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RESEARCH ARTICLE

Benefits of integrated soil fertility and water management in semi-arid West Africa: an example study in Burkina Faso

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Abstract The synergistic effect of soil and water conservation (SWC) measures (stone rows or grass strips) and nutrient inputs (organic or mineral nutrient sources) was studied at Saria station, Burkina Faso. The 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, as compared with the control plots. Plots with no SWC measure lost huge amounts of soil (3 t ha^{-1}) and nutrients. Annual losses from eroded sediments and runoff reached 84 kg OC ha^{-1}, 16.5 kg N ha^{-1}, 2 kg P ha^{-1}, and 1.5 kg K ha^{-1} in the control plots. The application of compost led to the reduction of total soil loss by 52% in plots without barriers and 79% in plots with stone rows as compared to the losses in control plots. SWC measures without N input did not significantly increase sorghum yield. Application of compost or manure in combination with SWC measures increased sorghum grain yield by about 142% compared to a 65% increase due to mineral fertilizers. Yields increase did not cover annual costs of single SWC measures while application of single compost or urea was cost effective. The combination of SWC measures with application of compost resulted in financial gains of 145,000 to 180,000 FCFA ha^{-1} year^{-1} under adequate rainfall condition. Without nutrient inputs, SWC measures hardly affected sorghum yields, and without SWC, fertilizer inputs also had little effect. However, combining SWC and nutrient management caused an increase in sorghum yield.

Keywords Stone row · Grass strip · Nutrient input · Sorghum · Economic benefit

Introduction

Soil degradation is a major constraint to the sustainability of agricultural systems in the arid and semiarid tropics (Ryan and Spencer 2001) and particularly in the semiarid zone of West Africa (Laflen and Roose 1998; Lal 1998). Water erosion is a serious threat to sustainable agricultural land use as it affects soil productivity (Laflen and Roose 1998). In this region, erosion is

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worsened by poor soil and crop mismanagement, which jeopardize the integrity of soil's self-regulatory capacity (Lal 1998). Indeed, erosion by runoff water is responsible for negative nutrient and carbon balances in most farming systems in West Africa (Stoorvogel and Smaling 1990) and for the reduction of crop rooting depth (Morgan 1995). Erosion influences several soil properties, such as topsoil depth, soil organic carbon content, nutrient status, soil texture and structure, available water holding capacity and water transmission characteristics.

In addition, plant nutrient use efficiency in cereal-based farming systems is often very low because of limited soil moisture conditions (Buerkert et al. 2002). The low soil quality combined with the harsh Sahelian climate leads to a low efficiency of fertilizers (Breman et al. 2001). Indeed, considering the importance of soil moisture for crop growth and for the uptake of plant nutrients in this zone, the effectiveness of soil fertility enhancing measures should be related to the rainfall regimes (FAO 1986).

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). 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. 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. 2000b). Moreover, alleviating erosion-induced loss will require the development and adoption of land use systems that are capable of replenishing or maintaining the nutrient status of the soil in addition to controlling water runoff and soil erosion (Sanchez et al. 1997; Quansah and Ampontuah 1999). Therefore, interactions of soil and water conservation measures with organic or mineral source of nutrients need to be examined. Indeed, combining soil and water conservation measures (SWC) with locally available nutrients inputs may optimize crop production and economic benefit in cereal-based farming systems. This can be best illustrated through work conducted at Saria agricultural station (INERA-Burkina Faso) on the combined use of runoff barriers (stone rows or grass strips) and organic or mineral nutrient sources.

Materials and methods

Site description and experimental design

The experimental field was at Saria Agricultural Research Station in Burkina Faso (12°16′ N, 2° 9′ W, 300 m altitude), characterised by a north-sudanian climate (Fontès and Guinko 1995). Over the last 30 years the average annual rainfall was 800 mm. Rainfall is mono-modal, lasts for 6 months (May–October) and is distributed irregularly in time and space. Mean daily temperatures vary between 30°C during the rainy season and may reach 35°C in April and May. The mean potential evapotranspiration is 2,096 mm in dry years and 1,713 mm in wet years. The site was previously under fallow for about 15 years. The soil type was a Ferric Lixisol (FAO-UNESCO 1994) with an average slope of 1.5% and a hardpan at 0.7 m depth. The textural class according to the USDA system is a sandy loam at 0.3 m (62% sand, 28% silt, 10% clay) with average gravel content of 30% at 0.1 m depth.

