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Water Fluxes in Oxisols: A Comparison of Approaches

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Two approaches to simulating soil water flow were evaluated: a capacity-type water flow model combined with a plant water uptake model based on the concept of plant-available water, and a numerical solution to the Richards equation combined with a potential-driven water uptake model. Irrigation water was applied at rates ranging from 0.3 to 1.6 potential evapotranspiration to an Oxisol under fallow and planted to corn (*Zea mays* L.). Results indicate that a two-parameter soil moisture release curve does not sufficiently describe these soils over the entire plant-available water range. Field saturated water contents were generally only 70% of total porosity. The potential-driven model better predicts profile water content distribution under fallow and cropped conditions than the capacity-type approach (R^2 = 0.80 and 0.83 versus R^2 = 0.59 and 0.70). When integrated over the growing season, drainage, evaporation and transpiration rates were very similar for capacity-type water movement and potential-driven water movement over the range of irrigation treatments.

INTRODUCTION

The ability to quantitatively describe field soil water fluxes is important for solving a wide range of agricultural and environmental problems. Soil water simulation models have been used to estimate crop irrigation water requirements [*Norman and Campbell*, 1983], to assess the environmental fate of agricultural chemicals [*Wagenet and Hutson*, 1986], and for soil classification [*Van Wambeke et al.*, 1986], among other purposes. The extent to which simulation models correctly represent important processes and interactions affecting soil water fluxes in the soil-plant-atmosphere system will determine their ability to be extrapolated to previously unstudied locations and conditions.

The major objective of this research was the quantitative description of water fluxes in Cerrado soils under cropped and fallow conditions. The Cerrado region in Brazil is a good example of the great need to extrapolate agricultural knowledge acquired in a short time to a large region, in which climatic conditions and soil properties vary considerably. Most of the existing understanding of soil and crop management under Cerrado conditions has been acquired within the last 15 years, when the large-scale agricultural development of this region was first conceived. Only a few experimental research sites exist in an area larger than the corn and wheat belt of the United States. Furthermore, there are several features of acid savanna systems that make proper evaluation of water fluxes critical to sound management. Low soil water contents at field capacity due to the presence of macropores and high water contents at "permanent wilting point" due to clay contents of 50% or greater result in very low amounts of plant-available water stored in the soil profile of the Oxisol common to this region [*Wolf*, 1975]. Under these conditions, crop rooting depth determines the likelihood of crop survival during "veranicos" or drought periods that occur in the wet season. In Oxisols of this region, crop rooting depths are frequently restricted by chemical boundaries such as Al toxicity or severe Ca deficiency [*Ritchey*, 1982]. Nutrients leached below the plow layer may be unavailable to the crop. Understanding water fluxes therefore is an important prerequisite for determining proper fertility management to minimize drought stress and nutrient losses.

A variable line source sprinkler experiment planted to maize was established during the dry season at the Centro de Pesquisa Agropecuaria dos Cerrados (CPAC) in the Federal District, Brazil. Data obtained from this field experiment were compared to simulated data using two soil water simulation models. Two alternative approaches to modeling soil water flow, the Richards equation [*Campbell*, 1985] and the tipping bucket method [*Jones and Kiniry*, 1986; *Ritchie et al.*, 1986], were compared with respect to their ability to predict measured soil water contents. The general purpose simulation model GAPS developed by *Buttler and Riha* [1987, 1989] was used to implement alternative simulation model representations and to compare the effect of their respective assumptions and limitations on model performance.

Comparisons between the Richards equation and capacity-type, water content–based representations of soil water flow have been limited [*Da Silva and de Jong*, 1986]. This is partly due to the difficulties encountered when comparing two different simulation models that contain other component processes besides the ones to be compared. GAPS provides an environment in which two alternative representations can be compared without changing the other component processes given that both modules provide the needed output for the other procedures in use. Choosing one of these two water flow models has clear effects on the freedom of choice regarding other component parts, e.g., a potential-driven plant water uptake routine cannot be linked to the tipping bucket routine since the latter does not provide needed estimates of soil water potentials over time and space.

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MATERIALS AND METHODS

Experimental Design

The experimental site was located on the Empresa Brasiliera de Pesquisa Agropecuaria (EMBRAPA)-CPAC research station near Brasilia, latitude of 15.5°S and longitude of 27.5°W, at an altitude of 1000 m. The soil is classified as an Oxisol (Typic Haplustox, isohyperthermic, fine, kaolinitic) or a dark red Latosol in the Brazilian classification system [*Macedo and Bryant*, 1987]. Maize (*Zea mays* L., "Cargill 111 S") was planted on April 21, 1987 (day of year (DOY), 111) in 80-cm-wide rows at a final population density of 62,500 plants/ha. The crop was grown during the dry season in order to have optimal control of irrigation water treatments.

A line source sprinkler irrigation system [*Hanks et al.*, 1976] was used to establish a gradient of irrigation water application. Twenty rows of maize were planted on each side of (north and south) and parallel to the sprinkler line, resulting in a gradient of water application perpendicular to the maize rows. Irrigation water was applied at the same frequency to all plots, but at rates ranging from approximately 3 to 25 mm h^{-1}. Quantities of applied water were measured after each irrigation event with catch cans located between the corn rows just above the crop canopy. Three rows of 40 catch cans each and spaced approximately 15 m apart were used to collect the irrigation water. Uniformity parallel to the irrigation line was very good, with coefficients of variation generally around 5%. This allowed the mean of the three sampling locations to be used to represent amounts of irrigation water applied as a function of time and distance from the line source. Wind conditions led to a consistently different distribution of water between the two halves of the experimental field, prohibiting treating plots on opposite sides of the irrigation line as replicates.

