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Seasonal water balance of a sandy soil in Niger cropped with pearl millet, based on profile moisture measurements[1]

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ABSTRACT

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In the Sahel, calculation of the field water balance from neutron-probe measurements is often difficult for pearl millet (*Pennisetum glaucum* (L.) R. Br.), which is due to the rapid drainage (D) of the sandy soils, on which it is typically grown.

We present a simple method of calculating D in these soils from weekly neutron-probe data. The method divides the water balance into two phases. In the first, applicable early in the season, water flux across the maximum depth of probe measurement (Z_m) is assumed negligible, and evapotranspiration (E) and D are calculated from the change in soil water content (θ) between the bottom of the rootzone (Z_r) and Z_m, thus allowing calculation of unsaturated hydraulic conductivity, $K(\theta)$, from the flux across Z_r. In the second phase, when soil water starts to percolate across Z_m, D is calculated from $K(\theta)$, assuming a hydraulic head gradient of -1. The method is used to calculate a one-dimensional water balance of a pearl-millet crop grown in a deep sandy soil at two fertility levels during a season of normal rainfall.

Results show that the calculated $K(\theta)$ functions compare well with those based on laboratory measurements. An acceptable estimate of drainage, and therefore E could be made. Mean cumulative E and D were, respectively, 211 and 207 mm for the unfertilized crop, and 268 and 148 mm for the fertilized crop with 440 mm of rainfall received during the crop cycle. The fertilized millet crop water balance was simulated, which compared to the calculation method resulted in an about 10% higher seasonal E and a 10% lower seasonal D.

Our study shows that E can be corrected for D using a simple but accurate method, and consistent with other studies in the region indicates that rainfall is usually not the primary limiting factor to pearl-millet production.

INTRODUCTION

The rainfed agricultural systems in the Sub-Saharan Zone are subject to a seasonal, variable and erratic rain. Rain tends to fall with high intensities on

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initially bare, both chemically and physically poor, soils, which may result in wasteful runoff. Once the profile has been replenished, soil water and valuable nutrients may percolate beyond the crop root zone and be lost to the crop. To increase and stabilize crop production efficient use of rainfall and nutrients is of crucial importance. Evaluation of the various water balance components during the crop cycle can answer questions such as: How well is the growth cycle of a crop adapted to availability of water? In this respect pioneering work in the region was done by Cochème and Franquin (1967). Crop water requirements of major cash and staple crops have been extensively studied by the Institut de Recherche Agronomique Tropicale (IRAT) at the Centre National de Recherche Agronomique (CNRA) in Bambey, Senegal (Dancette, 1974). Other questions are how would soil and crop management influence the components of the water balance.

Some field studies in the region report water use of pearl millet, but they generally lack accuracy because the drainage component was either ignored or estimated by using only rough approximations. For example, Agnew (1982) assumed a seasonal drainage of 10% of rainfall, and Nouri and Reddy (1991) assumed a negligible drainage at 3 m, the maximum depth of soil water measurement. Payne et al. (1990) recognized the importance of the drainage component, but the authors did not attempt to separate drainage from evaporation. Cissé and Vachaud (1988), by contrast, reported a comprehensive water balance study, based on soil hydraulic conductivity obtained with the instantaneous profile method, and periodic (7–10 days) simultaneous soil water profile and tensiometer measurements. Similarly, elsewhere, with Bermuda grass, Rice (1975) was able to measure evaporation and soil water fluxes bihourly, using fast-response tensiometers. But the instantaneous profile method is expensive and time consuming, and high within-field spatial variability of conductivities has been reported (Vauclin et al., 1983a).

The objective of this paper is to present a basic soil water balance calculation scheme, based exclusively on weekly soil water content measurements. The scheme includes an estimation of the unsaturated hydraulic conductivity function, and the terms drainage and evaporation. We then apply the scheme to soil moisture and crop data from a long term replicated full factorial soil and crop management field experiment. We selected two contrasting management treatments enabling both an estimation of water balance terms during the season, and their analysis of variance. Results of the water balance will be compared with those obtained with a sophisticated simulation program of water use and crop growth.

THEORY

The water balance equation of a given soil profile specifies that, over a time interval, changes in the amount of water stored in the profile (ΔS) are equal to the difference between the amount of water added (input) and the amount of water removed (output):

$$\text{Input of water} - \text{Output of water} = \Delta S \quad (1)$$

In dryland agriculture, input terms include rainfall (R), overland flow, and capillary upward flow. Output terms are runoff, drainage, and soil- and crop evaporation. Usually, in a simple seasonal soil water balance, no attempt is made to separate the evaporation from the soil and from the crop. Both processes being driven by atmospheric demand, the two terms are summed and termed evapotranspiration (E).

Due to high infiltration rates, runoff may generally be ignored. Furthermore, sustained capillary upward flow is negligible due to deep groundwater levels. Therefore the water balance (Eqn. 1) simplifies to:

$$R - (E + D) = \Delta S \quad (2)$$

The terms of Eqn. 2 are summed over a typical time period of 1 week to 10 days.

To solve Eqn. 2, R is measured with a raingauge and ΔS is established using a neutron probe. With the terms ($E + D$) remaining, an estimation of D is required to yield E as the remainder of Eqn. 2.

Depending on the soil water conditions described hereafter, either of two schemes can be considered to calculate drainage for water balance calculations (Vachaud et al., 1991). We will present these schemes in detail.