The trial was conducted over three seasons (2000–2002) and combined linear SWC measures with organic or fertiliser sources of nitrogen. The experimental design was a randomized Fisher bloc with nine treatments and two replications:

T_{SR}: stone rows, no N input	T_{GS}: grass strips, no N input
T_{SRC}: stone rows + compost-N	T_{GSC}: grass strips + compost-N
T_{SRM}: stone rows + manure	T_{GSM}: grass strips + manure
T_{SRU}: stone rows + urea-N	T_{GSU}: grass strips + urea-N
T_0: no SWC measures, no N input	

Taking into consideration that in 2000, results of treatments with compost or animal manure showed the same trend and because compost was more available than manure (Sédogo 1993), treatments T_{GSM} and T_{SRM} were replaced in year 2001 respectively by T_C (Compost-N, no SWC measure) and T_U (Urea-N, no SWC measure).

The plots, of 100 m by 25 m, were isolated from the surrounding area by an earth bund 0.6 m high.

The first replication was instrumented with runoff collection devices and equipment to record runoff. Runoff and sediment in each plot were collected from a 100 m by 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 rain event. Each pit in one replicate only was equipped with a water level recorder (TD-divers, Eijkelkamp, Giesbeek, The Netherlands) that recorded the overland flow hydrograph. Rainfall intensity was recorded using an automatic rain gauge (tipping bucket). In each plot, 36 subplots of 10 m by 2 m were delimited. These subplots, which were used to record sorghum yield variation down the length of slope, 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 (Zougmoré et al. 2000a, b). 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. Stone rows were about 0.2–0.3 m high. Grass strips were made of three rows of grass, resulting in a thick barrier of 0.3 m width.

The 110-day sorghum (*Sorghum bicolor* (L.) Moench) variety Sariasso 14 was sown by hand in rows across the slope at 31,250 seedlings per hectare in all plots. The plots were weeded with hand hoes twice a year. Prior to sowing, plots were ploughed to 0.15 m depth using oxen power to incorporate manure, compost, and urea. Manure, compost and urea were applied each year at a rate of 50 kg N ha^{-1}. The amounts of compost or animal manure applied to attain this N-rate varied between 5 to 7 t ha^{-1}, and were about the minimal rates recommended in Burkina (Sédogo 1993; Berger 1996). Urea application was split into two rates (at 21 and 56 days after planting). All plots received a basal dressing of 20 kg ha^{-1} P in the form of triple superphosphate to eliminate phosphorus deficiency.

Data collection

Runoff was recorded for each rainfall event that generated overland flow using the TD-divers placed in the runoff collection pits. Before pumping out the water, runoff water was thoroughly stirred and sampled in plastic barrels (60 l) after each runoff-producing rain event for the determination of suspended sediment concentration. The amount of water that was pumped-out divided by the amount of well-stirred sample in the barrel is called sample fraction (SF). The fine sediments, after decantation and filtration of the barrel content, were dried and weighted. Coarse sediment in the pit after each runoff event was also dried and weighted. The total soil loss per each rain event was the sum of the dried fine sediment times SF and the total collected coarse sediment. Sorghum grain and straw yields were measured after sun drying at harvest from the 36 subplots in each plot.

Data analysis

Runoff was analyzed from 10 erosive rain events for the 2000 rainy season, 9 erosive rain events for the 2001 rainy season, and 16 erosive rain events for the 2002 rainy season. Cumulative runoff during the crop-growing period (from sorghum planting to its harvest) of each year was related to cumulative rainfall to assess the ratio of annual runoff. Cumulative soil loss was compared per treatment to assess the effect of treatment on erosion during the 3 years. STATITCF package (Gouet and Philippeau 1986) was used for statistical analyses of sorghum grain and straw yields. Newman-Keuls test was used for mean separation at $P < 0.05$.