Irrigation water applied every 3–5 days for 2–3 hours after dusk, when wind speed was lowest. The total amount of irrigation water received at the two extreme sampling locations during the experimental period (including 104 mm natural precipitation) was 188 mm (sampling location S-16) furthest away from and 1020 mm (N-01) closest to the sprinkler line. Comparisons between measured and predicted data will be discussed primarily for four levels of irrigation (N-01, N-11, N-16, and S-16), representing approximately 1.6, 1.0, 0.6, and 0.3 of potential evapotranspiration (PET, equal to 640 mm), respectively, when averaged over the whole growing season.

Treatments perpendicular to the irrigation water gradient consisted of three different nitrogen fertilizer application rates (0, 100, and 200 kg N/ha) in plots planted to corn and replicated twice on each side of the sprinkler line and two nonreplicated fallow plots. Only the results from the cropped treatment receiving 200 kg N/ha nitrogen fertilizer and the fallow treatments are reported here.

Soil and Plant Sampling

Soil samples were collected eight times (DOY 96, 127, 141, 154, 169, 182, 197, 225) between specified corn rows. Of the 20 rows of corn on each side of the sprinkler line (numbered 1–20 starting at the irrigation line) rows 1/2 (N-01, S-01), 6/7 (N-06, S-06), 11/12 (N-11, S-11), and 16/17 (N-16, S-16) were designated as soil sampling locations. Soil cores were collected with augers from three locations per treatment combination. Sampling depths were in intervals of 0.15 m to a depth of 0.60 m and 0.30 m from 0.60 m to 1.80 m, totaling eight depth increments. The three separately collected samples were combined for each soil layer and a representative sample was used to determine water content gravimetrically.

Sequential harvests of the aboveground part of the maize plants were made weekly for the first 5 weeks starting 30 days after emergence and then biweekly on the same days as the soil was sampled. Five plants per row were harvested from the same row numbers at which soils were sampled. Leaf area was measured using a leaf area meter. Root fresh and dry weights were measured shortly after pollination in soil cores collected from within the corn rows.

Simulation Procedures

Two different soil water transport models were used to simulate soil water content distributions over time and as a function of depth under the different irrigation treatments. The soil water balance was obtained using the Richards equation, i.e.,

$$\rho \frac{\partial \theta}{\partial \psi} \frac{\partial \psi}{\partial t} = \frac{\partial}{\partial z}\left(k \frac{\partial \psi}{\partial z} + kg\right) + U$$

where ρ is the density of water, θ is the volumetric water content, ψ is the soil water potential (joules per kilogram), t is time, k is the hydraulic conductivity, z is soil depth, g is the acceleration of gravity and U is the source-sink term. This equation is solved using a finite element approach similar to that described by *Campbell* [1985]. The upper boundary condition is a specified flux (0 when no infiltration is occurring). At a depth well below (>1 m) the root zone a lower boundary is set at which no water flux is assumed to occur. Input requirements include defining the relationships between θ, ψ, and k.

The soil water balance was also obtained using a capacitance-type approach adapted from the CERES maize model [*Jones and Kiniry*, 1986; *Ritchie et al.*, 1986]. In this approach the soil is conceptualized as consisting of a series of tipping buckets each having a specified capacity to hold water. Water is transferred from one layer to the next downward in the soil if the amount of water entering the layer exceeds its capacity to hold water. The water-holding capacity of each layer is the difference between the saturation water content and the current volumetric water content. Input requirements include knowing or calculating the saturated water content, the drained upper limit (DUL), which we assume to be the volumetric water content at field capacity and the lower limit (LL) or volumetric water content at wilting point.

The Priestley-Taylor equation (α = 1.26) was used to estimate potential evapotranspiration [*Priestley and Taylor*, 1972], which was partitioned into potential soil evaporation and potential transpiration depending on the leaf area index of the maize [*Stockle and Campbell*, 1985]. For simulating plant water uptake, two different water uptake procedures compatible with each water flow simulation procedure were used. In the case of the Richards equation, which predicts hourly changes in soil water potentials, a potential-driven plant water uptake procedure was used to estimate root water uptake and actual transpiration [*Riha and Campbell*,

1985]. Actual transpiration is determined by the response of stomatal resistance to leaf water potential [*Fisher et al.*, 1981]. Water flow into roots was assumed to be inversely dependent on the resistance to water flow in the soil and in the root [*Gardner and Ehlig*, 1962] and directly dependent on the gradient between roots and soil water potentials [*Gardner*, 1960]:

$$U_i = \frac{\Phi_i(\psi_i - \psi_{\text{root}})}{r_i \text{ soil} + r_i \text{ root}}$$

where U_i is the root sink strength at node i, Φ_i is the root density, ψ_i is the soil water potential, ψ_{root} is the root water potential, and r_i soil and r_i root are the resistances to the flow of water to the root and into the root, respectively. The root water potential was first calculated using the equation:

$$\psi_{\text{root}} = \frac{\text{TA} \sum_{i=1}^{j} \psi_i / r_i}{\sum_{i=1}^{j} 1/r_i}$$

where TA is actual transpiration, $r_i = r_i$ soil + r_i root and j is the number of nodes in which roots occur. Soil evaporation is incorporated into the Richards equation as proposed by *Campbell* [1985], with actual soil evaporation being controlled by the humidity at the evaporating surface during first-stage drying and by the liquid flux to the evaporating surface during second- and third-stage drying.

