water scarcity, which becomes most evident during drought years which are mostly related to the El-Nino phenomenon. Hence, the efficient use of water (irrigation or precipitation) is of major importance. Fertilizer trials in temperate regions have demonstrated, that the coefficient of transpiration of wheat and rye are strongly increased through the application of mineral fertilizers (N, P, K, Ca) with or without farmyard manure under different soil conditions (Klapp 1962, Schulze und Schulze-Gehmen 1957, Eck 1988). In semiarid West Africa, water use efficiency of millet had been doupled through fertilizer application (Gregory 1988). Therefore, fertilizer trials were conducted in the state of Piauí (NE Brazil) on a typically light-textured plateau soil (Alumi-Haplic Acrisol (FAO 1988), Latossolo Amarelo Alico (EMBRAPA 1981)) with low soil nutrient availability in order to study the effect of the application of N, P, K and lime on biomass production and efficiency of water use by maize and cowpea.

3 Material and Methods

3.1 Field experiment

The field experiment was a randomized complete block design with four repetitions. Five fertilizer treatments were tested: (1) Complete fertilization (N, P, K) with lime (Complete), (2) Complete without nitrogen, (3) Complete without phosphorous, (4) Complete without potassium,

(5) Complete without lime and (6) control (CR). Nitrogen (30 kg N ha^{-1} a^{-1}) was split applied as ammonium sulfate, phosphorous (18 kg P ha^{-1}) was appplied as superphosphate and potassium (33 kg K ha^{-1}) as potassium chloride. Lime (3000 kg ha^{-1}) was broadcast once at the beginning of the experiment. Total dry matter of maize and cowpea was determined at harvest.

Soil moisture dynamics were studied during two years in the treatment with complete fertilization and lime (Complete) and in the control plot (Control), using TDR probes (three replications per treatment) that measured five depth segments (0-15, 15-30, 30-60, 60-90 and 90-120 cm). Rainfall amount and distribution differed between the two years. In 1999/00 rainfall (1189mm) was sufficient and well distributed, whereas the year 2000/01 was drier with a total amount of rainfall of only 684mm, which reflects more the average conditions at this site. Maize (São Vicente) and Cowpea (EPACE 10) were planted in intercropping arrangement with 4.5 and 9 plants m^{-2} respectively.

3.2 Simulation of soil water balance and calculation of actual transpiration

For the calculation of transpiration two different model approaches were used:

a. HILLFLOW, a physically based soil water balance model system, that considers rainfall intensity (variable temporal resolution), interception, surface runoff, evapotranspiration, interflow, and water movement in macropores and in the soil matrix (Bronstert and Jürgens 1995). Water transport in the soil matrix is calculated by elementwise solution of the Richards equation. Potential transpiration (TR_p) is calculated by subtracting potential evaporation EV_p (according to Belmans et al. 1993) from ETP (according to Monteith 1965) and is then reduced depending on the soil water suction to obtain the crop transpiration. Leaf area index is input manually, but only EV_p is sensitive to leaf area index development. Effects of nutrient supply and aluminium saturation on plant water uptake are not considered.
b. EPICSEAR is derived from the Erosion Productivity Impact Calculator (EPIC, USDA 1990) by adapting the model to soil conditions with high aluminium saturation and low nutrient availability. In antecedent tests, the model showed a good performance for simulating biomass and yield of cowpea and maize at this site (De Barros 2002) and high sensitivity to changing soil chemical conditions. However, the soil water module uses the „bucket“ approach to describe soil water dynamics. The soil is subdivided in at maximum 10 soil layers with their maximum field capacity (FC) and permanent wilting point (PWP). As soon as soil water content in a layer exceeds field capacity, the water is routed to the underlying layer using the saturated hydraulic conductivity. In addition, EPICSEAR does not consider interception of rain by the crop.

