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Effect of combined water and nutrient management on runoff and sorghum yield in semiarid Burkina Faso

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Abstract. In the semiarid regions of sub-Saharan Africa, fertilizer recovery and nutrient release from organic sources are often moisture limited. Moreover, in these regions runoff brings about large nutrient losses from fertilizer or organic inputs. This study was conducted in the north sudanian climate zone of Burkina Faso (annual rainfall 800 mm, PET 2000 mm yr^{-1}). We assessed the combined and interactive effects of two types of permeable barriers (stone rows and grass strips of *Andropogon gayanus Kunth* cv. *Bisquamulatus (Hochst.) Hack.*) and organic or mineral sources of nitrogen on erosion control and sorghum yield. The field experiment (Ferric Lixisol, 1.5% slope) was carried out during three rainy seasons and consisted of 2 replications of 9 treatments, in which the barriers were put along contours and combined with compost, manure and fertilizer nitrogen (N). Compared with the control plots, the average reduction in runoff was 59% in plots with barriers alone, but reached 67% in plots with barriers + mineral N and 84% in plots with barriers + organic N. On average, stone rows reduced soil erosion more than grass strips (66% versus 51%). Stone rows or grass strips without N input did not induce a significant increase of sorghum production. Supplying compost or manure in combination with stone rows or grass strips increased sorghum grain yield by about 142%, compared with a 65% increase due to mineral fertilizers. The sorghum grain yields at 1 m upslope from the grass strips were less than those 17 m from the grass strips. As stones do not compete with plants, the opposite trend was observed with stone rows. We conclude that for these nutrient depleted soils, permeable barriers improve nutrient use efficiency and therefore crop production. However, grass strips must be managed to alleviate shade and other negative effects of the bunds on adjacent crops.

Keywords: Stone rows, grass strips, nutrient input, sorghum, Burkina Faso

INTRODUCTION

Soil degradation is a major issue for arid and semiarid tropics (Ryan & Spencer 2001), where the combined effects of depletion of soil organic matter (SOM), mismanagement of the fragile ecosystem and the harsh climatic conditions have resulted in a very low level of primary production (Mando *et al.* 2001). In sub-Saharan Africa, agricultural production is presently dominated by cereal-based systems, which are 97% rainfed (FAO 1995). The main constraint to crop production is not the limited annual rainfall, but the small proportion of rainfall that enters the root zone (Sivakumar & Wallace 1991). Furthermore, as the soils are very poor in nutrients, especially in N and P (Sédogo 1981; Bationo *et al.* 1998), nutrients and moisture emerge as the primary factors limiting crop growth (Stroosnijder 1996). There is therefore little point in maximizing rain-use efficiency unless nutrient deficiency is corrected at the same time and vice versa.

Various studies have demonstrated the benefits to the soil water balance of semipermeable obstacles such as stone rows and live hedges (Lamachère & Serpantié 1991; Perez *et al.* 1998). The technique is particularly effective in reducing runoff and improving rainwater infiltration; because of its filtering function it also reduces fine sediment transport (Mando *et al.* 2001). However, some studies have reported that the beneficial effect of stone rows on soil productivity was limited under continuous non-fertilized cereal cropping (Walle & Sims 1999; Zougmoré *et al.* 2002). This implies that there is no benefit in water use efficiency without improved nutrient management. If agricultural systems are to be sustained in the region therefore, water and nutrient issues need to be addressed simultaneously.

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In the continuous cultivation systems of sub-Saharan Africa, organic resources play a dominant role in both the short-term nutrient availability and the long-term maintenance of SOM. Indeed, one effective way of achieving the above goals is to use adequate amounts of locally available amendments such as manure or compost in combination with rainwater harvesting techniques (Piéri 1989; Morin 1993; Fatondji *et al.* 2001). Moreover, integrated water and nutrient management geared to land use practices that are ecologically sound and economically viable remain the key factors for the sustainability of agricultural systems in West Africa (Buerkert *et al.* 2002).

The objective of this study was to assess the interactive effects of two soil and water conservation (SWC) measures (stone rows and *Andropogon gayanus* grass strips) combined with an organic/mineral source of N on sorghum (*Sorghum bicolor* (L.) *Moench*) yield and erosion control. We hypothesized that soil and water conservation measures could improve sorghum water and nutrient use efficiency under semiarid conditions.