The tipping bucket procedure was combined with a plant water uptake routine based on the concept of plant-available water. Plant water uptake from any layer in the soil containing roots is allowed to proceed until a lower limit of plant-extractable water (permanent wilting point) is reached. The root density distribution in the soil profile is used to partition the transpirational demand between soil layers. Demand not met in any one layer is transferred to other layers as an additional demand. Root densities thus do not limit root water uptake in this simple representation, but serve solely to partition transpiration in the soil profile. Soil evaporation was included in the tipping bucket water flow procedure as simple first-stage evaporation, which was allowed to proceed until the soil water content reached 25% (or 50% for second node) of its value at permanent wilting point. Soil evaporation occurred only from the first 10 cm of the soil profile (first two soil nodes). No upward water flow was simulated in the tipping bucket water flow routine. An hourly time step was used for both water flow models. Simulations were conducted from April 6, 1987 (DOY 96), starting with a measured soil water content distribution, to September 9, 1987 (DOY 252). Detailed documentation of the two water flow models, the evapotranspiration procedure, and the plant water uptake procedures with explanations of governing equations and their solutions is contained in the GAPS user's manual [*Buttler and Riha*, 1989].

Simulation Input Data

Daily climate data for the experimental site were obtained from CPAC's main meteorological station located approximately 50 m from the experimental location. Climate data used included daily precipitation, solar radiation, daily average wind speed, maximum and minimum air temperature, and maximum and minimum relative humidity. Daily minimum and maximum air temperatures and daily total solar radiation were transformed into hourly values [*Buttler and Riha*, 1989].

Soil physical properties were characterized to the extent that they were needed as inputs to the water flow routines. Soil particle density and texture were determined on soil samples collected from three randomly chosen locations in the experimental field in 0.15-m depth intervals to a depth of 1.80 m [*Gee and Bauder*, 1986]. Mean soil clay, silt, and sand percentages were 58.7 (1.8), 6.0 (1.1), and 35.3 (1.3), with the numbers in parentheses being the standard deviations. The mean particle density was 2.66 Mg m^{-3} (0.02 Mg m^{-3}). Differences in soil texture and particle density were not significant between depths.

Dry bulk density and hydraulic parameters were measured on undisturbed soil cores. A pit (2 m by 1.5 m) was excavated in the border area of the experimental field to a depth of 1.85 m. Twelve soil cores per depth (depth increments corresponding to experimental soil sampling depths) were collected along the 2-m face of the pit. Stainless steel rings (5 cm in diameter and length) were inserted vertically into horizontal planes created at various depths along the face of the pit. A total of 110 core samples was collected. An additional 80 core samples were collected to a depth of 0.65 m at four other sites randomly chosen within the experimental field, to test for within-field variability. Mean bulk densities and hydraulic conductivities measured on the latter 80 samples did not differ significantly (P = 0.05) from the samples collected in the deep pit, and are not reported.

Soil saturated hydraulic conductivity was determined on the cores using the constant head method [*Klute and Dirksen*, 1986]. Saturated hydraulic conductivities measured in the laboratory were similar to values reported by others for the same soil under field conditions [*EMBRAPA-CPAC*, 1981]. A field-measured value of 125 cm d^{-1} (0.00148 kg s m^{-3}) was obtained for satiated hydraulic conductivity by *Luchiari* [1988] which compares well to the conductivity measured in the soil layer with the highest bulk density (0.0016 kg s m^{-3}) in this study (Table 1). *Bouldin et al.* [1979] reported higher infiltration rates between 17 and 22 cm h^{-1} (0.004 and 0.006 kg s m^{-3}, respectively) for these soils, which is in agreement with the laboratory measurements on uncompacted soil cores in this study. Soil bulk densities significantly (P = 0.001) increased at the 0.15 to 0.45 m depths, probably due to compaction. The higher soil bulk densities were highly negatively correlated with measured saturated conductivities.

Moisture characteristic curves were determined on 60 of the above 110 core samples using pressure plates [*Klute and Dirksen*, 1986] (Figure 1). Soil water potentials below the air entry potential are described as a function of soil water content using an equation proposed by *Campbell* [1974, 1985]: WP = ae (WC/WS)$^{-b}$, where WP is the soil water potential (joules per kilogram), WC is the soil water content (m^3 m^{-3}), WS is the saturation water content (m^3 m^{-3}), ae is the air entry potential (joules per kilogram) and b is empirically determined.

Input data for the tipping bucket water flow routine were calculated from moisture release data. Both the volumetric water content at −33 J kg^{-1} (0.272 m^3 m^{-3}) and at −10 J

TABLE 1. Soil Profile Input Data

Node	Depth, m	Bulk Density, Mg m^{-3}	Saturated Hydraulic Conductivity, kg s m^{-3}	Initial Water Content, m^3 m^{-3}	Root Density, m m^{-3}
1	0.01	1.07	0.0026	0.32	0.0E + 04*
2	0.08	1.07	0.0026	0.32	5.0E + 04
3	0.23	1.22	0.0016	0.31	3.0E + 04
4	0.38	1.15	0.0031	0.31	1.0E + 04
5	0.53	1.07	0.0039	0.28	0.6E + 04
6	0.75	1.00	0.0054	0.27	0.4E + 04
7	1.05	1.00	0.0061	0.27	0.2E + 04
8	1.35	1.00	0.0061	0.27	0.0E + 04
9	1.65	1.00	0.0050	0.27	...
10	1.85	1.00	0.0035	0.27	...