Estimation of water balance components

Let Z_m be the maximum depth of soil moisture measurement, and Z_r be the maximum rooting depth. Ideally Z_m exceeds Z_r by a large margin. The amount of water stored in the profile from the surface Z_0 down to the depth Z_m is denoted S_{0m}. Similarly, the amount of water held in the root zone, that is between the soil surface and maximum rooting depth is denoted S_{0r}, and S_{rm} is the water stored in the layer from the maximum rooting depth to the maximum depth of soil moisture measurements.

The first scheme is applicable after the prolonged dry season, during which drainage and evapotranspiration have exhausted the profile to a considerable depth. The profile moisture distribution of 7 May 1986 is typical of this situation (Fig. 1). With the onset of the rains, the crop is sown and the profile, being gradually recharged, provides water for crop growth. Normally there exists a period during which soil moisture at Z_m remains sufficiently low, so that the hydraulic conductivity can be considered to be negligible, and therefore the water flux at $Z = Z_m$, given Darcy's equation, is negligible. Consequently, both the cumulative E and D_r can be calculated on the basis of the change in total water stored in the profile to the depth $Z = Z_m$. Between soil water content measurements at time t and time $t + dt$, E can be estimated by:

$$E = R + S_{0m(t)} - S_{0m(t+\Delta t)} \tag{3}$$

and the drainage through the Z_r plane is calculated from the change in moisture stored in the profile between depth Z_r and Z_m:

$$D_r = S_{rm(t)} - S_{rm(t+\Delta t)} \tag{4}$$

or, in terms of water flux density:

$$q_r = D_r / \Delta t \tag{5}$$

Conditions applicable to scheme 1 prevail longer with low rainfall and high evapotranspiration demands, and with a greater Z_m.

The second scheme comes into effect when the new rains have recharged the profile to the extent that the soil water content at Z_m begins to increase (corresponding to 12 July in Fig.1). Percolation of water through the Z_m plane ceases to be negligible. The calculation of E between times t and $t + \Delta t$ requires the estimation of the amount of water draining below the root zone. This can be done applying Darcy's equation at depth $Z = Z_r$:

$$D_r = q_r \Delta t = -K(\theta) \text{ grad } H \, \Delta t \tag{6}$$

where q_r is the water flux density, and $K(\theta)$ the unsaturated hydraulic conductivity at the maximum rooting depth $Z = Z_r$. K is a function of the volu-

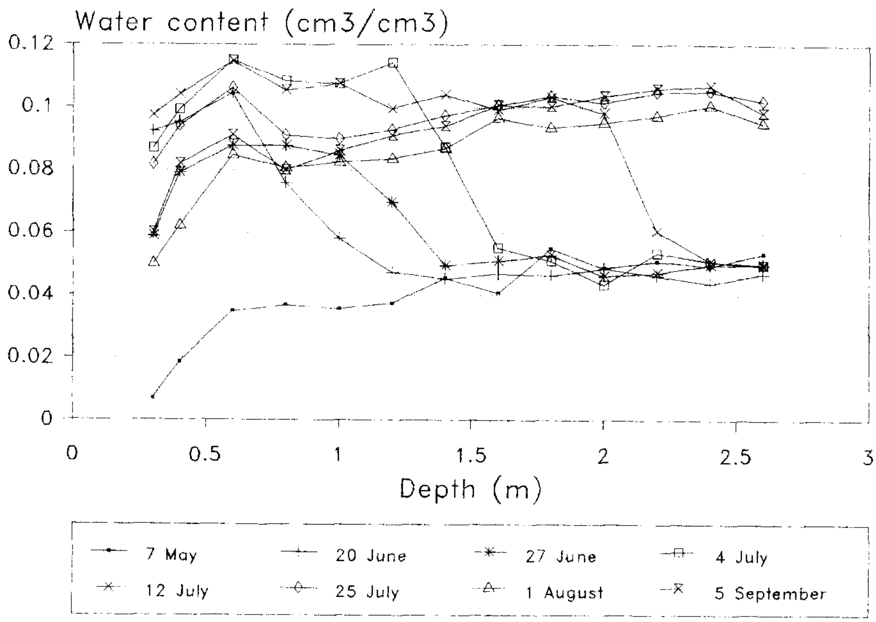

Fig. 1. Typical seasonal plot profile water distribution for an unfertilized pearl millet cropped deep sandy soil, ISC, Niger, 1986 rainy season.

metric water content of the soil θ ($cm^3\ cm^{-3}$), and grad H ($m\ m^{-1}$) is the hydraulic head gradient at depth $Z = Z_r$ with $H = h - z$ (m), the sum of pressure and gravitational potential, with Z expressed as depth measured positive downwards. The water balance equation in scheme 2 is:

$$E = R + S_{0r(t)} - S_{0r(t+\Delta t)} - q_r \Delta t \tag{7}$$

with $S_{0r}(t) - S_{0r}(t+\Delta t)$ equal to the change in soil water amount held in the profile from the surface to the maximum rooting depth Z_r between times t and $t + \Delta t$.

Clearly the soil water balance in scheme 2 is more complicated to determine, as it requires the a priori knowledge of the $K(\theta)$ relationship and the simultaneous measurement of grad H with tensiometers. In this paper we surmount this problem by making an initial simplification, namely the assumption of gravitational flow, or grad $H = -1$, which would be correct if, in a flow situation, θ remained constant with depth ($d\theta/dZ = 0$) in the neighbourhood of the depth considered. This assumption also permits an estimation of the $K(\theta)$ function at $Z = Z_r$ during the period of crop establishment making use of scheme 1, as we will see shortly.