Assuming $x_1 =$ Stone rows or grass strips, $x_2 =$ Application of compost-N or urea-N, $x_0 =$ Control (no SWC measures, no N input), $Y =$ yield, $(x_1 + x_2) =$ Combined SWC measure (x_1) and compost-N or urea-N (x_2). The interaction effect (IE) in crop yield is the benefit in crop yield (in comparison to the control treatment) of the combined application of both SWC measure and urea-N or compost-N ($\Delta Y(x_1 + x_2)$) minus the sum of the benefits from the two components (ΔYx_1 and ΔYx_2) when applied in isolation (Iwuafor et al. 2002).

$$\Delta Yx_1 = Y(x_1) - Y(x_0) \tag{1}$$

$$\Delta Yx_2 = Y(x_2) - Y(x_0) \tag{2}$$

$$\Delta Y(x_1 + x_2) = Y(x_1 + x_2) - Y(x_0) \tag{3}$$

$$\mathrm{IE} = \Delta Y(x_1 + x_2) - (\Delta Yx_1 + \Delta Yx_2) \tag{4}$$

There is positive interaction between x_1 and x_2 when $\mathrm{IE} > 0$, and negative interaction between x_1 and x_2 when $\mathrm{IE} < 0$.

A minimum yield value, which corresponds to the minimum excess yield that supports the annual cost of the applied technology, was calculated per treatment to determine the economic benefit of single or combined N-input and SWC measures. To that end, the yield increase per kg N ($\Delta Y/\Delta$N) was calculated for the applied 50 kg ha^{-1} urea-N or compost-N. ΔY stands for yield increase and ΔN for applied N amount i.e. 50 kg N ha^{-1}.

In 2001 and 2002, the price of 1 kg urea-N was about 544 FCFA (1 USD = 650 FCFA in 2003). The price of 1 kg of sorghum in the region of Saria fluctuated between 100 FCFA and 180 FCFA. The average of 140 FCFA for 1 kg sorghum and a minimum of 3.9 kg sorghum per kg of urea-N were used in this paper. This corresponds to a minimum yield of 195 kg ha^{-1} for urea-N.

Several studies (Graaff 1996; Zougmoré et al. 2000b; Posthumus et al. 2001) have defined total costs for stone rows and grass strips installation in Burkina Faso to be 75,520 CFA ha^{-1} and 33,200 CFA ha^{-1}, respectively. The calculation of annual costs took into account the amortization, the opportunity cost of the capital and the repair and maintenance costs. The discounted average cost for stone rows using truck transport was 48,312 FCFA ha^{-1} year^{-1} while grass strips installation cost using root transplanting was 26,240 FCFA ha^{-1} year^{-1}. The minimum yield was therefore 345 kg ha^{-1} sorghum grain for stone rows and 187 kg ha^{-1} sorghum grain for grass strips.

The discounted annual cost for compost was evaluated to 37,900 FCFA ha^{-1} and the price of 1 kg of nitrogen deriving from compost was 758 FCFA. A minimum sorghum yield for compost-N was 5.4 kg kg^{-1}, which corresponds to a minimum yield of 271 kg ha^{-1}. This implies that for a technology to be beneficial, its excess yield, which is the difference between yield increase (ΔY) and the minimum yield, should be greater than zero.

Results and discussions

Rainfall characteristics

Figure 1 shows the cumulative rainfall patterns over the 3 years which were less than the regional average of 800 mm. 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, 2 of which were greater than 50 mm and very influential on total runoff and soil loss. The rainfall during the sorghum cropping period (June–October) was more evenly distributed in 2001 and 2002 than in 2000; this contributed to the better crop performance in 2001 and 2002 (Table 2). A drought of 13 days occurred early in September 2000 (Fig. 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 delay of the rainy season in June postponed crop establishment in 2002.