For the Richards equation, Campbell b value is 10.31 and the air entry value is -0.42 J kg^{-1}. For the tipping bucket routines, the drained upper limits are 0.30 and 0.27 and the lower limit is 0.20.
*Read 0.0E + 0.4 as 0.0×10^4.

kg^{-1} (0.30 m^3 m^{-3}) were used as the drained upper limit (DUL) or "field capacity" in alternative runs and the volumetric water content at -1500 J kg^{-1}(0.20 m^3 m^{-3}) was used as the lower limit (LL). The profile drainage constant and other parameters used in the tipping bucket procedure were calculated according to the equations given by *Ritchie et al.* [1986]. The soil input data used for the simulations are presented in Table 1.

For the purpose of the water flux simulations presented here, leaf area was treated as an input to the model rather than being simulated. An exponential and a series of linear equations were fit to the time course of measured leaf area development obtained from the sequential harvests. These equations were then used in the model to estimate leaf area index as a function of time [*Buttler*, 1989]. Root dry weights were used to determine relative root density distributions in the soil profile. The maximum rooting depth observed in the high water/high-nitrogen treatments was 1.20 m. More than half of the total root weight in the 90-cm soil profile was concentrated in the uppermost 15 cm. Root length reported by *Gonzales-Erico* [1979] for the same location and corn variety was 4.6–5.1 cm cm^{-3} under limed conditions and, consequently, a root length value of 5.0 cm cm^{-3} was assumed for this experiment for the 1–15 cm depth increment. Root lengths were then reduced with depth according to the measured relative root weight distribution. To simulate root growth, the crop growth components included in GAPS and based on a simulation model developed by *Stockle and Campbell* [1985] were used. They are described in greater detail elsewhere [*Buttler and Riha*, 1989]. Rooting depth was simulated on the basis of simulated daily dry matter partitioned to roots [*Foth*, 1962]. Instead of changing root densities in each layer over time, a static root density distribution was assumed and additional layers were activated as the season progressed in accordance with the simulated rooting depth.

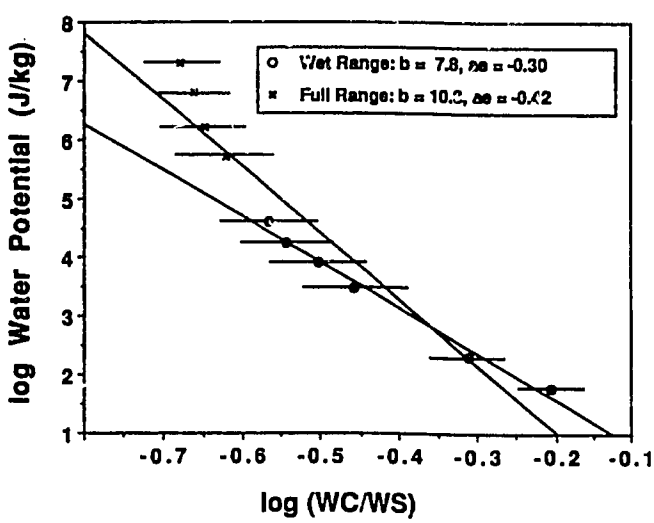

Fig. 1. Soil moisture release parameters for the Campbell equation, fit to the full range (-6 to -1500 J kg^{-1}) of water potentials (crosses) and to the wet range (-6 to -100 J kg^{-1}) only (circles). Error bars represent plus or minus one standard deviation.

Statistical analysis of the experimental data was performed using the statistical analysis system [*SAS Institute*, 1985]. The main objective of the statistical analysis of the measured water content data was to obtain a mean and standard deviation of soil water content as functions of applied irrigation water and as a function of time and depth. These measurements were then compared to data obtained from the simulation model.

Multivariate analysis of the soil water content data was performed using the "repeated measure option" in PROC ANOVA, treating measurements over depth as repeated measures and performing the analysis for each sampling date. IRRIG was treated as nested within SIDE due to the differences in irrigation water application rate between sides.

RESULTS AND DISCUSSION

There was very little variability in soil water content distribution in the field when soils were initially sampled on April 6 (DOY 96). Coefficients of variation ranged from 1 to 2%. By DOY 127, 16 days after planting, but before the first irrigation water treatment application, water contents throughout the field still varied very little.

On DOY 141, 9 days after the first and 4 days after the second irrigation water application, irrigation water treatment (IRRIG) already showed a significant effect on water contents in the profile. Throughout the soil profile to a depth of 1.80 m, IRRIG (SIDE) was significant at $P = 0.0001$ and remained significant throughout the soil profile for water contents throughout the season.