The soil moisture dynamics were simulated with both models and compared with measured volumetric water contents in order to assess the performance of the soil water simulations by EPICSEAR compared to the physically based HILLFLOW model. Rooting depth was set to 60 cm as observed in the field. The crop parameter files for the Maize and Cowpea cultivars had been previously developed (Saboya et al., unpublished). The most critical factor, the „Al tolerance index“, being set to 2.5 (moderately tolerant) for Cowpea and 1.0 (sensitive) for Maize. The soil hydrological properties field capacity (FC) and permanent wilting point (PWP) are important input parameters in EPICSEAR. EPICSEAR calculates these parameters, if they are not available from measurements or calculated by other pedotransfer functions. For the parametrization of FC and PWP two approaches were used (Table 1):

a. FC and PWP calculated by „EPICSEAR“
b. FC and PWP calculated by means of pedotransfer functions accroding to Gaiser et al. (2000) („EPICSEARpt“)

Table 1: Soil water content (% per volume) at field capacity (FC) and permanent wilting point (PWP) in 15-30 cm soil depth as calculated by different approaches

	EPICSEAR	EPICSEARpt
FC	24	14
PWP	10	6

The mean absolute error (m) between measured (θ_m) and simulated (θ_s) volumetric water content was calculated according to Papula (1982):

$$m = \sqrt{\frac{\sum_{i=1}^{n}(\theta_s - \theta_m)^2}{n-1}}$$

Soil water balance and crop transpiration during the growing period were calculated for both treatments, Control and Complete, respectively. The transpiration coefficient was calculated by dividing the measured total dry matter production of cowpea and maize in g m^{-2} by the actual transpiration (in liter per m^{-2}) calculated by the simulation models.

4 Results and Discussion

4.1 Calculation of soil water balance and plant transpiration

In general, the changes in soil water content in both years were described best by the HILLFLOW model (Figures 1 and 2). EPICSEAR simulated the occurrence of dry periods well, regardless of the parametrization of field capacity (FC) and permanent wilting point (PWP). However, when the default pedotransfer functions to estimate FC and PWP were used, the soil water content was overestimated in both years. This resulted in mean absolute errors of the simulated water content of 8.1 to 9.5% per volume depending on treatment and year (Table 2).

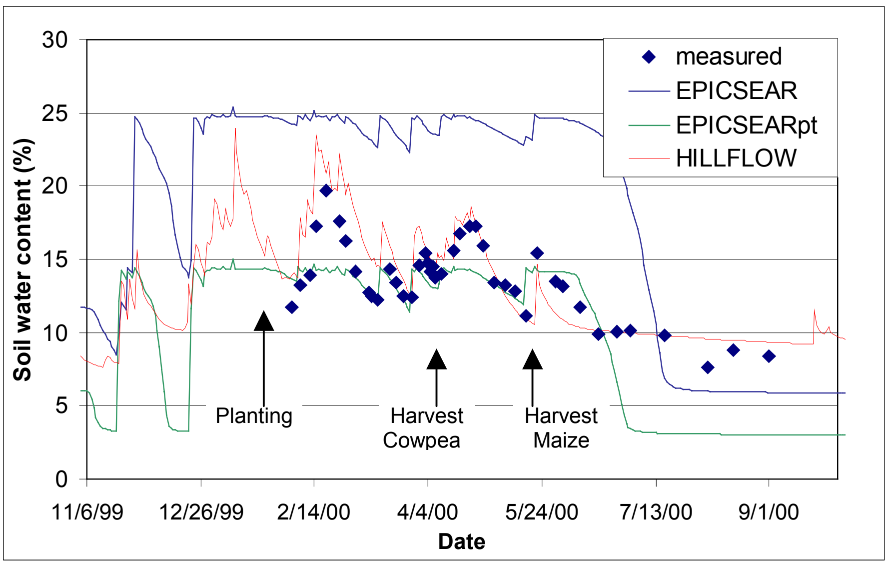

Figure 1: Comparison of measured versus simulated soil water content (% per volume) in 15-30 cm soil depth by HILLFLOW and EPICSEAR in the control treatment in 1999/2000