MATERIALS AND METHODS

Site description and experimental design

The experimental field is at Saria Agricultural Research Station (12°16′N, 2°9′W, 300 m altitude) in Burkina Faso. The climate is north-sudanian (Fontes & Guinko 1995), with an average annual rainfall of 800 mm (30 yr average). Rainfall is mono-modal, lasting for 6 months (May to October) and is distributed irregularly in time and space. Mean daily temperatures vary between 30 °C during the rainy season and 35 °C in April and May. The mean potential evapotranspiration is 2096 mm in dry years and 1713 mm in wet years (Somé 1989). The site was previously under fallow for about 15 years, typically an open woody savannah (Fontes & Guinko 1995). The soil type is Ferric Lixisol (FAO-UNESCO 1994) with an average slope of 1.5% and a hardpan at a depth of 80 cm which limits rooting (Barro 1999). The textural class according to USDA system is sandy loam in the 0–30 cm layer (62% sand, 28% silt, 10% clay) with a gravel content decreasing from 36% at 0–5 cm layer to 30% from 10 cm deep. Average bulk density is 1.7 at 0–15 cm depth. Soil in the 0–30 cm depth had 6 g $kg^{-1}$of organic C, 0.5 g kg^{-1} of N, 46 mg kg^{-1} of exchangeable K and 15 mg kg^{-1} of available P. The pH (H_2O) decreased from 5.3 in the topsoil to 4.9 at 80 cm depth.

The trial was conducted over three seasons (2000–2002) and combined two linear SWC measures with three types of N input. The experimental design was a randomized block with nine treatments and two replications coded as follows.

T_{SR}: stone rows, nil N supply T_{GS}: grass strips, N 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 + fertil. N T_{GSU}: grass strips + fertil. N
T_0: no SWC measures, nil N supply (control plots)

In the 2000 season, results of treatments with compost or animal manure showed the same trend. For this reason, and because compost is more available than manure (Sédogo 1993), treatments T_{GSM} and T_{SRM} were replaced in year 2001, respectively, by:

T_C: compost applied without SWC
T_U: urea applied without SWC.

Each plot (100 m × 25 m) was isolated from the surrounding area by an earth bund 0.6 m high. The first replication was fitted with runoff collection devices and recording equipment. Runoff and sediment of each plot were collected from a 100 m × 1 m subplot. A metal sheet was used to direct runoff into a 6 m^3 cement-lined pit. The covered pits were designed to cope with an exceptional 120 mm rainfall event. Each pit, in one replicate only, was equipped with a water level recorder (TD-divers, Eijkelkamp, Giesbeek, Netherlands) which recorded the overland flow hydrograph. Rainfall intensity was recorded using an automatic rain gauge (tipping bucket). In each plot, 36 subplots of 10 m × 2 m were delimited. These subplots were used to record sorghum yield and soil moisture variation down the length of slope, and were located in pairs at 99, 96, 83, 78, 70, 67, 65, 62, 50, 45, 37, 34, 32, 29, 17, 12, 4 and 1 m from the downslope border of each plot. Stone rows and grass strips had been installed during the preceding 1999 rainy season, spaced 33 m apart (i.e. 3 barriers per plot) along the contours. Previous studies showed that for the more common case of farmers working with an NGO to trace contours and transport rocks, the optimal spacing that maximizes the financial return from a sorghum-based system was between 30 m and 43 m (Zougmoré *et al.* 2000a; Zougmoré *et al.* 2000c). Each stone row consisted of two rows of stones placed in a furrow. The upslope row of large stones was stabilized by the downslope row of small stones. Each stone row was about 0.2–0.3 m high and weighed about 80–90 kg m^{-1}. Each grass strip comprised three rows of grass, resulting in a thick barrier 0.3 m wide.

In all plots, a 110-day sorghum (*Sorghum bicolor* (L.) *Moench)* variety (Sariasso 14) was sown by hand across the slope in rows at 31 250 seedlings per hectare (0.8 m x 0.4 m). The plots were tilled with hand hoes twice a year for weed control, and ploughed to 15 cm depth annually to incorporate manure, compost and urea. The QUEFTS model (Janssen *et al.* 1990) was used to calculate the crop nutrient requirement on the basis of the soil organic matter (SOM) and pH (H_2O) of the soil. Manure, compost and urea were applied each year at a rate of 50 kg N ha^{-1}. The amount of compost or animal manure derived from this N-rate corresponds to about 5–7 t ha^{-1} of manure or compost, which is consistent with the recommended minimum application of organic amendment in Burkina Faso (Sédogo 1981; Berger 1996). Urea was applied in a split dressing at first hand hoeing (21 days after planting) and second hand hoeing (56 days after planting). All plots received a base dressing of 20 kg ha^{-1} P in the form of TSP to eliminate phosphorus deficiency.

Data collection

Runoff was recorded for each rain event that generated overland flow. Soil loss was quantified by drying and weighing the sediments collected from the pits after each runoff event. In 2000, soil moisture was measured

Table 1. Effect of treatments on runoff in the rainy seasons of 2000, 2001 and 2002 at Saria, Burkina Faso.[a]

