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Effect of soil and water conservation and nutrient management on the soil–plant water balance in semi-arid Burkina Faso

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Abstract

Degraded soils in the sub-Saharan zone are often unproductive because of nutrient imbalance and an inadequate water supply. We conducted an experiment in the northern sudanian climate zone of Burkina to study the effect of integrated local water and nutrient management practices on soil water balance, sorghum performance and sorghum's water use efficiency. The trial (Ferric Lixisol, 1.5% slope) consisted of two replications of nine treatments in which soil and water conservation (SWC) measures (stone rows, grass strips) and organic or mineral N-inputs (compost, manure, urea-N) were applied alone or in combination and compared to a control treatment with no N-input and no SWC measure. Application of compost improved soil water storage in the sorghum-rooting zone (0–80 cm) most when combined with stone rows or grass strips and when the year had well-distributed rainfall. However, during an erratic rainy season there was less soil water storage in the organic treatments than in the mineral treatment. Supplying compost increased evapotranspiration and soil drainage more than nutrient inputs did. Furthermore, stone rows allowed greater evapotranspiration and drainage than grass strips, and the two permeable barriers alone had a significant effect on soil water storage compared with treatments without barriers. In the rain-fed cropping system studied, we found that in an erratic rainy season with frequent periods of water stress, the stone rows or grass strips combined with compost reduced runoff and increased soil water storage and sorghum biomass production. These combined practices created sound soil water conditions and were able to satisfy the sorghum's water demand for growth. We conclude that the synergistic effect of water-harvesting practices and the supply of organic or mineral resources increased water use efficiency. It seems that an optimum combination of organic resources and fertilisers could improve the

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water use efficiency (i.e. reduce runoff and drainage losses) and the productivity of Sahelian rain-fed agriculture.

Keywords: Stone row; Grass strip; Nutrient input; Sorghum; Water use efficiency

1. Introduction

In Sahelian countries where land and vegetation are seriously degrading, there is an urgent need to develop sound technologies for resource management that optimise the efficient use of the limited water and soil resources to achieve sustainable agricultural production (Sivakumar and Wallace, 1991; Mando et al., 1999). Several studies have shown that soils in this region are structurally degraded (Casenave and Valentin, 1992; Morin, 1993) and nutrient depleted (Sédogo, 1981). Degraded soils in the sub-Saharan zone are often unproductive because of nutrient imbalance and inadequate water supply (Lal, 1991; Breman, 1997). What is responsible for water deficiency (i.e. more and/or longer periods of water stress), low water use efficiency and crop production is not primarily water shortage, but loss of water through runoff, soil evaporation and drainage below the root zone (Mando, 1997). In the last two decades, several water-harvesting technologies such as tillage, stone rows, hedgerows, earth bunds and dikes have been used to improve soil water infiltration and storage (Nicou and Charreau, 1985; Perez et al., 1998; Zougmoré et al., 2000).

According to Lal (1997), one of the key conditions to increase soil productivity in the sub-Saharan zone is to ensure effective water infiltration and storage in the soil. The soil's water-holding capacity is intimately linked to its texture, structure and organic matter content (Hillel, 1980; Ouattara, 1994). Bationo et al. (1998) have pointed out that in the Sudanian zone, important benefits resulting from the maintenance of soil organic matter (SOM) in low-input agro-systems include the retention and storage of nutrients and a greater water-holding capacity. Indeed, SOM improves the soil structure and thus affects the stocking of the soil water reserves (Ouédraogo et al., 2001). Hence, maintaining SOM is a key component of sustainable land use management (Feller and Beare, 1997).

Most water-harvesting practices have little effect on the soil's water-holding capacity or nutrient status. However, combining local runoff collection measures (stone rows, grass strips, etc.) with nutrient management practices such as application of compost, manure and fertiliser could be an interesting approach to improve water infiltration and plant water use efficiency (FAO, 1995; Bationo et al., 1998). The study described below therefore aimed to assess the effect of integrated local water and nutrient management practices on soil water balance, sorghum performance and sorghum water use efficiency.

2. Materials and methods

2.1. Site description

The experimental field is located at Saria Agricultural Research Station (12°16′N, 2°9′W, 300 m altitude) in Burkina Faso. The climate is north-sudanian (Fontes and Guinko, 1995).

Table 1
Physical characteristics of the experimental plots at Saria agricultural station, Burkina Faso[a]

	Clay ($<2\,\mu$m)	Silt (2–50 μm)	Sand (50–2000 μm)	Gravel (>2 mm)	Bulk density (Mg m^{-3})	Soil UAW (mm m^{-1})
T_{SR}	63.5	27.7	8.8	35.2 a	1.68	102
T_{GS}	65.8	26.3	7.9	34.3 ab	1.67	125
T_{GSM}/T_C	61.2	27.9	10.9	33.3 ab	1.74	115
T_{SRU}	55.2	29.2	15.5	32.8 ab	1.66	125
T_{SRC}	59.4	31.1	9.3	32.4 ab	1.74	130
T_0	63.8	26.6	9.8	30.5 ab	1.70	103
T_{GSC}	64.9	27.2	7.9	27.2 ab	1.71	123
T_{SRM}/T_U	58.4	26.0	15.6	23.8 ab	1.64	87
T_{GSU}	62.6	29.7	7.8	21.1 b	1.64	129
	n.s.[b]	n.s.	n.s.	*	n.s.	n.s.

[a] Where there are significant differences, treatments with the same letter are not statistically different at $P = 0.05$. UAW: useful available water. Treatments: T_{SR}—stone rows, no nitrogen supply; T_{GS}—grass strips, no nitrogen supply; T_{SRC}—stone rows + compost; T_{GSC}—grass strips + compost; T_{SRM}—stone rows + manure; T_{GSM}—grass strips + manure; T_{SRU}—stone rows + mineral nitrogen; T_{GSU}—grass strips + mineral nitrogen; T_0—no SWC measures, no nitrogen supply; T_C—compost application, no SWC measure; T_U—urea application with no SWC measure.

[b] Not significant.

* Significant at the 0.05 level of probability.