These results indicate that the experimental design and data collection scheme were able to provide statistically

TABLE 2. Summary Statistics of Simulated Versus Measured Soil Node Water Contents

	Fallow			Planted		
	Richards Equation	Tipping Bucket (0.27)	Tipping Bucket (0.30)	Richards Equation	Tipping Bucket (0.27)	Tipping Bucket (0.30)
Mean	0.279	0.274	0.304	0.282	0.275	0.301
Standard deviation	0.027	0.003	0.005	0.031	0.006	0.019
Slope	0.808	0.99	1.21	0.87	0.71	0.917
Intercept	0.056	−0.01	0.05	0.04	0.07	0.030
R^2	0.80	0.55	0.59	0.83	0.66	0.70
Standard error of Y_{est}	0.016	0.039	0.043	0.023	0.03	0.036
Standard error of slope	0.044	0.107	0.118	0.043	0.058	0.069
		Measured Values				
Mean		0.276			0.268	
Standard deviation		0.023			0.037	

Number of samples is 224. Regression coefficients were obtained by regressing simulated against measured soil water contents for seven sampling dates, eight sampling depths, and for the four treatments 1.6, 1.0, 0.6, and 0.3 PET.

significant differences in measured soil water contents between the sampling locations selected along the continuous gradient of irrigation water application. This is an important prerequisite for a meaningful comparison of these measured data with simulation model output.

Comparison of Predicted and Measured Soil Water Contents

Fallow treatments. Initial model execution using the Richards equation indicated that simulated soil water contents were consistently higher than field-measured values. It was concluded that the assumption that field saturated water content is equal to total porosity was not valid for this soil, with bulk densities around 1.00 Mg m^{-3} and in which approximately 15% of total porosity is macroporosity [*Luchiari*, 1988]. Although saturation percentages of about 95% (85–100) were obtained during measurements of saturated hydraulic conductivity on undisturbed soil cores in the laboratory [*Buttler*, 1989], the soil does not reach these high values under field conditions. *Luchiari* [1988] reported field saturated or "satiated" water contents of about 0.47 m^3 m^{-3} measured on the same soil in close proximity to this experiment's location. This would correspond to a saturation percentage of 75% of total porosity at a bulk density of 1.00 Mg m^{-3}.

Using 70% of total porosity (0.43 m^3 m^{-3}) as a saturation water content yielded results similar to measured data for most of the profile layers, except for those layers that exhibited increased bulk densities due to compaction. This value for field saturation water content was obtained using a subset of the experimental data, namely, the highest irrigation treatment of the fallow plot. The air entry potential was recalculated assuming the field saturated water content WS in the Campbell equation.

Increasing bulk density leads to lower predicted water contents at the same soil water potential when all other soil parameters are held constant. In reality, measured soil water contents at the 15–30 and 30–45 cm depth increments were consistently higher during the entire season than water contents below and above these layers. It was hypothesized that the process of compaction leads first to a loss of macroporosity, which in turn would result in field saturation water contents closer to calculated total porosity than in the uncompacted soil. Therefore, the field saturated water content for these layers was set equal to total porosity (0.43 m^3 m^{-3}).

Comparisons between predicted and observed soil water contents for the fallow plots under the four irrigation treatments were made for the seven sampling dates over the course of the experiment. Agreement between the water contents predicted by the Richards equation and measured values is generally good (R^2 = 0.80) (Table 2). The mean and the standard deviation of the predicted soil water content were very similar to measured values when taken over all sampling dates, depths, and treatments (Table 2). Using a soil profile that was homogeneous with respect to bulk densities and saturated hydraulic conductivities results in a lowering of the R^2 to 0.73, without substantially affecting predicted fluxes.

The predicted and measured water present in the total soil profile (upper 1.80 m) are shown in Figure 2*a* for the irrigation treatments 1.6 PET and 0.3 PET. A difference of 20 mm of total water in the soil profile (1.80 m) corresponds to only 0.01 m^3 m^{-3} difference in average water content throughout the profile. Good agreement is obtained between the Richards equation and measured data for all but the excess water (1.6 PET) treatment. The relationship of the log of soil water potential to the log of soil water contents is not linear over the whole range of soil water potentials for this particular soil (Figure 1). When the Campbell equation is fit to the range from −6 to −1500 J kg^{-1}, water contents at the wet end of the moisture release curve will be underpredicted, while a reasonable fit is provided at low water potentials (Figures 2 and 3). Soil water content predictions can be improved in the high water content range, when using parameters fit to moisture release data from −6 to −100 J kg^{-1}, only. The choice of the range of water potentials to use to calculate the air entry potential and *b* value has a strong effect on their values, particularly on the value for *b* in the Campbell equation (Figure 3).

While the tipping bucket routine predicts average soil water contents rather well (Table 2), variability of soil water content with depth in the soil profile and over time is not as well predicted (Table 2, Figure 2*a*). The tipping bucket routine is sensitive to the value chosen for field capacity, since it will (under fallow conditions) not decrease soil water