	Annual runoff (% of rainfall)			Runoff reduction (%)		
	2000	2001	2002	2000	2001	2002
T_0	15.9 (2.1)	12.2 (1.1)	17.6 (1.9)	0	0	0
T_{SR}	7.1 (2.0)	3.5 (1.3)	5.0 (0.9)	55	71	71
T_{SRU}	8.3 (2.7)	4.2 (1.6)	5.3 (0.87)	48	65	70
T_{SRC}	6.8 (1.6)	3.2 (1.6)	1.0 (0.6)	58	74	94
T_{GS}	8.3 (1.1)	5.9 (1.0)	8.2 (1.3)	48	51	53
T_{GSU}	11.4 (0.9)	9.5 (1.1)	7.6 (2.2)	29	22	57
T_{GSC}	7.1 (1.6)	4.5 (1.8)	2.8 (1.2)	56	63	84
T_{SRM} / T_U[b]	7.5 (2.2)	6.6 (0.9)	9.0 (1.0)	53	46	49
T_{GSM} / T_C[b]	8.2 (1.8)	8.2 (0.7)	2.4 (0.9)	48	32	87
Number of rain events	10	09	16	10	09	16

[a]Values in brackets are ± standard deviation between runoff volumes measured in pits and recorded values of runoff. [b]Treatment replaced in 2001 and 2002; see Materials and Methods.

T_0: no SWC measures, nil N (control plots); T_{SR} stone rows, no nutrient supply; T_{SRC}: stone rows + compost; T_{SRM}: stone rows + manure; T_{SRU}: stone rows + urea; T_{GS}: grass strips, nil N; T_{GSC}: grass strips + compost; T_{GSM}: grass strips + manure; T_{GSU}: grass strips + urea.

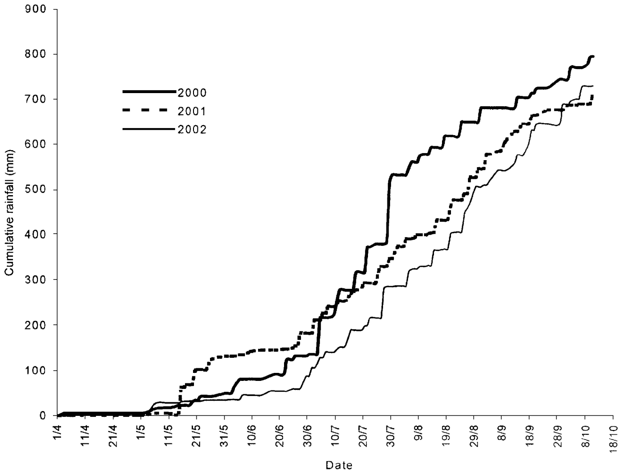

Figure 1. Daily cumulative rainfall for the rainy seasons of years 2000, 2001 and 2002 at Saria, Burkina Faso.

gravimetrically on 6 August and 18 October at depths of 0–10, 10–20, 20–30, and 30–50 cm from composite samples taken from each subplot. In 2001 and 2002, soil volumetric moisture was measured every 7 days with time domain reflectometry (TDR-TRIME-FM) at depths of 0–20, 20–40, 40–60 and 60–80 cm, at 0.1, 1, 2, 4, 6, 8, 10, 12 and 17 m upslope and 1, 2 and 4 m downslope from the first barriers. Three readings were made per position. Sorghum grain and straw yields were measured in the subplots.

Data analysis

Runoff was analysed from 10 erosive rain events for the 2000 rainy season, 9 events for the 2001 rainy season, and 16 events for the 2002 rainy season. Cumulative runoff during the crop-growing period (from sorghum planting to harvest) of each year was related to cumulative rainfall to assess the ratio of annual runoff (Table 1). Hydrograph parameters defined by Reid & Parkinson (1984) and successfully applied by Twomlow *et al.* (1990) were used to analyse runoff in relation to rainfall distribution and intensity. In order to cope better with runoff and rainfall behaviour in the study zone, these parameters (time to start of the hydrograph rise, t_s, time to peak discharge i.e. time of concentration, t_c, and peak discharge, Q_P) have been related to the time at which rainfall started (Lamachère & Serpentié 1991; Zougmoré *et al.* 2000a). Cumulative soil loss was compared per treatment to assess the effect of treatment on erosion during the three years. The STATITCF package (Gouet & Philippeau 1986) was used for statistical analyses of soil water content and sorghum grain yields. Newman–Keuls test was used for mean separation at $P < 0.05$.

RESULTS AND DISCUSSION

Rainfall characteristics

Figure 1 shows the cumulative rainfall patterns over the 3 years of the experiment, which were less than the regional average. The rainfall was 796 mm in 2000, 719 mm in 2001, and 733 mm in 2002. In 2000 there were 43 rain events, 4 of which were exceptionally heavy (53, 56, 81 and 127 mm during July); in 2001 there were 56 rain events, all less than 40 mm and well distributed in time. In 2002, 53 rain events occurred, of which 2 were greater than 50 mm and very influential on total runoff and soil loss. The rainfall during the sorghum cropping period (June to October) was more evenly distributed in 2001 and 2002 than in 2000; this contributed to the better crop performance in 2001 and 2002 (Table 5). A drought of 13 days occurred early in September 2000 (Figure 1), coinciding with the sorghum maturation stage. The total rainfall in September 2000 was only 65 mm compared with 131 mm in September 2001 and 183 mm in September 2002. After a long period of drought during the whole month of June, rainfall was well distributed from July to October 2002. However, the delayed onset of the rainy season in June postponed crop establishment in 2002.