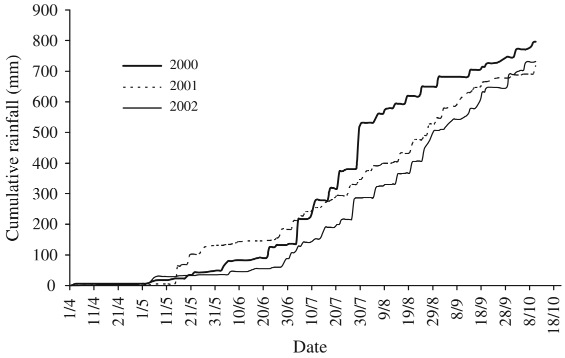

Fig. 1 Daily cumulative rainfall for the 2000, 2001 and 2002 rainy seasons at Saria, Burkina Faso

Runoff

During the 3 years of study, all treatments reduced runoff compared to control plots (Table 1). In the 2000 rainy season, the runoff in treatments with stone rows was always less than in treatments with grass strips when 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, 7% in non-amended plots, and 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, T_{SRC} and T_{GSC} had the

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

	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 (0.9)	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	7.5 (2.2)	6.6 (0.9)	9.0 (1.0)	53	46	49
T_{GSM}/T_C	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

Values in brackets: ±standard deviation between runoff volumes measured in pits and recorded values of runoff. Treatments are explained in materials and methods section

least runoff, followed by T_{SR}, T_{SRM}, T_{GSM}, T_{GS}, T_{SRU}, T_{GSU} and 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. Under the climatic conditions of the study zone, it appears that as filtering barriers, stone rows had a greater effect in reducing runoff than grass strips; this was certainly because the stone rows were better able to slow down runoff water than vegetation bunds. Indeed, the stone row structure (The second line of stones, which supports the first row of big stones), allows to close all small gaps in the first row; thus, the runoff flow is uniformly dispatched throughout the contour line; the consecutive reduced velocity of runoff leads to an increased storage and infiltration of water within the field plot. Although the grass strips comprised three regular lines of plants, the resulted runoff barrier in this experiment remained more permeable to runoff water than stone rows. Contrarily to stone rows structure, some gaps were observed throughout the grass strips, which lead to the concentration of runoff water flow at these specific places and to little retention of water within the field plot. Grass strips took a few years (2 years in this experiment) to become thick enough to be fully effective. Moreover, grass strips have to endure and need about one month of re-growth after the inhospitable dry season before they can fully resume their anti-erosion role. This is consistent with the results reported by Lamachère and Serpentié (1991) and Zougmoré et al. (2000a) in similar climatic zones. It is however reported by numerous studies (Buldgen and François 1998; Sharma et al. 1999) that under good climatic conditions, grass strips are very efficient soil and water conservation techniques that appreciably reduce runoff, leading to increased water infiltration into the land.

Compared to 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 applying fertilizer N (T_U: 46%). Treatments without barriers (T_U, T_0) showed the highest 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 induced the greatest reducing effect on runoff (Table 1). Application of compost for three successive years may notably improve soil physical properties, which could enhance water infiltration. This is in accordance with results of Cogle et al. (2002) in semiarid India who found that organic amendments, of farmyard and straw significantly reduced annual runoff, compared to non-amended treatments.

Soil and nutrient losses

All treatments reduced soil loss compared to the control treatment, which showed the average highest soil loss of 217 kg ha^{-1} in 2000, 236 kg ha^{-1} in 2001 and 32711 kg ha^{-1} in 2002 (Fig. 2a, b). In 2001, the effect of stone rows in soil loss reduction was much more noticeable than the effect of grass strips. Soil losses were very low and less than 70 kg ha^{-1} in the three stone row treatments (T_{SRC}, T_{SRU}, T_{SR}) and rose to more than 100 kg ha^{-1} in grass trips treatments (T_{GSC}, T_{GSU}, T_{GS}). Stone rows and grass strips alone (T_{SR}, T_{GS}) were able to reduce soil loss respectively by 70% and 58% as compared to the control treatment. Plots with stone rows or grass strips (T_{SR}, T_{GS}) were less erosive than those with compost-N or urea-N only (T_C, T_U). Indeed, the two latter treatments induced 51% soil loss reduction while treatments T_{SR} and T_{GS} induced respectively 70% and 58%, confirming the positive effect of permeable barriers on soil loss reduction.