Direct estimation of $K(\theta)$

If, during a time interval for conditions of scheme 1, the amount of water stored between the plane Z_r and the maximum depth of measurement increased by ΔS, the same amount of water must have drained through that plane (Eqn. 4). A single $K - \theta$ value of the soil hydraulic conductivity function can thus be estimated using Eqn. 6:

$$K(\theta_a) = -D_r / (\text{grad } H\, \Delta t) \tag{8}$$

where θ_a is the arithmetic mean of the soil water content at the beginning ($t = t$) and end of the time interval ($t = t + \Delta t$) measured at $Z = Z_r$. D_r is equal to the increase of water ΔS below $Z = Z_r$, and grad H is taken as -1. Two important restrictions must be kept in mind:

(i) Given the highly non-linear change of K with θ, calculations should be limited to those periods during which the changes in water content at $Z = Z_r$ are small.

(ii) The assumption of grad $H = -1$ holds when the curvature of the water content profile at $Z = Z_r$ is small, so that the case of a passing wetting front is inapplicable.

Repeating this calculation for different periods will yield per plot a $K(\theta)$ function over a range of θ_a values. The established $K(\theta)$ function will thus permit the calculation of drainage beyond the root zone as soon as the soil water content at the maximum depth of measurement begins to increase. The water balance, Eqn. 7, of scheme 2 is therefore rewritten as:

$$E=R+S_{0r(t)}-S_{0r(t+\Delta t)}-K(\theta_a)\Delta t \tag{9}$$

MATERIALS AND METHODS

We used soil moisture data from an experiment conducted at the ICRISAT Sahelian Center, 40 km southeast of Niamey, Niger. The soil is classified as Psammentic Paleustalf (West et al., 1984), with a sandy yellowish red surface horizon to a depth of 0.3 m (total sand about 91%), and a red sand Bt horizon to more than 2 m (total sand about 88%). Cation-exchange capacity is about 10 mmol kg^{-1}, the surface pH (KCl) is between 4.5–5.5, and organic matter levels are of the order of 0.3%. The highest soil bulk densities, 1.58 Mg m^{-3}, are found in the surface horizon (0.05–0.10 m depth). The bulk densities decrease reaching a minimum of 1.46 Mg m^{-3} at a depth of 0.3 m, and then gradually increase to 1.55 Mg m^{-3} at a depth of 2.6 m. Soil water content at field capacity is 0.09 to 0.10 cm^3 cm^{-3}, while residual soil water content is about 0.015 cm^3 cm^{-3}. The saturated hydraulic conductivity is high, decreasing from 5500 mm day^{-1} to 3000 mm day^{-1} as soil bulk density increases from 1.45 to 1.60 Mg m^{-3}. Further soil physical properties of this soil are given by Hoogmoed and Klaij (1990). Rainfall simulations on 1.5×1.5 m plots on a similar profile (3–4% slope) demonstrated a sustained infiltration capacity of 100 mm h^{-1} (the maximum rain simulator intensity) for over 2 hours (ICRISAT, 1985). Actual run-off from an untilled millet cropped plot of the experiment, resulting from individual storms, was 1.5% at most from 1984 to 1987.

Rainfall

In Niger, rainfall distribution is monomodal. At Niamey annual rainfall (1907–1988) is 560 mm with a standard deviation of 136 mm (Sivakumar, 1989). Normally rains begin early June and last until early September. Daily totals of rainfall were taken from an 8-inch diameter (20.3 cm) rain gauge at a height of 0.3 m between two replications adjacent to the experimental field.

Soil moisture measurements

We measured soil water content in the top 0.3 m by gravimetric sampling. To convert gravimetric moisture data to volumetric moisture content, we assumed an average soil bulk density of 1.5 Mg m^{-3}. A Troxler model 3322 neutron probe (Troxler Electronic Laboratories, Inc. Research Triangle Park, NC, 27709 U.S.A.)*was field calibrated, using four minute counts from soil depths of 0.3 m, and from 0.4 m to a depth of 2.6 m at 0.2 m intervals. All depths were combined to obtain a single linear regression equation relating θ to count ratio. For a total of 34 points we obtained a correlation coefficient of 0.975. Standard errors of measured water contents are typically 0.02 cm^3

cm^{-3} for gravimetric sampling, and 0.015 cm^3 cm^{-3} (Vauclin et al., 1983b) for neutron-probe measurements. The amount of water stored in the profile was calculated by trapezoidal integration of the soil moisture content values over the depth of the profile. Accuracy of this estimate almost entirely depends on uncertainties associated with calibration (Vauclin et al., 1983b) and is typically ± 4 mm for a storage of 260 mm (profile at field capacity).

Soil moisture measurements started on the day of sowing and were continued on a weekly basis until harvest. The obtained soil moisture content-soil depth profiles were plotted to establish the date of incipient drainage beyond the 2.6 m plane.

Experiment

Two contrasting management treatment combinations were selected from a long-term full-factorial soil management experiment conducted on a sloping (3–4%) deep sandy soil since 1984. The experiment is laid out in three replications along the slope. The low-fertility treatment represented the local practice, that is direct sowing without other inputs. The high-fertility treatment included the annual application of P (30 kg ha^{-1} of P_2O_5), before sowing, and a split application of N (40 kg ha^{-1}), and leaving the crop residue after harvest. The fertility treatment plots were 6×20 or 6×24 m (depending on the replication block). These plots were split into subplots (plot size 3×20 m, or 3×24 m) to compare the local millet (cv Sadoré local) with an improved variety (cv CIVT). Neutron-probe access tubes were installed in all subplots to a depth of 2.6 m. A 0.75×1 m planting pattern (13300 hills ha^{-1}, three plants per hill) was used. The crop was hand weeded regularly. Above ground dry matter yield was determined at harvest. We used the data of the 1986 rainy season, in which millet was sown on 29 May (day 0), following a storm of 40.7 mm.