Runoff

Figure 2a,b shows runoff hydrographs for selected major rain events. The associated hyetographs give the rainfall distribution over time. Time to start of the hydrograph rise

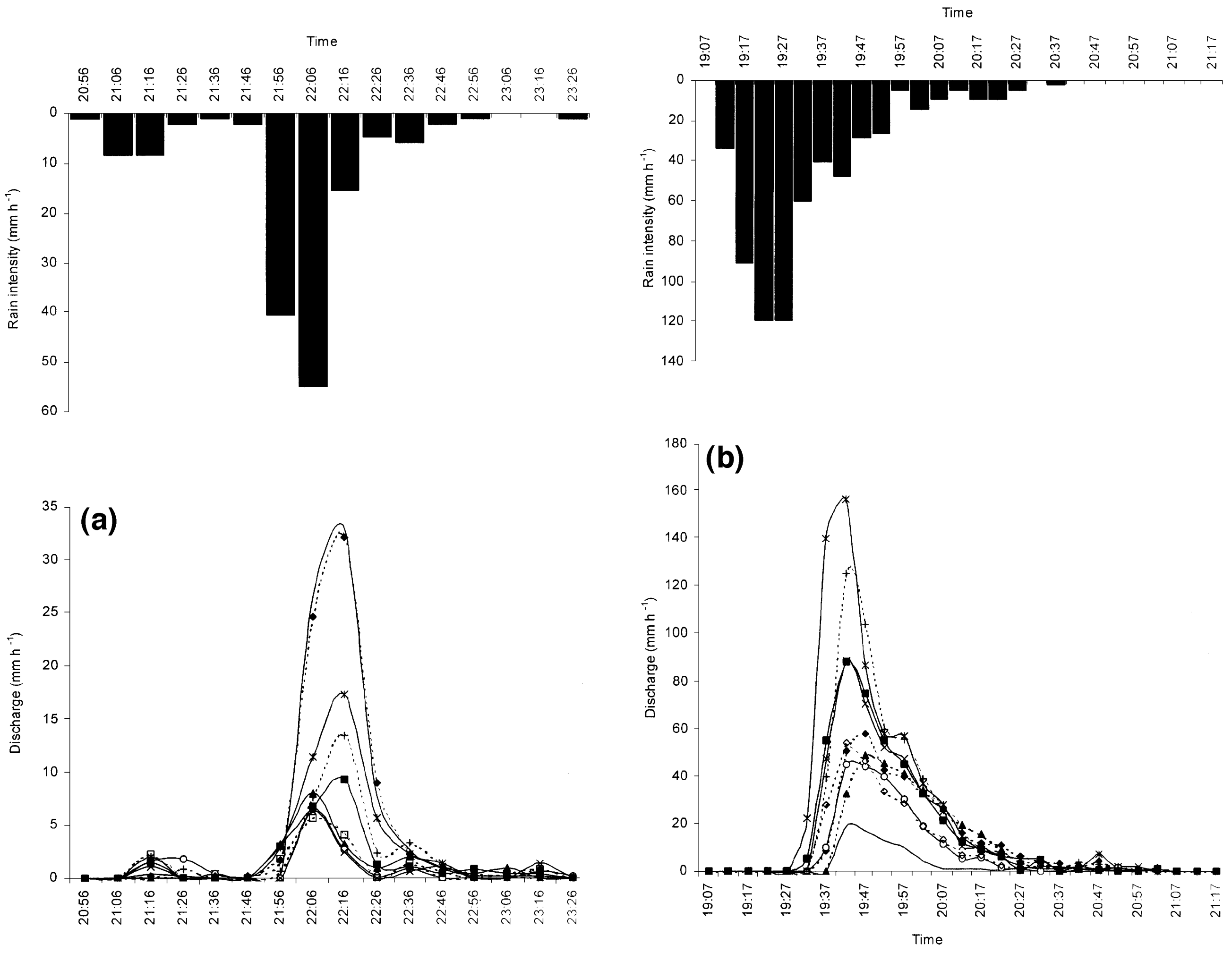

Figure 2. Rainfall hyetograph and runoff hydrograph for two major rain events at Saria, Burkina Faso: (a) for 2 July 2001 (28 mm); (b) for 27 July 2002 (52 mm). ▲—▲, T_{SRU}; *—*, T_{GS}; ○—○, T_{SR}; —, T_0; +—+, T_{GSC}; ◆—◆, T_{GSU}; ■—■, T_C; ×—×, T_{SRC}; □—□, T_U. For treatment key, see Table 1 and Materials and Methods.