Average annual rainfall during the last 30 years is about 800 mm. Rainfall is mono-modal and lasts for 6 months from May to October. The seasonal distribution is irregular in time and space. Mean daily temperatures vary between 30 °C during the rainy season and may reach 35 °C in April and May. Potential evapotranspiration is 2096 mm in dry years and 1713 mm in wet years (Somé, 1989).

The soil type is Ferric Lixisol (FAO-UNESCO, 1994) with an average slope of 1.5% and with a hardpan at 70 cm depth. This hardpan limits sorghum root growth to a maximum soil depth of 80 cm (Barro, 1999). The textural class according to the USDA system is sandy loam in the 0–30 cm layer (62% sand, 28% silt, 10% clay) with a gravel content decreasing from 36% in the 0–5 cm layer to 30% from 10 cm depth. Average bulk density reaches 1.7 Mg m^{-3} in the 0–15 cm layer (Table 1). The organic C content is less than 6 g kg^{-1}, the N content is less than 0.5 g kg^{-1}, the exchangeable K content is about 46 mg kg^{-1}, and the available P content is less than 15 mg kg^{-1}. The CEC is poor (2–4 cmol kg^{-1}), and we found that the base saturation ratio (SAR) fell from 70% in the topsoil to 30–50% at 80 cm depth, in line with the pH, which decreased from 5.3 to 4.9.

The vegetation type is an open woody savannah (Fontes and Guinko, 1995) in which the main species are *Parkia biglobosa*, *Vitellaria paradoxa* and *Tamarindus indica*. The herbaceous component is dominated by *Pennisetum pedicellatum*, *Andropogon* sp., and *Loudetia togoensis*.

2.2. Experimental design

The trial started in 2000 and consisted of a randomised Fisher block design with nine treatments in two replications (Fig. 1):

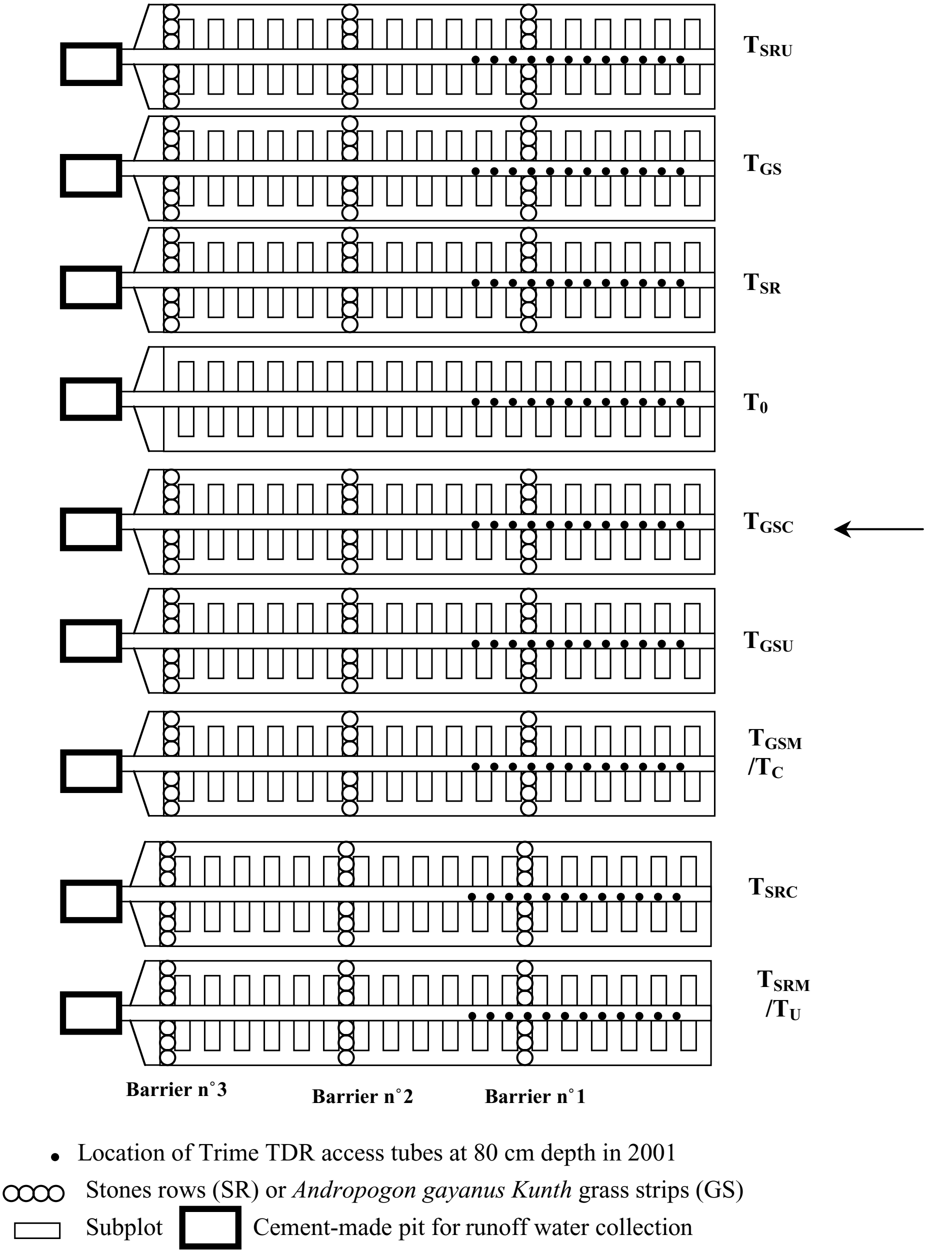

Fig. 1. Experimental design at Saria agricultural station, Burkina Faso. Treatments are explained in Table 1.

T_{SR}	stone rows, no nitrogen supply;
T_{SRC}	stone rows + compost;
T_{SRM}	stone rows + manure;
T_{SRU}	stone rows + mineral nitrogen;
T_0	no SWC measures, no nitrogen supply;
T_{GS}	grass strips, no nitrogen supply;
T_{GSC}	grass strips + compost;
T_{GSM}	grass strips + manure;
T_{GSU}	grass strips + mineral nitrogen.