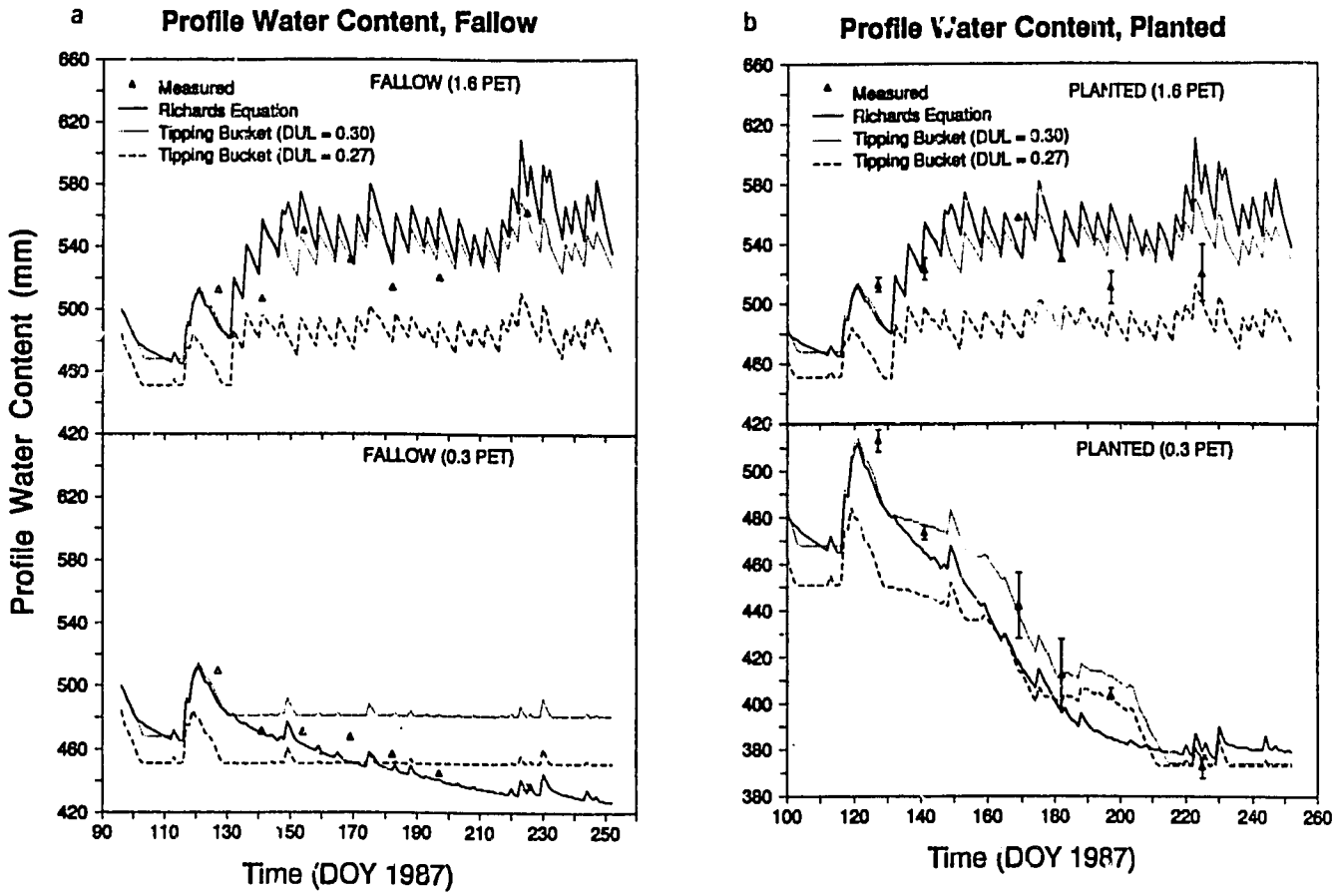

Fig. 2. Total soil profile water content (to 1.80 m) as measured and as predicted by the Richards equation and the tipping bucket procedures for irrigation treatments 1.6 PET and 0.3 PET. (*a*) Fallow soil. (*b*) Soil planted to corn.

contents, except for the surface soil, below this value (Figure 2*a*). Field capacity calculated at -33 J kg^{-1} is typically thought to underestimate the amount of available water in these soils [*Wolf*, 1975]. While the -33 J kg^{-1} value (0.27 m^3 m^{-3}) underpredicted "field capacity" water content for the wet treatment, it represented a reasonable average water content for the dry treatment (Figure 2*a*). The -10 J kg^{-1} value for field capacity of 0.30 m^3 m^{-3} resulted in better predictions in the wet treatments and across all treatments (Table 2). The total profile water content predicted by the tipping bucket routine oscillates around the value corresponding to field capacity. However, it cannot simulate continued drying as can the Richards equation and so is inconsistent with field observations.

Cropped treatments. For the purpose of predicting the soil water budget, measured leaf area indices over time were used in the model to partition potential evapotranspiration. Leaf area development also affected the modeled rate of dry matter accumulation, which in turn affected predicted rooting depth. As in the fallow plots, the Richards equation again predicts water contents and their distribution with depth reasonably well (R^2 = 0.83) (Table 2), except in the wet treatment (1.6 PET), where the misfit of the moisture release curve causes predicted water contents to be too high (Figure 2*b*). The tipping bucket method predicted average soil water contents in the dry range well. When DUL = 0.27 m^3 m^{-3} was used, soil moisture content in the wettest treatment was underpredicted (Figure 3*b*). The higher value for field capacity of 0.30 m^3 m^{-3} improved predictions in the wettest treatment. The dry treatments were not affected by the value chosen for field capacity due to water uptake by the corn crop. The correlation between simulated and measured water contents for the tipping bucket model is poorer than for the Richards equation (R^2 = 0.70 or 0.66 compared to 0.83), suggesting that the tipping bucket model has less ability than the Richards equation to predict water content distributions in the soil profile. The underprediction of water uptake by the Richards equation and the tipping bucket method toward the end of the growing season (DOY 215) in all treatments but the wettest could be the result of advection, which has been identified as an important factor in the energy budget under Cerrado conditions [*Luchiari*, 1988]. This is supported by the comparison of Priestley-Taylor predicted ET rates with "Class A" pan measurements. The increase in evaporative demand after DOY 180 as indicated by the pan data is not predicted by the Priestley-Taylor equation.