The application of compost and urea in plots with soil conservation barriers (stone rows or grass strips) improved the efficiency of the system to reduce soil loss (Fig. 2a, b). However, the efficiency of the water conservation system was better when compost is applied than when urea is applied. Applying compost on plots without barriers (T_C) enabled soil loss to be reduced by 52% while combining compost and stone rows (T_{SRC}) induced a 79% reduction in soil loss compared to the control (T_0). The difference in soil loss reduction rate was only 2% between T_C and T_{GSC} and was up to 26% between T_C and T_{SRC}. These trends were also observed in 2000 and 2002. Thus, in this study, application of organic amendment (compost) reduced soil loss more than application of mineral fertilisers (urea). Thanks to the better availability of macro-nutrients and micro-nutrients released along the cropping season from applied

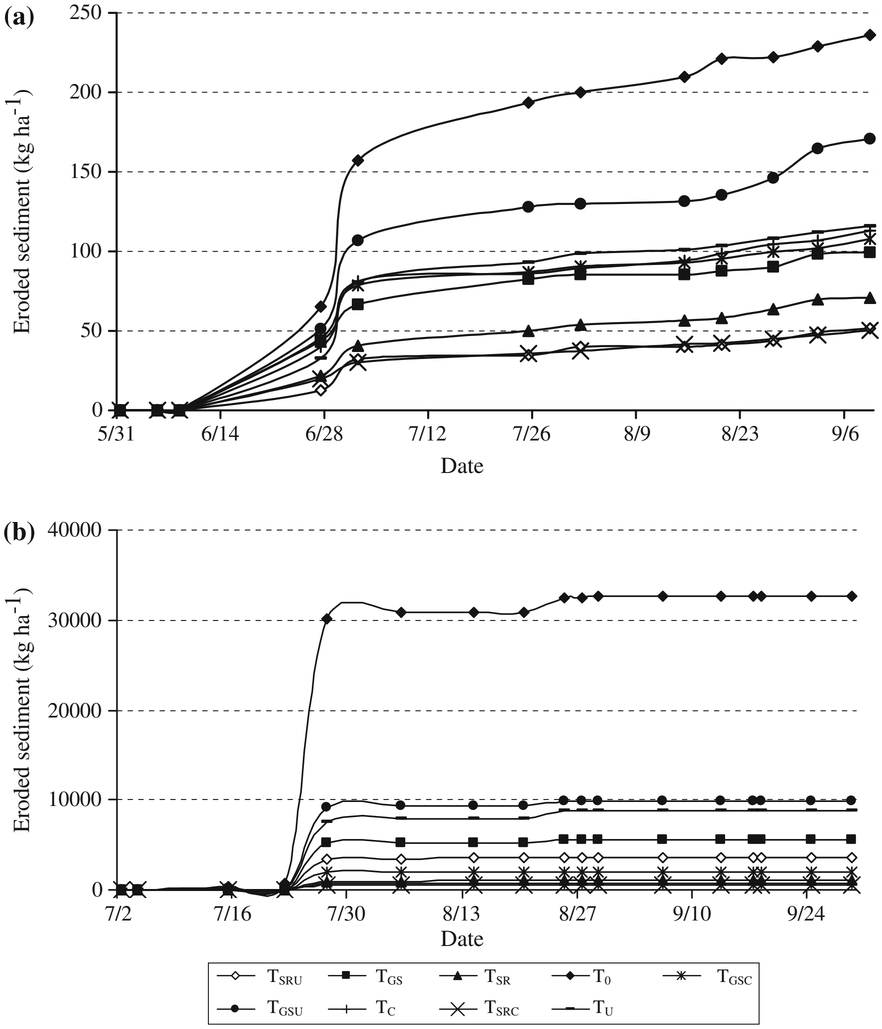

Fig. 2 Cumulative soil loss as affected by SWC measures and nutrient inputs at Saria, Burkina Faso; (**a**) 2001, (**b**) 2002. Treatments are explained in materials and methods section

compost, sorghum biomass was more important in plots with application of organic amendment than in plots supplied with urea; this important biomass ensured a good crop canopy and soil cover, which may contribute slowing down runoff and reducing the displacement of soil particles, particularly the finest (Zougmoré et al. 2000a). This is consistent with Lal (1998) who reported that permanently protecting the soil surface with a dead or living cover is one of the most effective ways of controlling erosion.