In 2001, T_{GSM} and T_{SRM} were replaced by, respectively, T_C (compost application with no soil and water conservation (SWC) measure) and T_U (urea application with no SWC measure). Each plot (100 m long, 25 m wide) was isolated from the surrounding area by an earth bund 0.6 m high. Stone rows and grass strips were installed during the 1999 rainy season, at a spacing of 33 m (i.e. three barriers per plot). They were laid out along the contour. The stone rows consisted of two rows of stones placed in a furrow. The upslope row consisted of large stones, while the downslope row consisted of small stones to stabilise the first row. Each stone row was about 0.2–0.3 m high. The grass strip (*Andropogon gayanus* Kunth cv. *bisquamulatus* (Hochst.) Hack.) consisted of three rows of grass, so that the barrier would be thick and 0.3 m wide.

A 110-day sorghum (*Sorghum bicolor* (L.) Moench) variety Sariasso 14 was sown in all plots at the rate of 3.13 seedlings/m^2. Oxen were used to plough to 15 cm depth, and incorporate the compost, manure and mineral nitrogen. The manure and compost were applied at a N rate of 50 kg ha^{-1}. The mineral nitrogen (applied in two splits: 30 DAS and 56 DAS) was in the form of urea; the N rate was 50 kg ha^{-1}. The QUEFTS model (Janssen et al., 1990) was used to calculate the crop nutrient requirement, using SOM content and pH data. To eliminate phosphorus deficiency as a factor in the experiment, all plots received a base treatment of 20 kg P ha^{-1} at sowing, in the form of TSP. Weeding was done manually with hand hoes twice a year.

2.3. Data collection

An automatic rain gauge (tipping bucket) and a simple manual rain gauge were installed on the site to record rainfall amount, intensity and duration. Each tip of the automatic rain gauge corresponds to 0.199 mm rain depth. Within each plot, a metal sheet delimited a subplot of 100 m × 1 m from which runoff and sediment were collected in a cement-lined pit of 6 m^3. The pits were designed to hold a 120 mm rain event. Each pit was equipped with a water-level recorder (TD-divers[2]) that recorded the overland flow hydrograph. Runoff was also recorded by measuring the volume of water in each cement-lined pit. In each plot, 36 subplots of 10 m × 2 m were delimited, to measure sorghum yield. These subplots were located in pairs at the following distances (m) from the downslope border of each plot: 99, 96, 83, 78, 70, 67, 65, 62, 50, 45, 37, 34, 32, 29, 17, 12, 4 and 1. In 2000, soil moisture was measured gravimetrically in each subplot on 6 August and 18 October at depths of

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[2] Eijkelkamp, Giesbeek, The Netherlands.

0–10, 10–20, 20–30, and 30–50 cm. For this purpose, one composite soil sample was taken from each subplot. In 2001, soil moisture was measured with the time domain reflectometry method (TDR-TRIME-FM, see footnote 1) at depths of 0–20, 20–40, 40–60 and 60–80 cm. The TDR system relates volumetric soil water content (m^3 H_2O m^{-3} soil) to the apparent dielectric constant of the soil (Topp et al., 1980). In August 2000, TDR access tubes were placed in each treatment at 0.1, 1, 2, 4, 6, 8, 10, 12 and 17 m upslope from the first barriers, and at 1, 2 and 4 m downslope from these barriers. The TDR-TRIME-FM was calibrated from gravimetric sampling at early rainy season 2001. Every 7 days from July to November, three readings were made per position.

2.4. Data analysis

In this study, we used the well-known water balance equation:

$$P + I = \mathrm{ET} + D + R + \Delta S \qquad (1)$$

where P is the precipitation, I the irrigation, ET the evapotranspiration, D the drainage below the root zone, R the runoff and ΔS the change in soil water storage over the root zone. We consider 0–80 cm as the effective sorghum-rooting depth and express all measured or calculated soil water parameters over this depth. As $I = 0$ in our rain-fed system and $P - R =$ infiltration (Inf), Eq. (1) could be simplified as

$$\mathrm{Inf} - \Delta S = \mathrm{ET} + D \qquad (2)$$

where Inf is the infiltration.

In 2001, P, R and ΔS were measured. The measured soil volumetric water contents at different depths (TDR method) were pooled to obtain the soil water storage, S, in the entire 0–80 cm depth. By comparing S values at different measuring dates, values for ΔS were obtained. For the separation of ($\mathrm{Inf} - \Delta S$) over the terms ET and D we used the following reasoning, based on the magnitude of ($\mathrm{Inf} - \Delta S$). Two cases may occur (Mando, 1997):

$$\text{If PET} > (\mathrm{Inf} - \Delta \mathrm{S}) \geq 0,\ \text{then ET} = (\mathrm{Inf} - \Delta S) \text{ and } D = 0 \qquad (3)$$

$$\text{If PET} < (\mathrm{Inf} - \Delta S) > 0,\ \text{then ET} = \text{PET and } D = (\mathrm{Inf} - \Delta S) - \text{PET} \qquad (4)$$

where PET is the potential evapotranspiration. PET was calculated using the FAO Penman–Monteith equation (Allen et al., 1998) and climatic data from the weather station installed on the experimental site. The case where ($\mathrm{Inf} - \Delta S$) < 0 is not possible for our situation, since it would mean that the soil profile had acquired water from a source other than infiltration. The above method is the most commonly used technique in water balance studies in the Sahel (Stroosnijder and Koné, 1982; Vachaud et al., 1991).

For the year 2000 (without frequently measured soil volumetric water content), we used SARRABIL (Baron et al., 1996), a model that simulates the soil water balance. Among the variables it calculates are soil water storage (S) and soil drainage (D) below 80 cm, and the amount of soil and crop evaporation (ET). It requires soil data (the maximum useful depth of soil, the water-holding capacity, the maximal rooting depth, the initial soil water content, and runoff), crop data (duration of crop cycle, date of sowing and crop coefficients) and climate data (daily rainfall, potential evapotranspiration, temperature, etc.).