Water Budget Components

The predicted fluxes of applied water (soil evaporation and drainage) for the entire crop growing season (DOY 111–252) are shown in Figure 4*a* for the fallow soil. When totaled for the whole growing season, predictions of actual soil evaporation by the Richards equation were similar across all irrigation treatments to predictions obtained from the tipping bucket routine. Predictions of drainage using the two methods were generally very similar, with lower predictions at

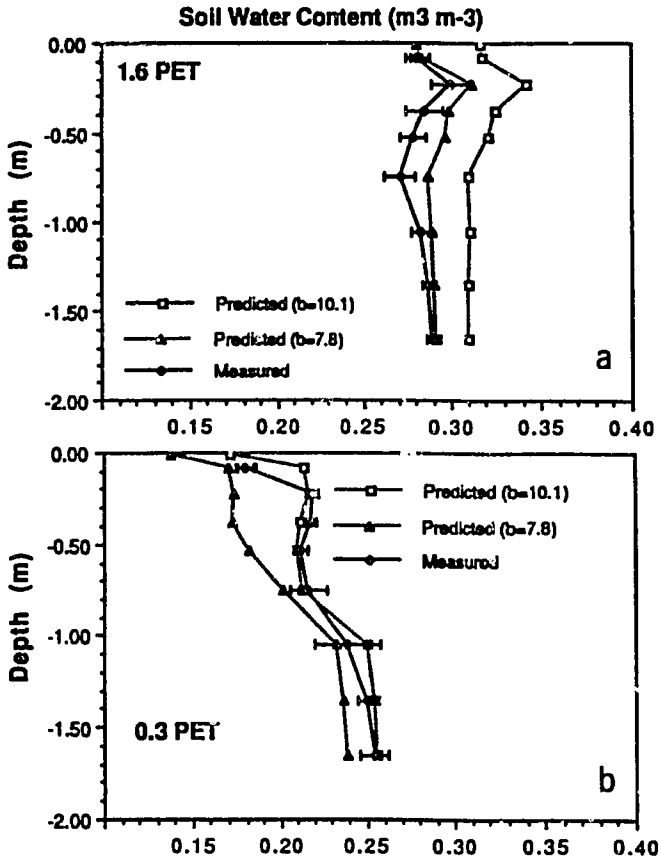

Fig. 3. Effect of moisture release curve parameters on water content predictions fit to whole water potential range (b = 10.1) and fit to wet range only (b = 7.8) for irrigation treatments (a) 1.6 PET and (b) 0.3 PET.

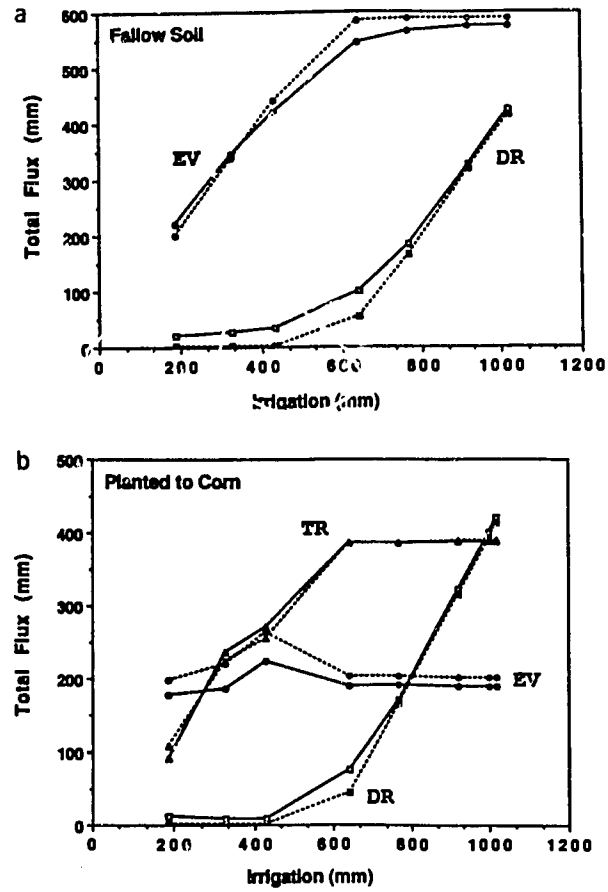

Fig. 4. Predicted season totals of drainage below 1.20 m (DR), predicted soil evaporation (EV) and predicted actual transpiration (TR) for soil over a range of irrigation water applications. Values for the Richards equation are shown by open symbols, for tipping bucket routines by closed symbols. (a) Fallow soil. (b) Soil planted to corn.

the dry end using the tipping bucket method due to the concept of a set field capacity.

Water fluxes in cropped treatments predicted by the tipping bucket and Richards equation approaches when summed over the entire growing season and across all irrigation water treatments are very similar (Figure 4b). For irrigation amounts less than PET (640 mm), the Richards equation predicts somewhat higher flux for actual transpiration, except for the driest treatment, where the tipping bucket (with DUL = 0.30) predicts a slightly higher amount.

While total fluxes predicted by the two models are rather similar when summed over the entire growing season, water fluxes predicted on individual days differ greatly. Because the tipping bucket routine redistributes water in the soil profile in discrete increments, predicted soil water fluxes across the 1.20-m depth (maximum crop rooting depth) are not continuous, as are fluxes predicted by the Richards equation (Figure 5). In the tipping bucket routine, on a daily time scale drainage rates are higher and of shorter duration than drainage rates predicted by the Richards equation (Figure 5).