(t_s) for rain event of 27 July 2002 was below 30 min but reached 50 min for that of 2 July 2001. This indicates that rainfall distribution and intensity has a strong influence on t_s. Indeed, a close examination of rainfall hyetographs revealed that rainfall of 2 July 2001 started at a very low intensity during the first 50 min before rising to its highest level. This was not the case for the 27 July 2002 event, which started with very high rain intensity. Time to peak discharge (t_c) was very much influenced by rainfall intensity: for the 27 July 2002 rain event, during which maximum half-hourly rainfall intensity reached 82 mm h^{-1}, average t_c was shorter (35 min) than that of the 2 July 2001 rain event (70 min). The latter's rainfall intensity was 36 mm h^{-1}. Hydrographs also showed that treatments had a significant effect on the runoff process. As shown in Figure 2b, the t_s for plots with and without fertilizer N (T_U, T_{GS}, T_{GSU}, T_0), was 20 min but reached 30 min in plots with organic amendments (T_{SRC}, T_{GSC}, T_C). The highest peak discharges (Q_p) were observed on control plots, followed by unamended plots and organic plots. As an example, Q_p for treatments with inorganic input in Figure 2b were two to four times that of treatments with organic input. The greater Q_p with grass strip treatments, when compared in pairs to stone row treatments, confirmed the advantage of stone rows in slowing runoff. The lowest values of Q_p were obtained in the treatment that combined stone rows with compost (T_{SRC}).

During the three years of study, all treatments reduced runoff compared with control plots (Table 1). In the 2000 rainy season, the runoff in treatments with stone rows was always less than that in treatments with grass strips when these were compared in pairs (T_{SR}/T_{GS}; T_{SRC}/T_{GSC}; T_{SRM}/T_{GSM}; T_{SRU}/T_{GSU}). This difference in runoff reduction between stone rows and grass strips was only 2% in composted plots, 5% in manured plots and 7% in unamended plots, but reached 19% in plots with fertilizer N. The same trend was observed in 2001 and 2002 with larger differences than in 2000 (Table 1). Overall in 2000,

Table 2. Effect of treatments on soil loss in the rainy seasons of 2000, 2001 and 2002 at Saria, Burkina Faso.[a]

	Soil loss (kg ha^{-1})			Soil loss reduction (%)		
	2000	2001	2002	2000	2001	2002
T_0	217	236	32711	–	–	–
T_{SR}	98	71	1035	55	70	97
T_{SRU}	136	52	3621	38	78	89
T_{SRC}	67	50	569	69	79	98
T_{GS}	150	99	5639	31	58	83
T_{GSU}	105	171	9858	52	28	70
T_{GSC}	145	108	1933	33	54	94
T_{SRM} / T_U	86	116	8705	60	51	73
T_{GSM} / T_C	97	113	802	55	52	98
Number of rain events	10	09	16	10	09	16

[a]For treatment key, see Table 1 and Materials and Methods.

T_{SRC} and T_{GSC} had the least runoff, followed by $T_{SR} < T_{SRM} < T_{GSM} < T_{GS} < T_{SRU} < T_{GSU} < T_0$.

In 2001 and 2002, except for T_{GSU}, the treatments without barriers (T_U, T_C, T_0) showed the greatest runoff, confirming the positive effect of stone rows and grass strips on runoff reduction. Compared with the control treatment, runoff was reduced more in the stone row and grass strip treatments with compost (by 74% and 63%, respectively). Combining stone rows or grass strips with fertilizer N also resulted in runoff reduction: stone rows with urea reduced runoff by up to 65%, whereas grass strips with urea reduced runoff by 22%. Applying compost (T_C) alone reduced runoff by 32%, which was almost as much as the reduction from applying fertilizer N (T_U: 46%). Treatments without barriers (T_U, T_0) generated the most runoff in both 2001 and 2002. Organic amendments were more effective than fertilizer N in reducing runoff, but combining stone rows or grass strips with compost application effected the greatest reduction in runoff (Table 1).

Application of compost for three successive years notably improved soil physical properties and water infiltration. This accords with results of Cogle *et al.* (2002) in semiarid India who found that organic amendments of farmyard manure and straw significantly reduced annual runoff, compared to unamended treatments. From results of these initial three years of observation, it appeared that as filtering barriers, stone rows had a greater effect in reducing runoff than grass strips (Figure 2a,b); this was undoubtedly because the stone rows were better able to slow runoff and to improve water infiltration. The better performance of stone rows in controlling runoff compared with vegetation bunds is attributable to the difference in architecture between the two types of barrier. The second line of stones, which supports the first row of big stones, closes small gaps in the first row. Although the grass strips comprised three regular lines of plants, the barrier as a whole remained more permeable than stone rows and took a few years (2 years in this experiment) to become thick enough to be fully effective. Moreover, grass strips have to endure the inhospitable dry season and then need about one month of re-growth before they can fully resume their anti-erosion role. However, both of these soil and water conservation techniques enable runoff to be reduced appreciably, leading to increased water infiltration into the land. This is consistent with the results reported by Lamachère & Serpentié (1991) and Zougmoré *et al.* (2000a) in similar climatic zones.