Root profile measurements made during the same season in a parallel experiment showed that, 68 days after planting, roots sampled in the 0.9 to 1.05 m soil layer represented no more than 1.2% of the total root mass. Therefore we took $Z_r = 1.4$ m as maximum effective rooting depth and reference plane of drainage. Payne et al. (1990) reported a maximum rooting depth of 1.4 m on a similar soil.

Soil water balance calculation

Initially, D beyond the maximum rooting depth Z_r, was calculated from changes in S_{om} as in Eqns. 3 and 4, and used to determine $K(\theta)$ as described in scheme 1. Bearing in mind the inherent errors in the estimation of water stored, we estimated $K(\theta)$ exclusively for time intervals (of 7 days) during

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which the increase of water stored in the profile exceeded 3 mm. Thus the minimum K value that could be estimated was $3/7=0.43$ mm day^{-1}.

After the water flux across the maximum measuring depth of soil water, Z_m, became significant, E and D were calculated using Eqn. 9 of scheme 2.

Each period yielded one value of E and D per subplot, and the analyses of variance were computed.

Simulation of field water balance

We used the simulation program DUET (Huygen, 1988) as a reference for comparing the evolution of the various balance terms resulting from the simple method. DUET combines two simulation programs: WOFOST, a dynamic crop growth model, and SWATRE which solves the one-dimensional water flow in the unsaturated zone. Principles underlying the crop growth program are described by van Keulen and Wolf (1986); details of the program are documented by van Diepen et al. (1988). SWATRE is a revised (Extended) version of SWATR (Belmans et al., 1983), based on the work of Feddes et al. (1978).

The soil hydraulic conductivity was determined according the 'hot-air method' (HAM) (Arya et al., 1975) for a soil water content up to 0.15 cm^3 cm^{-3}. The wet range $K(\theta)$ function was obtained by fitting the measured saturated conductivity and textural properties using a regression equation of Vauclin et al. (1983a). Tensiometer data were fitted to obtain the soil water content pressure head curve $h(\theta)$, using the model of van Genuchten (van Genuchten, 1980).

DUET was calibrated using field crop observations of the LAI development of a millet crop grown under similar (date of sowing, soil water conditions, fertilizer application) conditions. The LAI is the basis for calculations of the daily soil evaporation, and crop transpiration. No low-fertility LAI data were available, hence only the high-fertility millet was simulated.

RESULTS AND DISCUSSION

Seasonal rainfall

Periodic rainfall during the experiment is given in Table 1. The monthly rainfall received was in close agreement with the long-term monthly rainfall. A total of 61.4 mm was received in the month of June (mean= 67 mm), 138 mm in July (mean=143 mm),and 194 mm in August (mean=193 mm). The monthly distribution of rainfall in terms of rainy days per month was also close to the average.

The soil hydraulic conductivity

The wetting front, resulting from the cumulative rain, did not advance be-

TABLE 1

Crop fertility management effect on periodic average (mm day^{-1}) evapotranspiration (E), and drainage[1] (D) rates of a pearl millet crop. ISC, 1986 rainy season

Period	Number of days	Number of storms	Rainfall in period (mm)	Av. daily open pan (mm)	E			D		
					low-fert.	high-fert.	SE ±[2]	low-fert.	high-fert.	SE ±
29 May–6 June	7	1	0.7	10.7	1.61	2.54	0.207	0.12	0.03	0.091
6 June–13 June	7	2	3.0	9.6	1.07	0.87	0.182	0.21	0.12	0.080
13 Juhne–20 June	7	2	45.5	10.9	1.87	2.76	0.980	0.19	0.40	0.133
20 June–27 June	7	1	12.2	10.2	2.38	2.55	0.103	−0.15	−0.26	0.137
27 June–4 July	7	1	38.5	9.6	0.88	1.60	0.781	0.58	0.12	0.189
4 July–12 July	8	2	61.0	7.2	3.12	4.52	0.354	2.89	1.22	0.598
12 July–18 July	6	2	39.1	7.3	4.37	4.00	0.094	3.84	2.98	0.915
18 July–25 July	7	4	32.1	8.3	1.74	3.38	0.882	3.82	3.18	0.487
25 July–1 August	7	2	5.8	7.0	1.84	3.16	0.225	2.84	2.50	0.487
1 Aug.–8 August	7	2	78.1	5.5	1.56	3.90	0.468	2.90	1.86	0.509
8 Aug.–15 August	7	1	28.3	6.6	5.72	4.63	0.859	3.27	1.79	0.429
22 Aug–29 August	7	2	19.6	6.6	1.09	0.62	0.379	3.17	2.44	0.307
29 Aug.–5 Sept.	7	2	14.8	8.6	2.64	1.87	0.331	3.01	3.16	0.361

[1]Drainage at a soil depth of 1.4 m.
[2]Standard error of the fertility means in the two preceding columns.

yond the maximum depth of soil water content measurement until 12 July on the low-fertility plots (Fig. 1), and 18 July on the high-fertility plots.

Hence, 6–7 consecutive time intervals were available for water balance calculations based on scheme 1. Each time interval yielded per plot a value for the drainage D, from which in principle a single K value could be estimated. Analyses of variance of D for the time intervals in scheme 1 showed coefficients of variation decreasing from 184% for an average calculated drainage rate of 0.06 mm day^{-1} to 41% for an average drainage rate of 3.85 mm day^{-1}. There were no cultivar-, nor cultivar × fertility interaction effects. A weak fertility effect ($P=0.136$, and $P=0.109$) at the later dates possibly reflected a higher transpiration rate from a more rapidly growing high-fertility millet.