Carbon and nutrient concentrations of generated sediments were very high and reached 14–29 g kg^{-1} for OC, 1.0–3.7 g kg^{-1} for N and 318–709 mg kg^{-1} for total P. Treatments with stone rows barriers had on average NO_3^--N concentration in runoff water of 23 mg L^{-1} compared to only 2 mg L^{-1} with treatments without barriers (11 times greater). Annual losses of organic C, N, P and K were high and greatly dependant on the magnitude of soil loss. Combining runoff barriers with compost application induced the least organic C and plants nutrients losses. Integrated water and nutrient management is effective in alleviating total soil, carbon and nutrients losses by water erosion and therefore could play a major role in sustaining crop production in Sahelian smallholder farming systems.

Effects of SWC measures and nutrient management on sorghum performance

Sorghum yields were significantly different among treatments over the 3 years (Table 2). Except for T_{GS} (grass strips alone), sorghum grain yield was lower in the control treatment than in the water and nutrient management treatments during the 3 years. In 2001, although not statistically different, sorghum yields with stone rows alone (T_{SR}) increased by 12% whereas with grass strips alone (T_{GS}) sorghum yield decreased by 18% when compared to the control (T_0). In 2002, single stone rows plots induced 12% grain yield increase whereas in single grass strips plots, grain yield decreased by 15% compared to the control. These results indicate that during well-distributed rainfall years in the Sahel, implementing water conservation measures without adding nutrients induced little or even negative influence on crop yields. This may be explained by the inherent low nutrient content of soils, mainly for N and P (Bationo et al. 1998). Also, thanks to the better water availability induced by the runoff barriers, nutrient needs of sorghum plants may increase, leading to greater deficits and competitions between sorghum plants and those from the grass strips. This is consistent with results of previous studies in the region (Hamer 1996).

In 2001, application of compost (T_C) or urea (T_U) alone significantly increased sorghum yield by respectively 107% and 92% compared to the control (T_0). Thus, applying nutrient inputs alone (T_C, T_U) induced much higher grain yields than laying SWC barriers without nutrient inputs: 80% compared to stone rows plots (T_{SR}) and 145% compared to grass strips plots (T_{GS}).

Table 2 Effect of treatments on sorghum performance for rainy seasons 2000, 2001 and 2002 at Saria, Burkina Faso

	Grain yield (kg ha^{-1})			Straw yield (kg ha^{-1})		
	2000	2001	2002	2000	2001	2002
T_{SRC}	2,308 (18) a	2,535 (43) a	2,766 (58) a	4,844 (244) ab	5,139 (208) a	4,598 (175) a
T_{GSC}	2,324 (75) a	2,338 (73) ab	2,536 (74) b	4,997 (401) a	4,742 (240) a	4,564 (212) b
T_{GSM}/T_C	1,558 (78) b	2,278 (68) ab	2,385 (79) b	3,591 (181) ab	4,570 (84) a	4,038 (147) b
T_{SRU}	1,444 (10) bc	1,796 (50) c	1,511 (39) c	3,891 (116) ab	4,024 (193) ab	3,023 (165) c
T_{GSU}	932 (13) cd	1,537 (22) c	1,411 (30) c	2,815 (169) ab	3,523 (204) ab	2,376 (76) c
T_0	838 (70) cd	1,099 (76) d	1,164 (75) d	2,623 (99) ab	2,857 (172) ab	1,967 (143) d
T_{SR}	739 (53) d	1,226 (74) d	1,308 (54) cd	2,439 (121) b	3,005 (118) ab	2,374 (87) cd
T_{GS}	664 (9) d	896 (72) d	983 (42) d	2,321 (215) b	2,056 (162) b	1,669 (159) d
T_{SRM}/T_U	1,692 (55) b	2,106 (14) b	1,403 (30) c	3,534 (68) ab	3,823 (220) ab	2,468(165) cd
Prob.	<0.001	0.022	0.021	0.020	0.021	0.026