Soil loss

All treatments reduced soil loss compared with the control (Table 2). In the rainy season of 2002, two exceptionally heavy rain events produced 90% of total soil loss mostly in the form of fine sediments. Soil loss in the control treatment was very large and represented 3 to 30 times that of the other treatments. It was clearly observed that treatments with compost application reduced soil loss more than treatments with and without fertilizer N. In the 2000 rainy season, stone rows reduced soil erosion by 55%, whereas the reduction by grass strips was about 31% compared with the control. Plots with stone rows or grass strips (T_{SR}, T_{GS}) were eroded less than those with compost or fertilizer N only (T_C, T_U), confirming the additive effect of permeable barriers on soil loss reduction. Applying compost on plots without barriers reduced soil loss by 35%, while combining compost and stone rows reduced soil loss by 52% compared with the control. The combined results for the three years showed that the soil losses were least in treatments that combined the application of organic amendments and runoff barriers (T_{SRC}, T_{SRM}, T_{GSC}, T_{GSM},). Treatments with organic amendments (T_{SRC}, T_C, T_{SRM}, T_{GSM}, T_{GSC}) produced less erosion than treatments with fertilizer N (T_{SRU}, T_{GSU}, T_U) (Table 2). This was particularly noticeable during 2000 and 2002. Soil cover reduces soil loss by slowing down runoff and thus reducing the displacement of solid particles, particularly the finest (Zougmoré *et al.* 2000b). This is consistent with Lal (1975) and Roose (1981), who found that permanently protecting the soil with a dead or living cover is one of the most effective ways of controlling erosion.

Soil moisture

Statistical analysis revealed significant differences of soil water content between treatments (Table 3). However, these slight differences were mainly observed during wet periods, soon after the rain events had induced runoff (6 August 2000 and 27 August 2001). This could be explained by the fact

Table 3. Effect of treatments on volumetric soil water content in the root zone (%) for years 2000, 2001 and 2002 at Saria, Burkina Faso.

	06 August 2000	27 August 2001	15 July 2002
T_{SRU}	18.9 (1.7) a	14.4 (0.7) a	12.4 (0.4) a
T_{SR}	16.3 (1.6) b	12.8 (1.0) b	11.4 (1.1) b
T_{GSC}	16.5 (1.6) b	13.4 (1.9) b	09.3 (0.6) e
T_{GSU}	16.1 (1.3) b	10.5 (0.7) d	10.0 (0.4) cd
T_{SRM} /T_U	15.8 (1.8) b	10.4 (0.6) d	10.3 (0.3) c
T_{SRC}	15.2 (1.3) bc	10.9 (0.5) d	08.6 (0.5) f
T_{GS}	14.4 (1.0) c	12.1 (0.6) c	10.3 (0.6) c
T_{GSM} /T_C	14.2 (1.4) c	11.6 (1.0) c	09.8 (0.7) d
T_0	14.0 (1.1) c	10.1 (1.3) d	10.1 (0.6) cd
Probability	<0.001	<0.001	<0.001

[a]Values in parentheses are ± standard deviation. Treatments in a column bearing the same letter are not statistically different at $P = 0.05$.
For treatment key, see Table 1 and Materials and Methods.

Table 4. Average volumetric soil water content in the root zone (%) for different positions upslope of the barriers during wet period (27 August 2001) and dry period (15 July 2002) at Saria, Burkina Faso.

		T_{SRU}	T_{GS}	T_{SR}	T_0	T_{GSC}	T_{GSU}	T_C	T_{SRC}	T_U
27 August	0 m	15.2 (0.8) a	15.9 (0.7) a	16.6 (0.6) a	12.9 (0.5) a	09.2 (0.2) c	13.5 (0.2) a	13.6 (0.4) a	16.3 (0.6) a	13.3 (0.5) a
2001	1 m	13.0 (0.6) b	13.0 (0.5) b	10.9 (0.6) b	10.3 (0.6) b	12.8 (1.4) a	10.4 (0.6) b	10.8 (1.0) b	10.3 (0.3) b	10.7 (0.3) b
	2 m	13.0 (0.5) b	11.4 (0.7) c	10.8 (0.5) b	10.3 (1.0) b	12.7 (0.8) a	11.0 (0.4) c	10.6 (0.7) b	09.2 (0.4) c	09.1 (0.9) c
	17 m	12.1 (0.8) c	08.7 (0.4) d	11.1 (0.9) b	11.0 (0.3) b	11.5 (0.5) b	07.8 (0.4) d	12.0 (0.7) a	07.4 (0.5) d	09.5 (0.4) c
15 July	0 m	17.0 (0.3) a	13.1 (0.3) a	18.1 (1.1) a	10.3 (0.5) a	08.4 (0.3) b	14.9 (0.4) a	11.0 (0.5) a	9.0 (0.5) b	12.1 (0.2) a
2002	1 m	12.1 (0.2) b	11.6 (0.4) b	10.1 (1.0) b	09.1 (1.1) b	08.8 (0.9) b	09.4 (0.6) b	09.6 (0.6) b	10.9 (0.3) a	09.6 (0.3) c
	2 m	10.5 (0.3) c	08.8 (0.6) c	09.3 (0.6) bc	10.6 (0.4) a	10.1 (0.4) a	08.5 (0.4) c	09.0 (1.0) b	08.5 (0.6) c	10.4 (0.2) b
	17 m	10.0 (0.5) d	07.6 (0.8) d	08.2 (1.4) c	10.5 (0.6) a	09.7 (0.8) a	07.0 (0.4) d	09.7 (0.5) b	06.0 (0.4) d	09.2 (0.3) c