However, replication was the single most important effect, with D significantly different among replications for two time intervals ($P=0.019$, and $P=0.015$) and at one time interval less significant ($P=0.096$). In view of the replication effect we pooled all the obtained $K\times-\theta_a$ plot values per replication. The θ_a values were regressed against the K values using the equation:

$$K=a\theta^{\beta} \qquad (10)$$

Regression analysis showed that regressions were significantly different between the 3 replications in level only ($P=0.021$). Within the field capacity soil water content range of 0.09–0.10 cm^{3}cm^{-3} $K-\theta_a$ values for individual plots all lie within a relatively narrow range (Fig. 2). Nevertheless, from Fig.

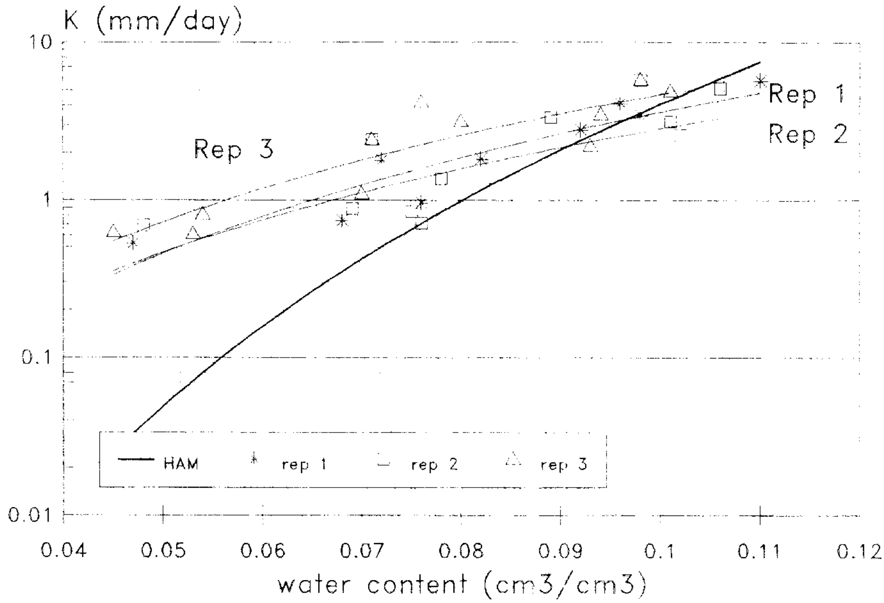


Fig. 2. Calculated $K(\theta_a)$ values and their regression compared to the HAM $K(\theta)$ function.

2 it can be seen that at an average water content of 0.10 cm^{3}cm^{-3}, regressed drainage rates are 3.5 mm day^{-1} in replication 1, 2.8 mm day^{-1} in replication 2, and 4.6 mm day^{-1} in replication 3. The use of one single $K(\theta)$ function in the calculation of drainage using scheme 2 resulted in a wider range of calculated cumulative E (data not shown).

The observed differences among the three replications of the $K(\theta)$ function are possibly caused by soil textural difference associated with the position of the plots along the slope. From the work of Vauclin et al. (1983a) it appears that K is highly sensitive to small textural differences. From ten sites in the Northern and central parts of Senegal, Vauclin et al. (1983a) used observed $K_i(\theta_i)$ values obtained by the instantaneous profile method to model K according:

$$K = K_0(\theta/\theta_0)^{\beta} \tag{11}$$

where θ_0 is the apparent saturated soil moisture content at the final infiltration rate K_0, and β a shape parameter. The sites have a measured percentage of clay+fine silt (particle size $< 20\ \mu$) of 3.5–13%, enabling the establishment of a correlation between this percentage with K_0, and the shape factor β.

We determined the average profile percentage of particles $< 20\ \mu$, for all subplots. The obtained values were within a narrow range (8.4 ± 0.39). However, analysis of variance showed no significant differences among replications. Applying the model of Vauclin et al. (1983a) to our data resulted in a hydraulic conductivity range at $\theta = 0.10\ cm^3cm^{-3}$ of 3.6 to 5.3 mm day^{-1}, agreeing well within the observed range in our experiment.

Recognizing the limitations of the HAM (Dirksen, 1991) we compared the $K(\theta)$ function with the calculated $K(\theta_a)$ values. The latter values show a higher hydraulic conductivities at the lower soil water content range. This was possibly caused by insufficient compliance to the two earlier assumptions of our method. The assumption of a hydraulic gradient of -1 may not have been valid during downward water movement in an initially dry profile. In this case, the gradient would be steeper (more negative), implying a lower K. The other assumption of a mean soil water content θ_a between two measurements, implies that $K(\theta)$ is linear over the particular soil moisture content interval, which is obviously not the case. During scheme 1, θ at the depth of drainage increased by and large steadily, and with it, progressively the actual momentary hydraulic conductivity. Therefore, most of the measured drainage occurred during the last part of the period, underestimating θ_a.