So, in 2000 P and R were measured and ET, D and ΔS were derived from calculations. All variables are expressed in millimetre. Research conducted by Chopart and Vauclin (1990) and Barro (1999) showed a good correlation between in situ measured values and data obtained by simulation with the model. For our experiment, linear regressions with

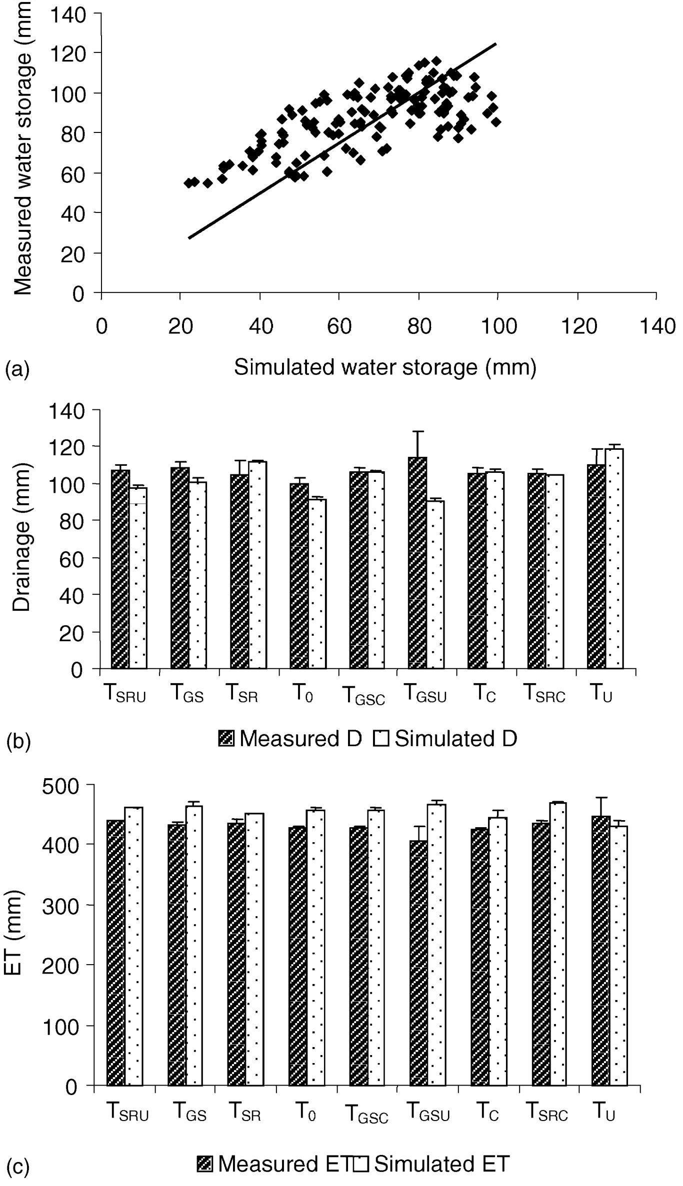

Fig. 2. Comparison between measured and simulated data in 2001 at Saria, Burkina Faso: (a) soil water storage at 0–80 cm depth; (b) cumulative soil drainage below 80 cm depth; (c) cumulative ET.

measured and simulated data for year 2001 also showed good correlations for ET, soil water storage and soil drainage below 80 cm depth (Fig. 2).

The ratio of ET:ETc (actual evapotranspiration:evapotranspiration when the crop grows without moisture stress) was used to determine the rate at which the water demand of a sorghum crop was satisfied. ETc was calculated using the formula:

$$\mathrm{ETc} = k_\mathrm{c} \times \mathrm{PET} \tag{5}$$

in which k_c is the crop coefficient and PET the reference ET obtained with the Penman–Monteith method (Allen et al., 1998). According to several authors (Forest and Clopes, 1994; Affholder, 1997; Barro, 1999), crop water demand is satisfactory when $\mathrm{ET{:}ETc} > 0.75$. Water deficiency is moderate if $0.3 < \mathrm{ET{:}ETc} < 0.75$, and very severe if $\mathrm{ET{:}ETc} < 0.3$. Infiltration water use efficiency (IUE) was calculated from Inf (infiltration) and total biomass (straw + panicle), so that the relation between total infiltrated water and sorghum biomass production could be discussed (Wallace, 2000).

The STATITCF package (Gouet and Philippeau, 1986) was used for the statistical analyses of soil physical characteristics, runoff and infiltration, cumulative ET and drainage, including ANOVA and the Newman–Keuls test for significant differences between treatments at $P < 0.05$.

3. Results

3.1. Rainfall characteristics

The rainfall was 796 mm in 2000 and 719 mm in 2001 (Fig. 3a). Rainfall for year 2001 was below the average annual rainfall in the region (800 mm). Table 2 shows the rainfall in different size classes. In 2000 there were 43 rain events, 4 of which were exceptional (53, 56, 81 and 127 mm) and occurred during July; in 2001 there were 56 rainfall events at the site, almost all less than 40 mm and well distributed in time. Rain events of more than 30 mm represented 18% of the rainfall in 2000, but only 7% in 2001. In 2000, 53% of rain events had an intensity exceeding 30 mm h^{-1} (with 18% showing an intensity above 50 mm h^{-1}). In 2001, only 42% rain events showed intensities higher than 30 mm h^{-1}. Fig. 3b shows the

Table 2
Rainfall distribution over size classes at Saria in 2000 and 2001[a]

Class of rainfall	2000, rainfall 796 mm			2001, rainfall 719 mm		
	Number of rain events	Rainfall (mm)	Average I_{30} (mm h^{-1})	Number of rain events	Rainfall (mm)	Average I_{30} (mm h^{-1})
<10 mm	23	117	14.3	30	169	13.1
11–30 mm	12	228	24.8	22	389	25.6
31–50 mm	4	134	34.2	3	103	36.9
>50 mm	4	317	63.8	1	58	69.3
Total	43	796	–	56	719	–

[a] I_{30}: the highest rainfall intensity during the 30 most rainy minutes.