[a]Values in brackets are ± standard deviation. Positions bearing the same letter in a column are not statistically different at $P = 0.05$. For treatment key, see Table 1 and Materials and Methods.

that sorghum was using water at the same time as runoff had been reduced by the barriers. For these periods, there was more water in the root zone (0–80 cm) in plots with SWC treatments than in the control (T_0). Plots with stone rows contained more water than plots with grass strips. Treatments supplied with compost (T_C) or urea only (T_U) were wetter than control plots but drier than treatments with stone rows (TSR) or grass strips alone (T_{GS}). This indicates that stone rows and grass strips play a major role in collecting water and increasing infiltration. However, plots with fertilizer N input (T_{SRU}, T_{GSU}, T_{SR}, T_{GS},) were wetter than plots with organic input (T_{GSM}, T_{GSC}, T_{SRM}, T_{SRC}, T_C), particularly after long periods of drought such as 15 July 2002. Owing to the greater biomass in plots with organic input, soil water consumption in these plots was probably greater than in the plots given non-organic amendments. Organic amendments improve soil drainage (Roose 1981; Mando 1997), which could be why there was less water in plots with organic N than in those with fertilizer N. This fact and our finding that water storage was greater immediately upslope from barriers than in the rest of the plot are consistent with reports by Perez *et al.* (1998) for live hedges in Senegal and Zougmoré *et al.* (2000a) for stone rows in Burkina Faso.

Table 4 summarizes variation in soil moisture along the length of plots, based on the measurements of 27 August 2001 and 15 July 2002. Soil water content decreased over a distance of 17 m upslope from the barriers, during both wet and dry periods. However, for treatments with grass strips and organic inputs (T_{GSC}, T_{GSM}) the soil was drier nearer the barrier than further away from it. This was not the case for plots with stone rows + organic input, however, probably because grass boosted by organic amendments resulted in extra evapotranspiration close to the strips.

Sorghum production

The treatment effect on sorghum grain and straw yields was statistically significant over the three years (Table 5). However, the crop production on plots T_{SR}, T_{GS} (without nutrient input) was not significantly different from that on the control plots. This demonstrates that under the average annual rainfall of this region, particularly if it is well distributed in time, implementing water conservation measures without adding nutrients will not enhance yields (Zougmoré *et al.* 2000a; Fatondji *et al.* 2001).

Comparison of water use efficiency (WUE) among treatments for the three years (Table 5) suggested that nutrient supply, more than water retention by the barriers, increased yields in plots with combined SWC and nitrogen from both organic and inorganic sources. Indeed, there were only slight differences of WUE values between plots given compost (T_C) or urea (T_U) and plots combining barriers and application of organic (T_{SRC}, T_{GSC}) or fertilizer N (T_{SRU}, T_{GSU}). The results shown in Table 5 are consistent with those of Ouédraogo *et al.* (2001), who observed in the same region and on the same soil that the greatest sorghum dry

Table 5. Effect of treatments on sorghum production for rainy seasons 2000, 2001 and 2002 at Saria, Burkina Faso.[a]

	Grain yield (kg ha^{-1})			Straw yield (kg ha^{-1})			Water use efficiency (kg mm^{-1})		
	2000	2001	2002	2000	2001	2002	2000	2001	2002
T_{SRC}	2308 (18) a	2535 (43) a	2766 (58) a	4844 (244) ab	5139 (208) a	4598 (175) a	8.7 (0.5) a	11.5 (0.2) a	10.1 (0.5) a
T_{GSC}	2324 (75) a	2338 (73) ab	2536 (74) b	4997 (401) a	4742 (240) a	4564 (212) b	9.6 (1.3) a	10.6 (0.1) a	9.7 (0.1) b
T_{GSM}/T_C	1558 (78) b	2278 (68) ab	2385 (79) b	3591 (181) ab	4570 (84) a	4038 (147) b	6.8 (1.7) abc	10.2 (1.2) a	8.8 (1.1) b
T_{SRU}	1444 (10) bc	1796 (50) ab	1511 (39) c	3891 (116) ab	4024 (193) ab	3023 (165) c	7.8 (1.1) ab	8.7 (0.4) ab	6.2 (1.2) c
T_{GSU}	932 (13) cd	1537 (22) ab	1411 (30) c	2815 (169) ab	3523 (204) ab	2376 (76) c	5.4 (0.4) bc	7.6 (0.8) ab	5.2 (1.5) c
T_0	838 (70) cd	1099 (76) ab	1164 (75) d	2623 (99) ab	2857 (172) ab	1967 (143) d	5.1 (0. 3) bc	5.9 (1.1) ab	4.3 (0.5) d
T_{SR}	739 (53) d	1226 (74) ab	1308 (54) cd	2439 (121) b	3005 (118) ab	2374 (87) cd	4.7 (0.2) bc	6.4 (1.9) ab	5.0 (0.9) cd
T_{GS}	664 (9) d	896 (72) b	983 (42) d	2321 (215) b	2056 (162) b	1669 (159) d	4.2 (0.8) c	4.5 (0.7) b	3.6 (0.4) d
T_{SRM}/T_U	1692 (55) b	2106 (14) ab	1403 (30) c	3534 (68) ab	3823 (220) ab	2468(165) cd	7.7 (0.5) ab	8.6 (1.4) ab	5.3 (0.8) cd
Probability	<0.001	0.022	0.021	0.020	0.021	0.026	0.004	0.019	0.020