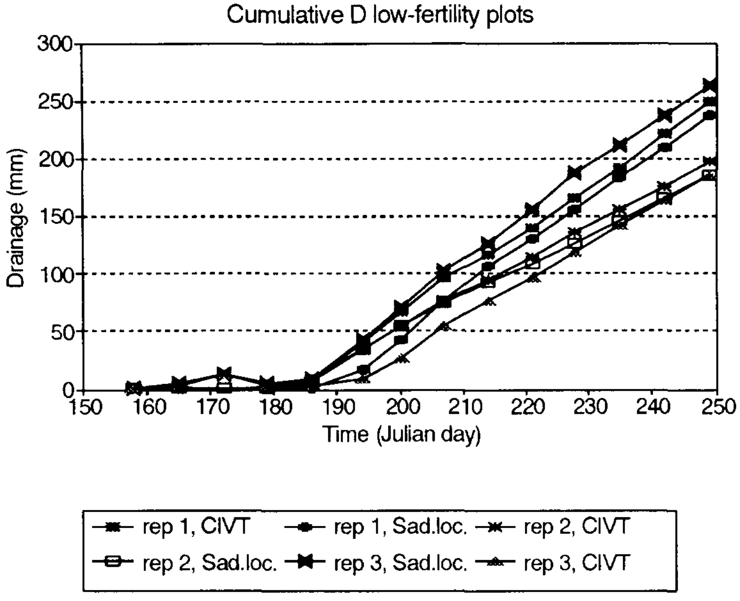
Soil water balance

A total of 440 mm of rain was captured between the date of sowing and harvest, 3% more than the average in that period, indicating that the season was close to a perfect long-term average. Values of D and E could be calcu-

TABLE 2
Crop fertility management effect on cumulative evapo-transpiration (E) and drainage[1] (D) (mm) of a pearl millet crop, compared to a simulated E and D of a high-fertility millet crop, ISC, 1986 rainy season

Date	Number of days since sowing	Cumulative rainfall (mm)	E			D			Simulation	
			low-fert.	high fert	SE±[2]	low-fert.	high-fert.	SE±	E	D
29 May	0									
6 June	7	0.7	11.3	16.8	1.43	0.9	0.2	0.94	11.0	0.1
13 June	14	3.7	18.6	22.9	2.36	2.3	1.1	1.05	18.6	0.2
20 June	21	49.2	31.8	42.2	7.19	3.6	3.9	0.63	34.7	3.3
27 June	28	61.4	48.5	60.0	7.34	2.6	2.1	0.35	54.8	6.2
4 July	35	99.9	54.6	71.2	8.90	6.7	2.9	1.60	78.6	8.8
12 July	43	160.9	79.5	107.1	11.14	29.7	12.7	6.35	106.3	13.7
18 July	49	200.0	105.5	131.0	12.20	52.8	30.6	11.59	125.2	48.9
25 July	56	232.1	117.3	154.7	15.56	79.4	52.8	12.92	153.4	60.6
1 August	63	237.9	130.5	176.8	14.71	99.2	70.2	13.96	175.6	65.0
8 August	70	316.0	141.3	203.8	17.72	119.2	83.3	13.96	201.8	71.8
15 August	77	344.3	183.3	236.3	14.17	142.2	95.7	13.38	224.2	93.5
22 August	84	405.8	185.0	250.2	17.72	163.0	108.5	14.29	253.4	97.0
29 August	91	425.4	192.8	254.5	20.33	185.3	125.3	15.98	281.1	124.7
5 September	98	440.2	211.2	267.8	22.43	207.2	147.5	18.34	295.2	131.7

[1]Drainage at a soil depth of 1.4 m.
[2]Standard error of the fertility means in the two preceding columns.



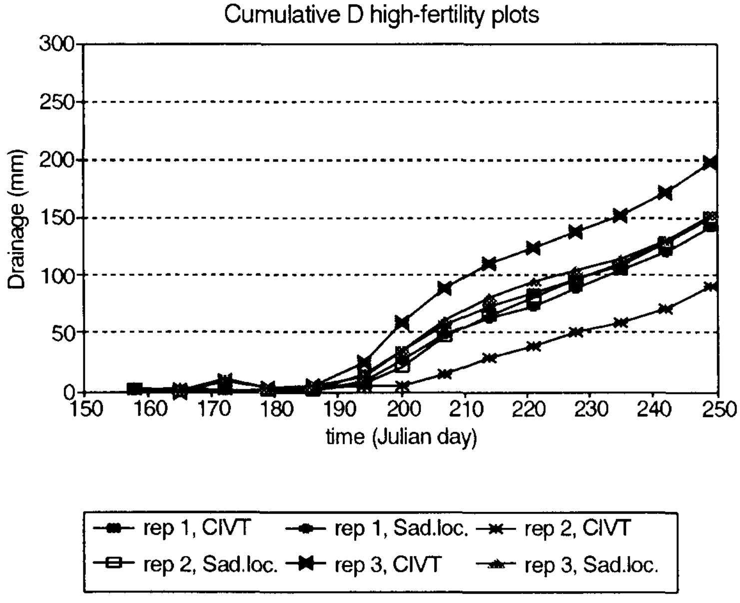
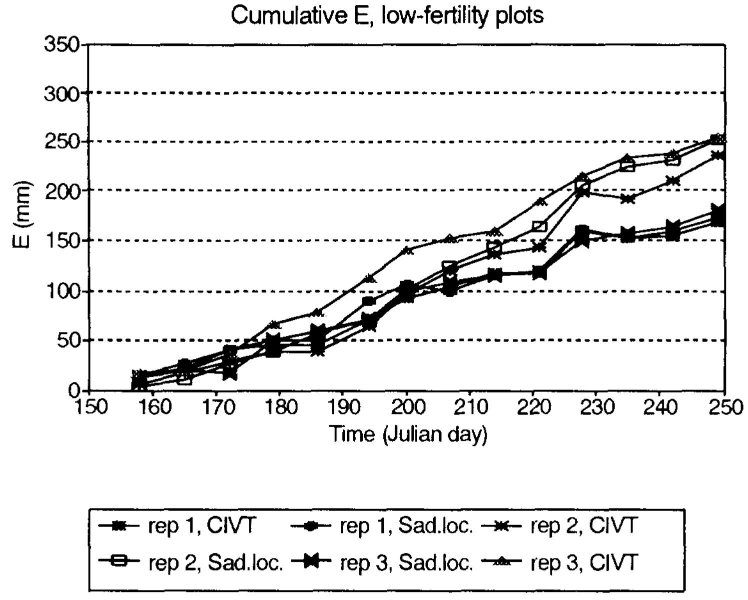