The temporal scale of observations is also important when comparing the predictions of actual transpiration. While total amounts for the season are quite similar, the two models predict a distinctly different time course of actual transpiration. Irrigation was initiated on DOY 132, after which actual rates of transpiration proceed at potential rates for 20 days in treatment 0.3 PET (Figure 6). After DOY 152, reduced transpiration is predicted by the tipping bucket while the reduction in transpiration predicted by the Richards equation does not occur until DOY 155 and is more gradual. The value chosen for field capacity in the tipping bucket model affects the predicted time course of actual transpiration (Figure 6).

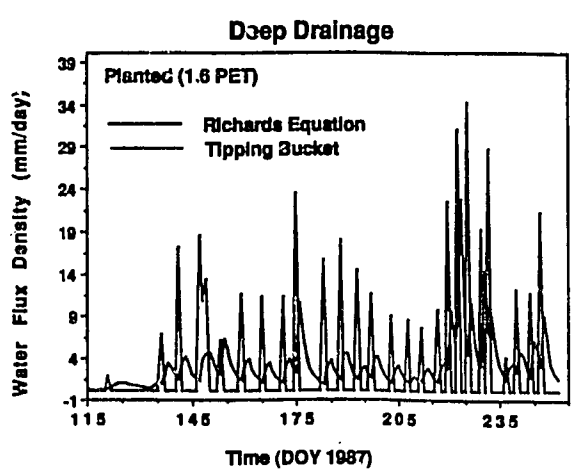

Fig. 5. Water fluxes below 1.20 m predicted by the Richards equation and the tipping bucket routines for irrigation treatment 1.6 PET.

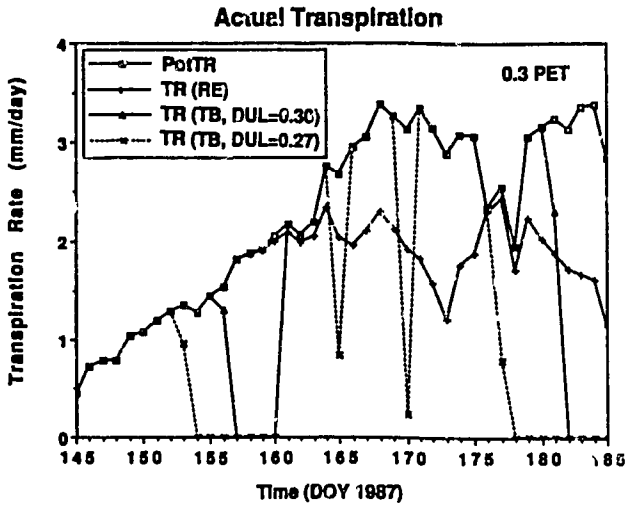

Fig. 6. Potential (PotTR) and actual (TR) crop transpiration predicted by the Richards equation (RE) and the tipping bucket (TB) routine for irrigation treatment 0.3 PET.

SUMMARY AND CONCLUSIONS

Several soil properties of highly weathered Oxisols have important implications for modeling water fluxes. The soil moisture release curve of the Oxisol studied in this research resembled a silt loam on the wet end and a clay on the dry end. The two-parameter function used to model the moisture release curve [*Campbell*, 1974, 1985] does not appear to provide a good enough fit to moisture release data for these Oxisols, when fitted over the whole range of water potentials to -1500 J kg^{-1}. If the emphasis of the modeling effort is the prediction of water flow and water contents under well-irrigated conditions, it is advisable to use parameters fitted to the wet range (to -100 J kg^{-1}) only. Under irrigated conditions, the soil would not reach water potentials of less than -100 J kg^{-1}. Ideally, a different function better describing the unique behavior of this soil should be used.

Field saturated water contents never reach total porosity in the field, and the percentage of total porosity at field saturated water contents appears to be much lower than the percentages assumed for temperate soils. A knowledge of the soil water content at saturation in the field is essential in order to predict soil water contents correctly, using the Richards equation. The effect of decreased total porosity due to compaction and reflected in increased bulk densities does not result in an equivalent decrease in saturated water contents under field conditions.

Both the Richards equation and the tipping bucket water flow models were found to predict soil profile water contents well. Predictions of water fluxes over the entire growing season and even shorter time periods were very similar. The close similarity between predicted actual transpiration of both methods over the entire range of irrigation treatments suggests that the concept of "permanent wilting point," though simplistic, is very powerful. Both methods have their respective strengths and weaknesses. The Richards equation performed better in predicting soil water contents over the whole range of irrigation water treatments and is better able to predict soil profile water content distributions. Drainage fluxes predicted by the Richards equation are continuous as opposed to the discrete flux events predicted by the tipping bucket method.

Capacity-type flow representations such as the tipping bucket routine are used extensively in crop simulation models due to their perceived conceptual simplicity and computational efficiency. It is also often argued that input parameters for the latter model are more easily available than the parameters necessary to estimate water content–water potential relationship needed for the Richards equation. The tipping bucket water flow procedure is sensitive to the value chosen for field capacity water content, and the choice is somewhat dependent on the overall field moisture regime, e.g., irrigated versus nonirrigated. This was particularly obvious in the simulations of fallow soil conditions. Given this sensitivity, the choice of the appropriate soil water potential for field capacity becomes crucial.

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