[a]Values in brackets are ± standard deviation. Treatments bearing the same letter are not statistically different at $P = 0.05$. For treatment key, see Table 1 and Materials and Methods.

Table 6. Sorghum grain yield (kg ha^{-1}) for different positions upslope of the barriers in 2000, 2001 and 2002 at Saria, Burkina Faso.[a]

	Year 2000		Year 2001		Year 2002	
	1 m	17 m	1 m	17 m	1 m	17 m
T_{GSM}/T_C	2525 (20) a	1469 (99) bc	3315 (151)	1974 (31)	2599 (81) a	2443 (81) a
T_{SRC}	2422 (23) ab	1943 (22) ab	2310 (50)	2398 (94)	2696 (22) a	2519 (28) a
T_{GSC}	1477 (38) abc	2308 (3) a	1987 (37)	2029 (13)	1922 (30) ab	2627 (30) a
T_{SRU}	2287 (111) ab	1084 (30) bc	2495 (134)	1852 (42)	1611 (22) ab	1228 (22) ab
T_{GSU}	537 (11) bc	1089 (64) bc	1021 (60)	2094 (121)	931 (31) b	1406 (31) ab
T_0	870 (18) abc	946 (48) bc	1104 (27)	802 (69)	1284 (21) b	1219 (21) ab
T_{SR}	1089 (29) abc	430 (62) c	1180 (33)	693 (99)	1281 (25) b	847 (25) b
T_{GS}	365 (13) c	620 (14) c	501 (82)	732 (46)	644 (23) b	1221 (23) ab
T_{SRM}/T_U	1753 (58) abc	855 (13) bc	2036 (30)	1343 (33)	1440 (88) b	1529 (87) ab
Probability	0.014	0.018	0.139	0.250	0.005	0.022

[a]Values in brackets are ± standard deviation. Yields bearing the same letter are not statistically different at $P = 0.05$. For treatment key, see Table 1 and Materials and Methods.

matter production was obtained from plots receiving compost. Studies by Bielders & Michels (2002) and Bielders *et al.* (2002) showed similar findings with millet in Niger where mulching (burial of residues) resulted in significant improvements in soil physical quality and crop yields.

Significant differences were observed for spatial variation of sorghum grain yield (Table 6). On average, 1 m upslope from the stone rows the grain yields were 45–60% greater than those obtained 17 m from the stone rows. However, yields 1 m upslope from the grass strips were 35–60% less than yields at 17 m. This effect of SWC barriers on the spatial variation of sorghum yield was more pronounced during 2000 (when the rainy season was erratic with frequent periods of water stress) than during 2001 and 2002 (when rainfall was better distributed). That sorghum production was less near the grass strips than further away from them was probably due to shading from the grass and competition for nutrients and water. As stones do not compete with plants, the opposite trend was observed near to stone rows.

CONCLUSIONS

The partially permeable soil and water conservation barriers combined with compost or animal manure application significantly reduced runoff and soil loss. These stone rows and grass strips increased soil moisture, especially upslope, and could thus play a major role in harvesting runoff water. However, our results showed that water conservation without nutrient addition does not boost crop production significantly, particularly if rainfall in the rainy season is well distributed.

Applying organic amendments in fields with partially permeable barriers resulted in substantial increased sorghum production. We conclude that in order to increase soil productivity, the practices of soil conservation and nutrient amendment should be integrated. Vegetative barriers must be managed to alleviate shading and other effects of competition on crops near to the strips. In the Sahel, animal manure is sometimes in short supply to smallholders employing cereal-based farming systems, but the additional crop residues produced with these combined practices allows the production of the required quantity of organic amendment. However, given the smallholders' difficulties in managing crop residues, the wide adoption of such practices would be encouraged if most of the available crop residues were composted. Evaluations of the cost-effectiveness of these technologies and the nutrient losses through runoff and soil erosion will be important in establishing the most sustainable options under semiarid conditions.

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