Fig. 3. Cumulative drainage of low-fertility and high-fertility millet plots, ISC, Niger, 1986 rainy season.

lated according scheme 1 for the first 6 time intervals in low-fertility plots, and the first 7 time intervals for the high-fertility plots. For the remaining time intervals the water balance was based the water balance calculating D



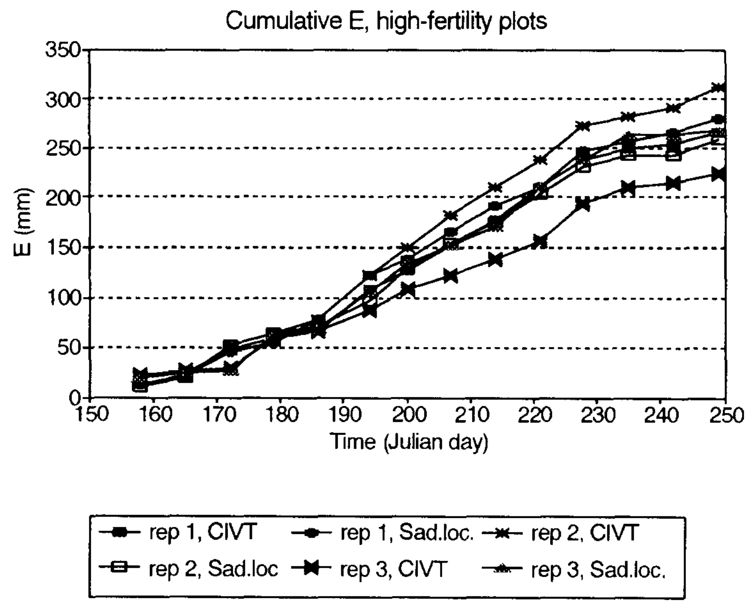


Fig. 4. Cumulative evapotranspiration of low-fertility, and high-fertility pearl-millet plots, Niger, 1986, rainy season.

with the help of the earlier established $K(\theta)$ functions, using for each replication the appropriate equation.

Analyses of variance of weekly, and cumulative E and D values were cal-

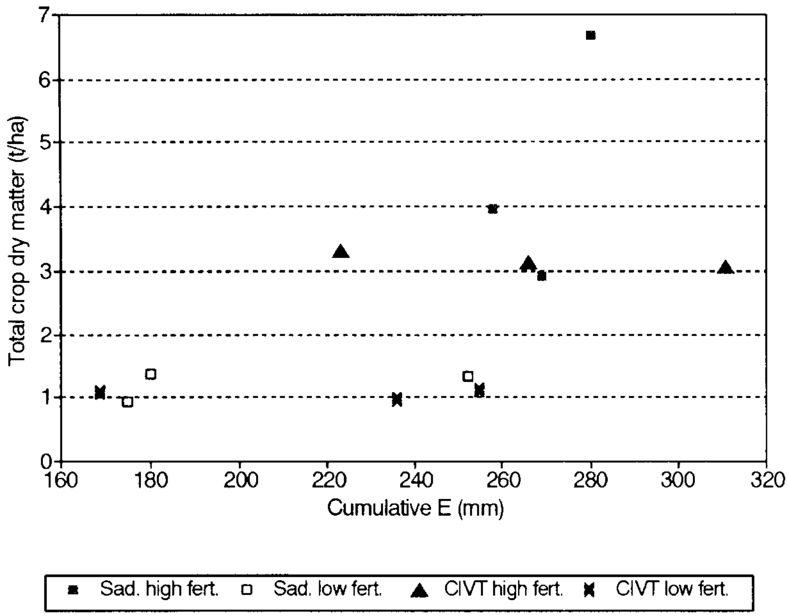


Fig. 5. Relationship between above ground total crop dry matter yield and cumulative evapotranspiration for low-fertility, and high-fertility pearl-millet plots, ISC, Niger, 1986, rainy season.

culated for all periods. Fertility became gradually more significant as the high-fertility treatment millet developed an increasingly higher LAI. Cultivar differences were not significant at any period. Average rates of low- and high-fertility plots along with weather data are presented in Table 1, and cumulative D and E are given in Table 2.

Under both fertility levels, drainage commenced about the same time at about 40 days after sowing. This was to be expected as during the early stages, with yet little difference in crop canopy development and much of the soil surface bare, soil evaporation is the main contributor to E. Once the root profile is at field capacity, and the crop growth differences due to fertility become more pronounced, much higher drainage rates are calculated in the low-fertility plots.

To appreciate the variability of the data, we plotted cumulative E and D for all plots. (Figs. 3 and 4). We would expect a positive relationship between E and crop dry matter and this is plotted in Fig. 5. Clearly, fertility greatly affected crop yield, with on average low-fertility millet yielding 1.14 t ha^{-1} and high-fertility millet yielding 3.85 t ha^{-1} of crop dry matter (SE$=\pm 0.410$). Though the data pairs are scattered, there seems to be a weak positive relationship between E and yield. Part of the scatter may be due to relating plot yield data which were obtained from the two center plant rows (1.5×20 or

24 m), with a plot water balance based on one neutron-gauge measurement which is a point measurement. Secondly, in general weed regrowth is more abundant in plots having lower LAIs thus generally the unfertilized plots, which would overestimate the crop E in those plots.