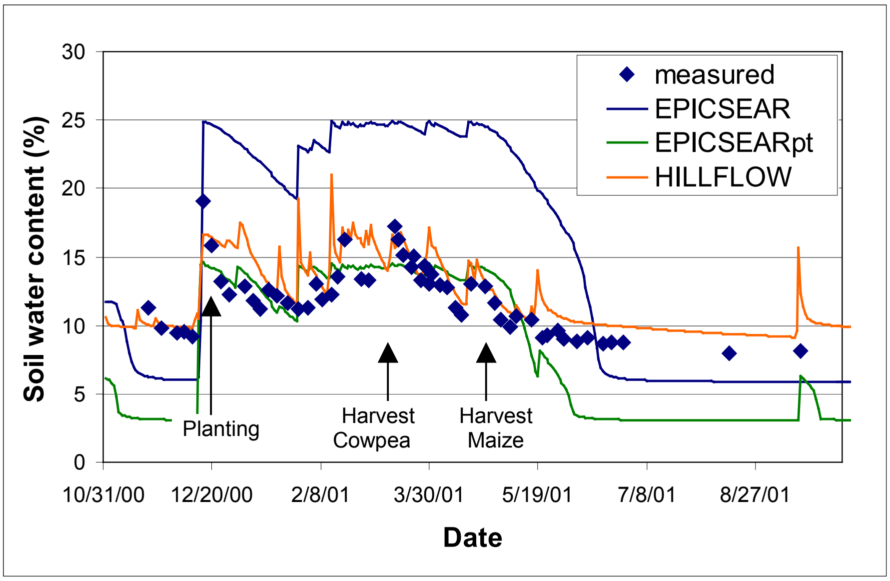

Figure 2: Comparison of measured versus simulated soil water content (Vol-%) in 15-30 cm soil depth in 2000/2001 by HILLFLOW and EPICSEAR in the control treatment

The HILLFLOW simulation produced the lowest mean absolute error in soil water content in all treatments and years, but the simulation of EPICSEAR with FC and PWP estimated by means of pedotransfer functions according to Gaiser et al. (2000) ("EPICSEARpt") gave similar mean absoute errors (+0.6 to +2.4% per volume higher than the errors of the HILLFLOW simulations).

Table 2: Mean absolute error of simulated water content (% per volume) by HILLFLOW and EPICSEAR within the main rooting depth (15-30 cm)

Year	Control			Complete with lime		
	EPICSEAR	EPICSEARpt	HILLFLOW	EPICSEAR	EPICSEARpt	HILLFLOW
1999/00	9.5	2.7	2.1	8.1	4.1	2.5
2000/01	9.5	3.2	2.4	8.2	4.2	1.8

However, the HILLFLOW simulations were not sensitive to the fertilizer treatments expressed by the same amount of transpiration, although the total dry matter production strongly differed between the treatments (Figure 3 and Table 3). In contrast, the soil water balance calculations by EPICSEAR were sensitive to the application of fertilizer, regardless of the parametrization method of FC and PWP. EPICSEAR calculated during the hydrological year 1999/2000 21 % higher transpiration in the complete fertilizer treatment compared to the control plots (Figure 3). During the growing periods of both years EPICSEAR calculated on average 40% higher transpiration in the complete fertilizer treatment (Table 3).