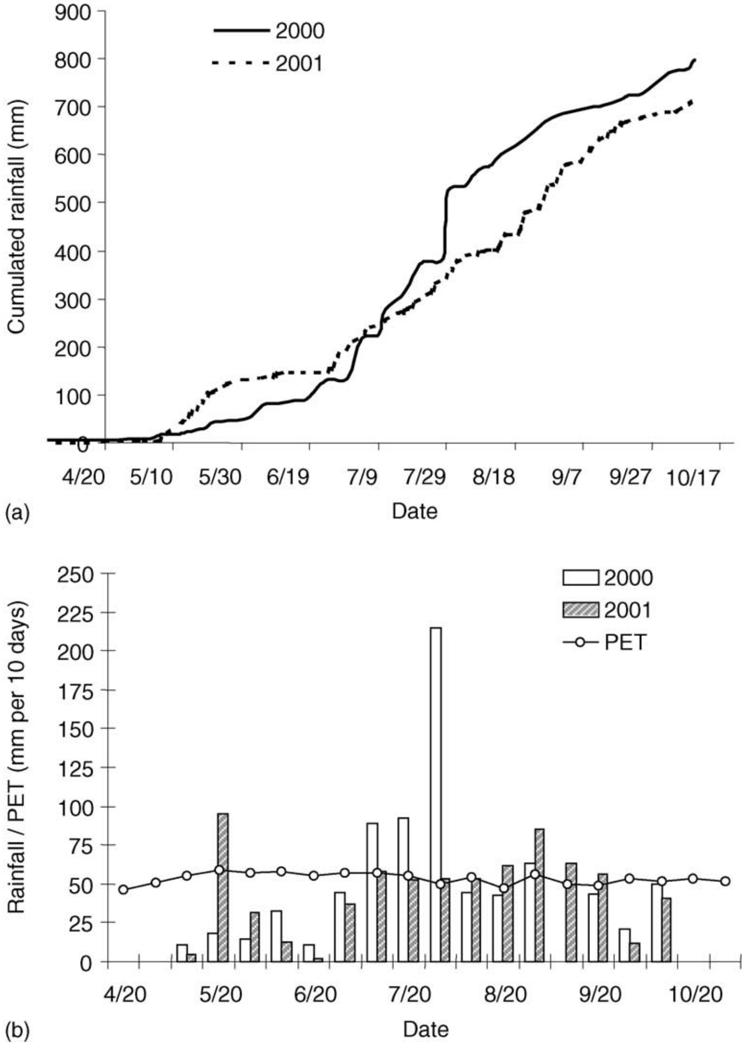

Fig. 3. Rainfall and PET per 10 days for the 2000 and 2001 rainy seasons at Saria, Burkina Faso: (a) cumulative rainfall; (b) potential evapotranspiration and rainfall per 10-day period.

rainfall characteristics per 10-day period for the 2 years. The distribution of rainfall over the period from June (sorghum sowing period) to October (plant maturing period) was better in 2001 than in 2000. In 2000, a dry spell of 13 days (September 2000) occurred during the sorghum maturation stage. The total amount of rainfall was only 65 mm in September 2000, against 131 mm in September 2001. During September 2000, the estimated PET was higher than the actual rainfall, which implies that the sorghum crop might have suffered more water stress in 2000 than in 2001.

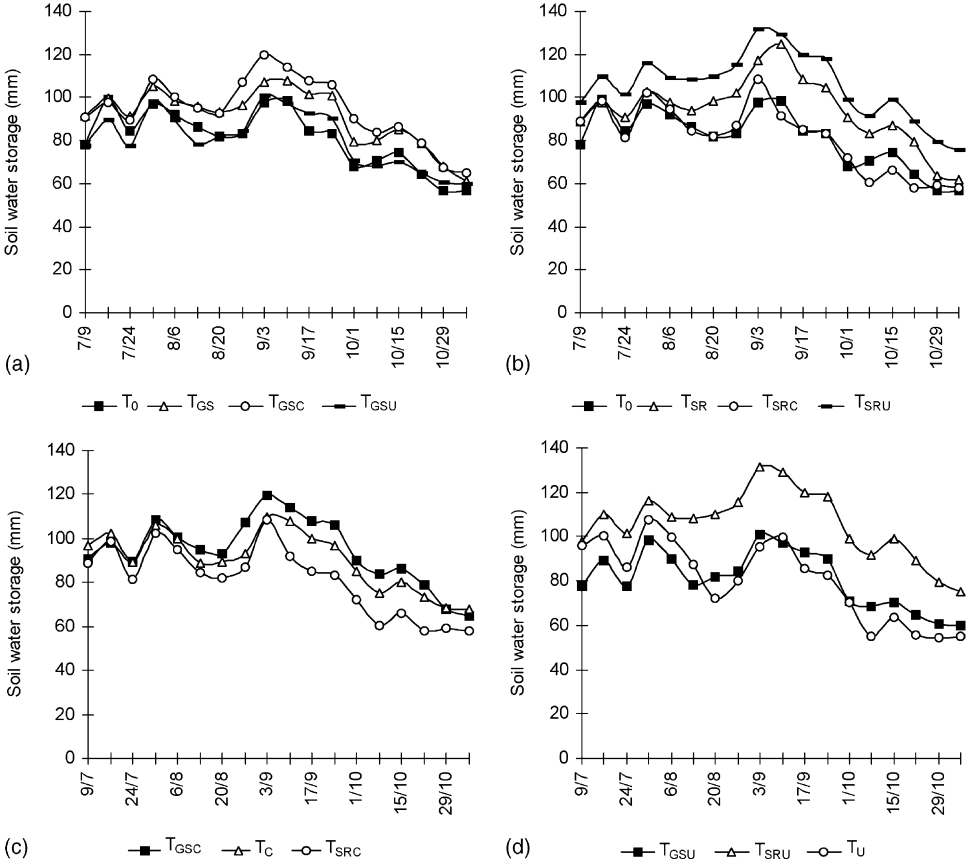

Fig. 4. Dynamics of measured soil water storage during the sorghum-cropping period in 2001 at Saria, Burkina Faso: (a) grass strip treatments; (b) stone row treatments; (c) organic treatments; (d) mineral input treatments.