Simulation

Estimated cumulative E values of the high-fertility plots agree very well with those of the simulation until 8 August (Table 2). In the following period, 8–15 August, the average soil water content is 0.08 $cm^3 cm^{-3}$ giving an average drainage of 1.8 mm day^{-1} for high-fertility plots, equal to 12.6 mm for the period. The simulation model shows a sudden increase in soil water content following abundant rainfall, declining at a falling rate hereafter (Fig. 6). Consecutive simulated daily fluxes in the period were 8.5, 5.6, 3.6, 2.8, 2, 1.6 and 1.3 mm, totaling 25.4 mm. In this case, the underestimated θ resulted in an under-estimation of 12.8 mm and consequently an overestimate of E.

Visible crop drought stress did not occur and the resulting E should be very close to the potential E. Indeed, the simulation model calculated equal cumulative potential and actual transpiration of 193 mm, and a cumulative soil evaporation of 102 mm, bringing the seasonal E to 295 mm. For a similar pearl millet and soil profile close to the ISC, Payne et al. (1990) report a seasonal E of 272 mm, very close to our result, with 312 mm rainfall received for the duration of the crop cycle. Nouri and Reddy (1991) report 328–331

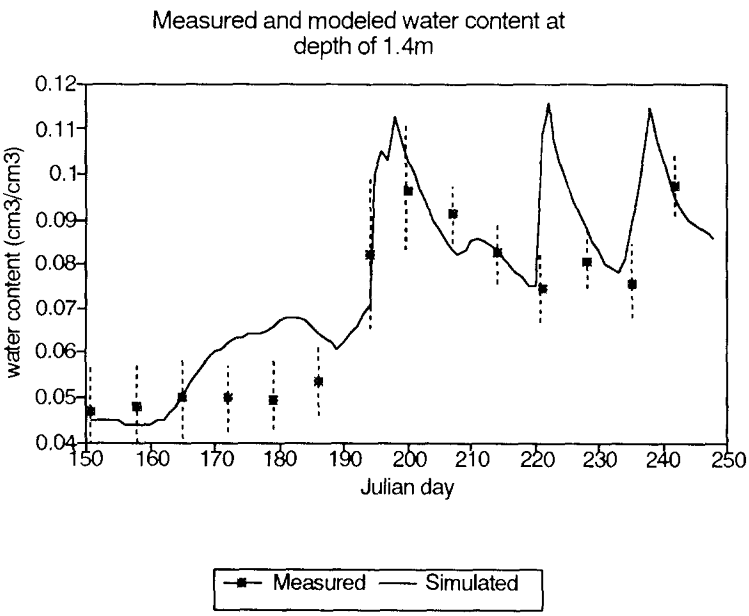


Fig. 6. Average measured and simulated soil water content at 1.4 m depth of a sandy profile cropped to high-fertility pearl millet, ISC, Niger, 1989 rainy season.

mm with 392 mm rainfall received. The latter assumed a zero drainage at the maximum dept measured, which could have overestimated E. Cissé and Vachaud (1988) report for millet under improved fertility management in Thilmakha (the center of Senegal) an E of 230 mm with a rainfall of 229 mm, and 260 mm with a rainfall of 301 mm. They measured a seasonal drainage of 42 mm at a soil depth of 1.8 m in the latter case.

Under average circumstances the amount of water stored in the profile at harvest is of no use to the next year's crop as the combined processes of soil evaporation and drainage during the long dry season result in an almost complete loss of the remaining soil water stored at the time of harvest. However, if an exceptionally dry year follows, an extra 10–20 mm stored in the profile might mean the difference between some yield and complete failure.

Though there seems to be a weak positive relationship between E and crop dry matter yield, the scatter of our field crop data from one season, and those of Cissé and Vachaud (1988), do at this stage not allow a general relationship between E and crop yield to be made. However, in an average year substantial amounts of water are not used in producing crop dry matter when millet is grown in the traditional manner. The cultivation system based on fertilization and use of crop residue combines a modest increase in total water use by 57 mm to 268 mm with a substantial higher production level. This indicates that on average, soil water is not the primary limiting factor, but low soil fertility, a conclusion earlier reached by Fussell et al. (1987).

CONCLUSION

The simple water balance terms are in good agreement with those calculated with the simulation model. This means that for an average year, soil water drainage amounts to 207 mm for local treatment, whereas modest doses of chemical fertilizer and the use of crop residues increase total water use by 57 mm to 268 mm. Because of the enormous crop response to improved soil fertility management, average yields increased considerably from 1.14 to 3.85 t ha^{-1}. The calculated $K(\theta)$ function allowed an acceptable estimate of drainage to be made and therefore a calculated realistic estimate of E. The E reported in the literature is often overestimated as the drainage component is altogether ignored. However, the rapid internal drainage typical of this deep sandy soil could lead to the under-estimation of the actual drainage, when between two soil profile water content measurements dates big storms are received. More frequent soil water content measurements would help reduce this type of error.

The calculation method of the field hydraulic conductivity allowed spatial differences to be accounted for, which decreased the coefficients of variability of plot water balance terms calculated in scheme 2.

In this average year, the total calculated E increased from 211 mm for low-fertility millet cultivation system to 268 mm for millet grown using modestly increased fertility management levels. Conversely, a considerable cumulative loss of 207 mm water due to drainage or about 37% of the seasonal rainfall was reduced to a 148 mm or 26% of the seasonal rainfall while a significantly higher millet yield could be realized.

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