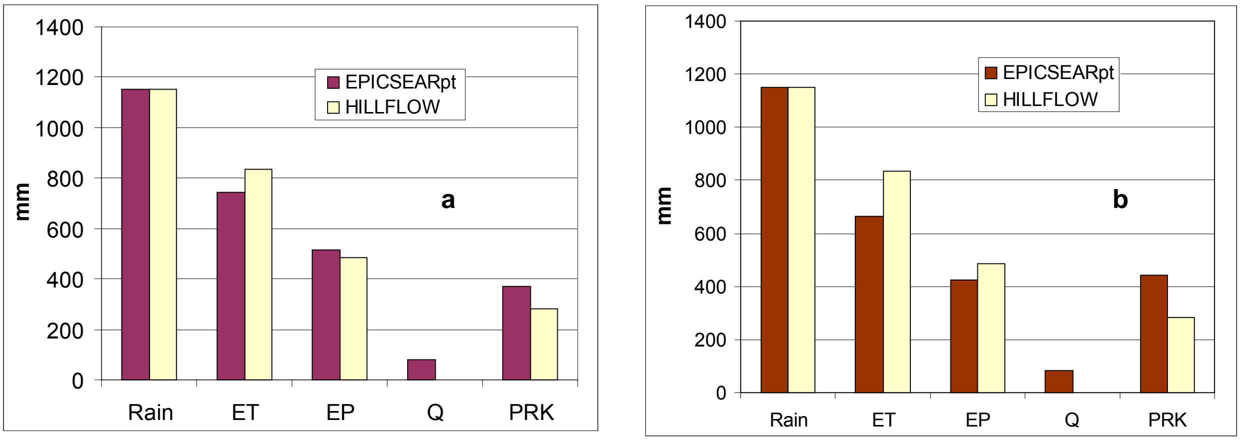

Figure 3: Water balance with (a) and without (b) fertilization as calculated by different simulation models in the hydrological year 1999/2000 (ET=Evapotranspiration, EP=Transpiration, Q=Run off, PRK=Percolation in 120 cm depth)

4.2 Calculation of dry matter production and coefficient of transpiration

In 1999/2000 total dry matter production was on average 138% higher in the treatment with complete fertilization compared to the control. This was well described by the EPICSEAR simulations, which produced a difference of 137% between the treatments (Table 3). However, in 2000/01 EPICSEAR calculated a much lower increase in total dry matter production by in the complete fertilization treatment compared to the measured values, which was due to a severe overestimation of the dry matter production in the control treatment in this drier year. De Barros (2002) observed a general overestimation of dry matter production by EPICSEAR in unfertilized plots, which was more pronounced in years with low or irregular rainfall. This could be due to the bucket approach that is used in EPICSEAR for describing soil water dynamics, which is more suitable for humid conditions. Another reason could be the fact that EPICSEAR does not consider interception by the plant cover, increasing unrealistically water availability in the soil, which may result in overestimations of dry matter production particularly in drier years.

Table 3: Measured and simulated total dry matter production by a maize/cowpea intercropping system and crop transpiration during the growing period (calculated by EPICSEAR) in relation to application of fertilizer

	Control			Complete fertilization		
	Simulated ($t\ ha^{-1}$)	Measured ($t\ ha^{-1}$)	Transpiration (mm)	Simulated ($t\ ha^{-1}$)	Measured ($t\ ha^{-1}$)	Transpiration (mm)
1999/00	1.39	1.70	175	3.29	4.05	259
2000/01	1.96	1.08	162	2.57	3.19	212
Mean	1.68	1.39	169	2.93	3.62	236

Comparing the coefficients of transpiration (CT) in both treatments indicates that on this site fertilization and liming increases the CT of maize/cowpea intercrop by 2 to 3 times depending on the method of calculating actual transpiration (Table 4). Since soil water simulations by HILLFLOW are in general more accurate, actual transpiration and the mean CT of 576 $l\ kg^{-1}$ in the treatment with complete fertilization may be more accurate than the mean CT of 653 l kg^{-1} derived from the estimation of actual transpiration by EPICSEAR. However, in the control treatment, estimation of crop transpiration by HILLFLOW is rather overestimated, because it does not take into account the negative effect of high Al concentrations in the soil solution to root growth and plant water uptake. Therefore the mean CT of 1265 l kg^{-1} derived from the EPICSEAR calculations seems to be more reasonable.

Table 4: Transpiration coefficients (l kg^{-1} total dry matter) of a maize/cowpea intercrop with (Complete) and without (Control) fertilization

	EPICSEARpt		HILLFLOW	
	Control	Complete	Control	Complete
2000	1029	640	1435	602
2001	1500	665	1620	549
Mean	1265	653	1528	576

5 Conclusions

The comparison of the soil water changes simulated by HILLFLOW and EPICSEAR shows that the HILLFLOW model gives more accurate results compared to measured soil water content. However, EPICSEAR produces comparable results when field capacity and permanent wilting point are estimated with PTFs according to Gaiser et al. (2000). EPICSEAR is sensitive to the effects of liming and fertilization on soil water balance and dry matter production on this soil with high Al saturation. Observations and simulations demonstrated that, under such conditions, coefficients of transpiration and hence the productivity of water in a maize/cowpea intercropping system can be increased by more than 100% through the application of lime and NPK fertilizer.

6 Acknowledgement

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7 References

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