Treatments with the same letter are not statistically different at $P = 0.05$. Values in brackets: ± are standard deviations. Treatments are explained in materials and methods section

In 2002, as in 2001, single application of N-input (T_C, T_U) induced significant higher grain yield than single application of SWC measures: applying urea (T_U) induced 7% and 43% yield increase compared to plots with stone rows (T_{SR}) or grass strips (T_{GS}) alone respectively, whereas application of compost alone (T_C) significantly increased yield by 82% and 143% compared to stone row (T_{SR}) and grass strip plots (T_{GS}), respectively. As the productivity of most soils in their native state in the study zone is very low (Bationo et al. 1998), applying plants nutrients (50 kg N ha^{-1}) in these poor soils induced great positive reaction in crop production (Table 2), particularly during good rainfall years (Fig. 1) when soil moisture constraint is small. In plots with compost application, the mineralization of compost releases not only the macronutrients such as nitrogen and phosphorus, but also considerable amounts of micronutrients for plants (Velthof et al. 1998). This explains also why in 2001, combining compost with stone rows (T_{SRC}) induced a significant yield increase of 106% when compared to plots with stone rows alone (T_{SR}). Similarly, combining grass strips and compost (T_{GSC}) induced a significant grain yield increase of 160% when compared to plots with grass strips alone (T_{GS}). Also, adding urea to plots with barriers (T_{SRU}, T_{GSU}) significantly increased grain yield by 46% and 71% respectively compared to plots with barriers only (T_{SR}, T_{GS}). In general, only slight differences were observed between treatments combining barriers with N-input (T_{SRC}, T_{GSC}, T_{SRU}, T_{GSU}) and receiving-N treatments without barriers (T_C, T_U). These results were confirmed in 2002: treatments combining barriers with compost (T_{SRC}, T_{GSC}) induced significant yield increase by respectively 138% and 118% compared to the control. Adding urea to plots with barriers (T_{SRU}, T_{GSU}) significantly increased grain yield by 30% and 21% respectively when compared to control plots. The above results suggest that under Sahelian conditions, SWC in combination with nutrient management can be used to alleviate risks and to achieve production intensification. This attests that to develop new strategies of agricultural production in sub-Saharan West Africa, one should take into account local SWC technologies and improved practices of soil fertility replenishment (Dudal 2002).

Economic benefit of water and nutrient management

Positive interactions ($\Delta Y(x_1 + x_2)$) of combined SWC measures and N-inputs were observed apart for T_{GSU} in 2001 (-367 kg ha^{-1}) T_{SRU} in 2001 (-437 kg ha^{-1}) and 2002 (-36 kg ha^{-1}). The high response of sorghum yield to added N-inputs only (T_C, T_U) suggests that nutrient supply more than water retention by the filtering barriers (T_{SR}, T_{GS}) increased the yield in combined SWC and nutrient plots. Yield increases did not cover annual costs of stone rows or grass strips alone (Table 3).

Conversely, economic benefits of treatments in Table 4 showed that single application of compost-N or urea-N were cost-effective but supply of urea-N was less beneficial (6,160 FCFA) in 2002 compared to compost-N (133,040 FCFA).

The combination of SWC measures with urea-N (T_{SRU}, T_{GSU}) or compost-N (T_{SRC}, T_{GSC}) induced positive economic benefits in 2001 (Table 5), indicating that at least the annual costs for implementing SWC measures and applying compost-N or urea-N were covered by the excess yields in the combined SWC measure and N-input treatments.

Ganry and Badiane (1998) noted that in cultivated sandy soils of dry tropical zones, organic matter becomes more important in the soil surface layer, because of its effects on the water balance and the mobility of mineral elements. Easily decomposable organic material like compost may well make available

Table 3 Economic benefits of single stone rows or single grass strips in 2001 and 2002

	Stone rows		Grass strips	
	2001	2002	2001	2002
Annual cost (FCFA ha^{-1})	48,312	48,312	26,240	26,240
Sorghum average price (FCFA kg^{-1})	140	140	140	140
Minimum yield (kg ha^{-1})	345	345	187	187
ΔY (kg ha^{-1})[a]	127	144	−203	−181
Excess yield (kg ha^{-1})	−218	−201	−390	−368
Economic benefit (FCFA ha^{-1})	−30,520	−28,140	−54,600	−51,520