3.2. Soil water storage

In 2001, the soil water storage (S) over the 0–80 cm layer was less in the control treatment than in other treatments (Fig. 4a and b). Treatments with permeable barriers (T_{SR}, T_{GS}) stored more water than treatments without barriers (T_C, T_U and T_0). The greatest S was recorded in T_{SRU} (stone row + mineral nitrogen) followed by T_{GSC} (grass strip + compost), T_{SR} (stone row without nitrogen supply) and T_{GS} (grass strip without nitrogen supply). S was greater in T_{GSC} than in T_{GS} and T_{GSU}, showing the positive effect of compost on S (Fig. 4a). Among treatments with compost, the decreasing S order was T_{GSC}, T_C, and T_{SRC} (Fig. 4c). S was greater in T_{SRU} than in T_{SR}, indicating the positive effect of mineral input (Fig. 4b). More water was stored in T_{SRU} than in T_{GSU} and T_U (Fig. 4d).

Fig. 5 shows the dynamics of S at depth 0–80 cm from the sorghum sowing period to its maturing period in the rainy season of 2000 (using the SARRABIL model). There are notable differences of S between treatments. All treated plots had a higher S than the control plots,

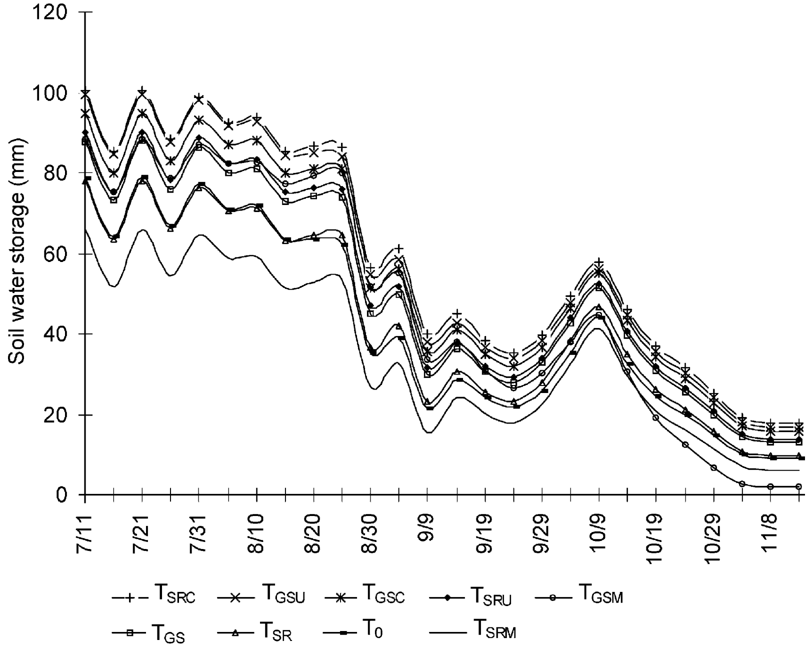

Fig. 5. Dynamics of soil water storage during the sorghum-cropping period in 2000 (simulated data) at Saria, Burkina Faso.

except for the treatment T_{SRM} (stone rows + manure) that had very little useful available water (Table 1). The highest *S* was observed in treatment T_{SRC} (stone rows + compost) followed by T_{GSU} (grass strips + mineral nitrogen), T_{GSC} (grass strips + compost), T_{SRU} (stone rows + mineral nitrogen), T_{GSM} (grass strips + manure), T_{GS} (grass strips without nitrogen supply), T_{SR} (stone rows without nitrogen supply), T_0 (neither SWC technology nor nitrogen supply), and T_{SRM} (stone rows + manure). Throughout the experiment, the greatest *S* was observed from July to August. In all treatments, *S* decreased throughout September. This was due to a dry spell during the first 15 days and the very low amount of rainfall during that month. The maximum amount of water stored in 2001 was greater than that recorded in 2000.

From the 2 years' data, it appeared that compost application improved *S* compared with urea supply or no nutrient input. When rainfall was well distributed over time, as in 2001, organic input induced a better *S* than mineral input, but there were only slight differences when comparing organic and mineral input effects on *S*. When rainfall was erratic, as was the case in 2000, there was less *S* in organic treatments than in mineral treatments. Permeable barriers alone had more effect on *S* than treatments without barriers. Stone rows resulted in a larger *S* than grass strips. Only when the rainfall was well distributed did compost alone improve the soil water storage.

3.3. ET and soil drainage

In 2001, the ET values were not significantly different between treatments (Table 3). However, the highest ET was for the T_U plot that had been the T_{SRM} plot in 2000. The mean

Table 3
Cumulative evapotranspiration (ET), cumulative drainage (D) below 80 cm depth and annual runoff rate over the sorghum-cropping seasons in 2000 and 2001 at Saria, Burkina Faso[a]

	Cumulative ET (mm)		Cumulative D below 80 cm depth (mm)		Annual runoff rate (% $\sum P^{b}$)	
	2000	2001	2000	2001	2000	2001
T_{SRU}	379 ab	439	217 b	107	8.3 b	4.2 c
T_{GS}	383 a	431	217 b	109	8.3 b	5.9 c
T_{SR}	378 ab	435	221 b	105	7.1 b	3.5 c
T_0	370 ab	427	197 d	100	15.9 a	12.2 a
T_{GSC}	388 a	427	219 b	106	7.1 b	4.5 c
T_{GSU}	387 a	405	209 c	114	11.4 ab	9.5 b
T_{GSM}/T_C	381 ab	425	217 b	106	8.2 b	8.2 b
T_{SRC}	388 a	435	219 b	106	6.8 b	3.2 c
T_{SRM}/T_U	368 b	448	222 a	110	7.5 b	6.6 c
	*	n.s.[c]	*	n.s.	*	*

[a] Where there are significant differences, treatments with the same letter are not statistically different at $P = 0.05$. Treatments are explained in Table 1.

[b] $\sum P$: cumulative rainfall.

[c] Not significant.

* Significant at the 0.05 level of probability.

values of ET were greater in the stone row plots (T_{SRU}, T_{SRC}, T_{SR}) than in the grass strip plots (T_{GS}, T_{GSC}, T_{GSU}). The lowest values for ET were obtained with T_0, T_C and T_{GSU}. Comparisons between treatments showed that plots with mineral input (T_{GSU}, T_U, T_{SRU}) had the most drainage, followed by compost plots (T_C, T_{SRC}, T_{GSC}) and no amendment plots (T_{SR}, T_0).