[a] ΔY stands for yield increase for stone rows or grass strips treatments compared to the control treatment

Table 4 Economic benefits of single urea-N or single compost-N in 2001 and 2002

Treatment	Urea-N		Compost-N	
	2001	2002	2001	2002
N-input cost (FCFA kg^{-1} N)	544	544	758	758
Sorghum average price (FCFA kg^{-1})	140	140	140	140
Minimum yield increase (kg kg^{-1})	3.9	3.9	5.4	5.4
$\Delta Y/\Delta N$ (kg kg^{-1})[a]	20.2	4.8	23.6	24.4
Excess yield increase (kg kg^{-1})	16.3	0.9	18.1	19.0
Excess yield (kg ha^{-1})	813	44	907	950
Economic benefit (FCFA ha^{-1})	113,820	6,160	127,020	133,040

[a] ΔY stands for yield increase and ΔN for applied N amount of 50 kg N ha^{-1}

Table 5 Economic benefits of combining stone rows or grass strips with compost-N or urea-N in 2001 and 2002 at Saria, Burkina Faso

	2001				2002			
	T_{SRU}	T_{GSU}	T_{SRC}	T_{GSC}	T_{SRU}	T_{GSU}	T_{SRC}	T_{GSC}
Minimum yield for N inputs (kg ha^{-1})	195	195	271	271	195	195	271	271
Minimum yield for SWC (kg ha^{-1})	345	187	345	187	345	187	345	187
Minimum yield for SWC + N input (kg ha^{-1})	540	382	615	457	540	382	615	457
Excess yield (kg ha^{-1})	158	54	821	782	−193	−135	987	915
Economic benefit (FCFA ha^{-1})	22,120	7,560	114,940	109,480	−27,020	−18,900	138,180	128,100

T_{SRC}: stone rows + compost-N; T_{GSC}: grass strips + compost-N; T_{SRU}: stone rows + urea-N; T_{GSU}: grass strips + urea-N

plant nutrients at crucial time of sorghum production (maturing phase), which, in combination with better water availability thanks to SWC measures, have improved sorghum productivity. Moreover, organic matter maintains soil physical, chemical and biological balance that would accelerate crop root formation in the soil profile (Piéri 1989). The best sorghum production resulting from this positive interaction effect of SWC measures and N-inputs explains their greatest economic benefits. Loss of available Urea-N through runoff or leaching could explain the lower interactive effect of urea-N that has resulted in lower economic benefits in comparison to organic-N (Ouédraogo et al. 2007).

Conclusions

Results of this study suggest that:

- The semi-permeable soil and water conservation barriers combined with compost application significantly reduced runoff and soil loss. Stone rows and grass strips increased soil moisture, especially upslope, and could thus play a major role in harvesting runoff water.
- Soil organic C, N, P and K concentrations of eroded sediments were very high, particularly for N, indicating severe losses of one of the more deficient element in West African soils.
- When annual rainfall is well distributed in time (as was the case in 2001 and 2002 at Saria, Burkina Faso), installation of stone rows only induced very limited sorghum yield increase while *Andropogon gayanus* grass strips induced sorghum yield decrease. These yields were not enough to support installation costs due to high labor, transport and material inputs.
- Application of the sole compost-N or urea-N induced significant greater sorghum yield increase than SWC measures only.
- Stone rows or grass strips combined with compost-N induced positive interaction effects while stone rows combined with urea-N showed negative interactions. A positive interaction of grass strips combined with urea-N was observed only after 2 years.
- Economic benefits when combining compost-N to both stone rows and grass strips were substantial (109,000–138,000 FCFA ha^{-1}) while the greatest amounts observed with added urea-N were small (7,560–22,120 FCFA ha^{-1}).

- These results indicate that in the Sahel, opportunities do exist for making more efficient use of local sources of nutrients such as compost in combination with locally accepted SWC measures. This may empower farmers to invest for sufficient nutrient supply in the sub-Saharan soils characterized by poor fertility.

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