In 2000, cumulative ET and drainage during the sorghum-cropping period were significantly different between treatments (Table 3). The greatest ET was observed in compost plots (T_{SRC}, T_{GSC}), followed by mineral plots and no nutrient amendment plots (T_{GSU}, T_{GS}, T_{SRU}, T_{SR}). T_0 and T_{SRM} recorded the least ET. For that year, with erratic rainfall (2000), organic amendments like compost improved ET more than mineral input and no amendment. Soil drainage was greater in organic plots (T_{SRM}, T_{SRC}, T_{GSC}, T_{GSM}) than in mineral plots (T_{SRU}, T_{GSU}). Plots with stone rows (T_{SRM}, T_{SR}, T_{SRC}) recorded more drainage than grass strip plots (T_{GSC}, T_{GSM}, T_{GS}, T_{GSU}).

In 2001, a year in which rainfall was better distributed than in 2000 (Fig. 3b), the mean values of ET were higher than those recorded in 2000. In both years, the control plots recorded the least soil drainage.

3.4. Plant water demand

In 2001, crop water demand was satisfactory (ET:ETc > 0.75) during the vegetation and maturation stages of sorghum (Fig. 6a). There was no water-deficient period in 2001, but there was in 2000. In that year, the ratio started to decrease from 1 October (90 DAS), but this could not affect sorghum production, as the crop was almost mature. However, at that time, the decreasing order of ET:ETc ratio was T_{SRC}–T_{SRU}–T_{SR} for the stone row

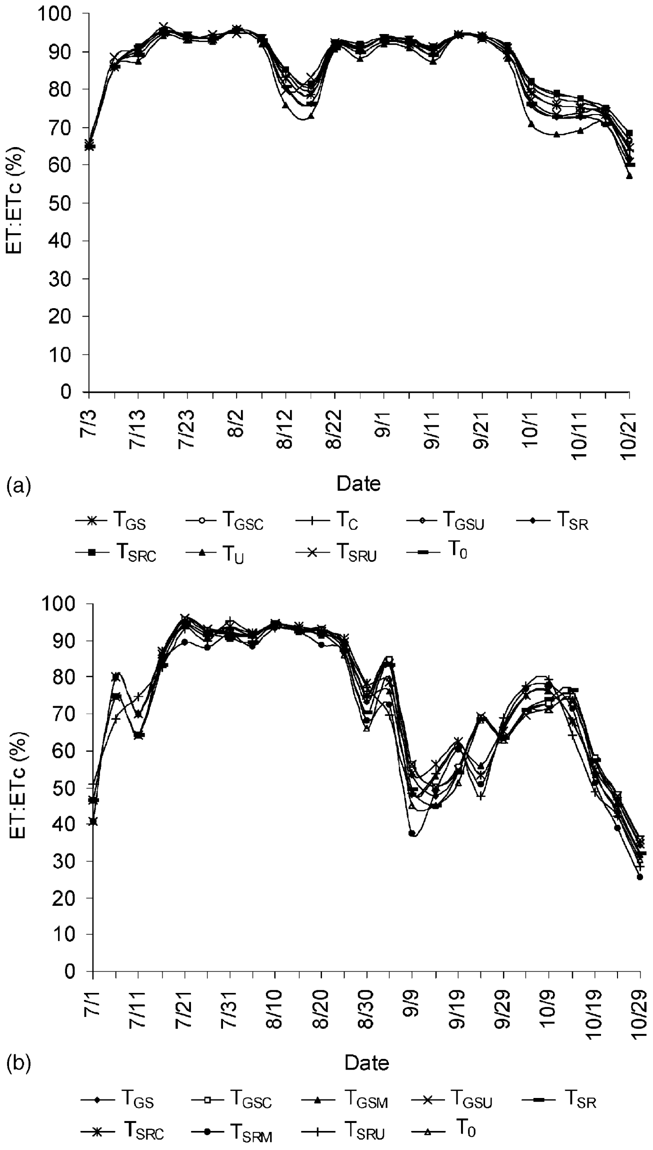

Fig. 6. Plant water demand satisfaction rate (ET:ETc ratio) for the sorghum crop at Saria, Burkina Faso: (a) 2001; (b) 2000.

treatments and T_{GSU}–T_{GSC}–T_{GS} (Fig. 6a) for the grass strip treatments. The ratio for T_{SRC} was greater than that of T_{GSC} while T_C, T_U and T_0 showed the smallest ratios.

The ET:ETc ratio curve for 2000 can be divided into two periods (Fig. 6b). In the first phase, which corresponds to the sorghum growth stage (0–50 DAS), the crop water demand was satisfactory: ET:ETc $>$ 0.75. A moderate to severe water deficiency phase was observed throughout September (51–79 DAS). This critical phase corresponded to the sorghum flowering stage, so it could have depressed grain production. However, crop water demand became satisfactory during the first half of October (80–95 DAS) before decreasing until the end of the rainy season. Comparisons between treatments did not show significant differences during the first phase. However, slight differences ($<10\%$) in the ET:ETc ratio between treatments appeared during the water deficiency phase. The decreasing order of ET:ETc ratio was T_{GSC}–T_{GSU}–T_{GS}–T_{GSM}–T_0 for grass strip treatments and T_{SRC}–T_{SRU}–T_{SR}–T_{SRM} for the stone row treatments. The water demand in T_{SRC} was more satisfactory than in T_{GSC}. The ratios for T_{GS} and T_{SR}, T_{GSM} and T_{SRM}, T_{GSU} and T_{SRU} were quite similar.

4. Discussion

Why was the soil water storage less in the organic plots than in the plots with mineral input in 2000, but not in 2001? It seems likely that the rainfall pattern was important. The rainy season of 2000 was characterised by several dry spells; these might have induced crop water deficiency more than in 2001. Moreover, because there was more biomass in the plots with organic input (Table 4), the soil water consumption by the sorghum crop was higher than in non-organic plots (Table 3). According to Vetterlein and Marschner (1994), an important relationship between nutrient supply and soil water balance is the increase in plant shoot size due to improved nutritional status and thereby, the increase in water requirement of the crop. Moreover, organic resources may increase root zone drainage (Roose, 1994; Mando, 1997). In our case, compost indeed increased infiltration, and the crop produced greater biomass, but nutrient deficiency could still have limited water use by the sorghum crop, which is why the drainage increased in the organic plots compared with the mineral and control plots. These reasons could explain why during dry years the *S* was lower in the organic plots than in the plots with mineral input. The cumulative drainage below 80 cm depth in 2000 was twice than that in 2001 (Table 3) because of the exceptional rain

Table 4
Sorghum performance and IUE for 2000 and 2001 at Saria, Burkina Faso[a]

	Grain yield (kg m^{-2})		Total biomass (kg m^{-2})		IUE[b] (kg m^{-3})	
	2000	2001	2000	2001	2000	2001
T_{SRC}	0.23 a	0.25 a	0.69 a	0.82 a	0.94 ab	1.19 a
T_{GSC}	0.23 a	0.23 ab	0.76 a	0.76 a	1.03 a	1.11 a
T_{GSM}/T_C	0.15 b	0.23 ab	0.54 abc	0.73 a	0.75 abcd	1.11 a
T_{SRU}	0.14 bc	0.18 ab	0.62 ab	0.62 ab	0.85 abc	0.91 ab
T_{SRM}/T_U	0.17 b	0.21 ab	0.61 ab	0.62 ab	0.84 abc	0.92 ab
T_{GSU}	0.09 cd	0.15 ab	0.43 bc	0.54 ab	0.61 bcd	0.84 ab
T_0	0.08 cd	0.11 ab	0.41 bc	0.43 ab	0.61 bcd	0.68 ab
T_{SR}	0.07 d	0.12 ab	0.37 bc	0.46 ab	0.50 cd	0.66 ab
T_{GS}	0.06 d	0.09 b	0.33 c	0.32 b	0.46 d	0.48 b

[a] Treatments with the same letter are not statistically different at $P = 0.05$. Treatments are explained in Table 1.
[b] Infiltration water use efficiency = annual total biomass (straw + panicle)/annual infiltrated water.

event (127 mm) on 30 July, which caused soil drainage to exceed 60 mm for all treatments. In 2001, the rainfall was more evenly distributed than in 2000 and the amounts that fell in individual rain events were too small to induce important soil drainage. With a better distribution of rain events, most water was used for ET, so less water was available for drainage.

The finding that more water infiltrated into the composted plots than into the non-organic plots (Table 3) confirms that compost application improves the soil's porosity and permeability and thus its water-holding capacity (Tolk et al., 1997). In the same region, Ouédraogo et al. (2001) observed that the compost amendment resulted in a better soil structure with well-developed aggregates and many voids that improved rainwater infiltration. Several authors have reviewed the multiple effects of organic resources (compost, manure) on soil structure and soil physical properties (Piéri, 1989; Ouattara, 1994; Carter and Steward, 1996).

Surface runoff is known to be a major cause of water loss in tropical rain-fed agriculture systems (Wallace, 2000), but the stone rows, which are permeable barriers, induced more surface water storage and infiltration than the grass strips (Table 3). Compared to grass strips, the architecture of stone rows allowed the runoff velocity to be reduced more than with grass strip barriers. Furthermore, because the grass strips take at least 1 month to regrow after the long, harsh, 6-month dry season, they are less effective at the start of the rainy season (Zougmoré et al., 2003). This is confirmed by the data in Fig. 6, which show that sorghum water demand (ET:ETc ratio) was satisfied more in the plots with stone rows than in the plots with grass strips. Grass strips increase the ET because at full growing stage their water need (transpiration) can be as high as 35 mm over an 8-day period (Ringersma and Sikking, 2001).

The better distributed rainfall in 2001 compared with 2000 explains why the sorghum crop's water demand was satisfied better in 2001 than in 2000. The ET:ETc ratio showed clearly that during periods of water deficit (sorghum flowering stage in 2000), supplying organic resources allowed the plant water demand to be satisfied better than when fertiliser was supplied. This is confirmed by the sorghum performance and IUE during 2000 and 2001 (Table 4), which showed that in all treatments the sorghum total biomass and IUE were higher in 2001 than in 2000. Plots supplied with compost obtained the greatest sorghum total biomass and showed the highest IUE, followed by mineral plots and no amendment plots. The IUE values on plots with combined organic resources and SWC measures (stone rows + compost, grass strips + compost) were twice those on plots with SWC measures without nutrient resources (stone rows without nitrogen supply, grass strips without nitrogen supply). On plots with combined mineral resources and SWC measures (stone rows + mineral nitrogen, grass strips + mineral nitrogen), the IUE was 1.5 times that that obtained on plots with SWC measures without nutrient resources. These results are consistent with those of Cissé (1986) and Affholder (1997) in Senegal, who found that after the application of organic resources, a millet crop was able to go through severe water stress at flowering and still produce double the grain yield obtained with inorganic resources. This may be due to the interaction between adequate water use and better nutrient availability due to the application of organic resources. Furthermore, in plots with application of fertilisers, there is probably greater loss of nutrients through runoff or drainage than from plots given organic input.

5. Conclusions

In this study, plots with stone rows stored more water than plots with grass strips. During the year in which the rainfall was well distributed over time, compost application improved soil water storage in the sorghum root zone (0–80 cm) most when it was combined with stone rows or grass strips. However, when the rainy season was erratic, soil water storage was less in treatments supplied with compost than in treatments supplied with urea. The compost effect was more effective during long, dry spells. Compost was found to increase ET and soil drainage more than nutrient inputs. Furthermore, stone rows induced greater ET and more drainage than grass strips. We conclude that during erratic rainy seasons with frequent periods of water stress in rain-fed Sudanian agriculture, stone rows or grass strips combined with compost are practices that create suitable conditions for sorghum growth. We infer that the combination of organic and mineral resources would have a great effect on the productivity of rain-fed agriculture in Sahelian countries.

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