Integrated water and nutrient management for sorghum production in semi-arid Burkina Faso

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TO:

- My late parents Pierre and Madeleine
- My wife Catherine and my son Elias

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Wageningen, 16 July 2003

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Chapter 1

General introduction

1.1 Constraints to rain-fed agriculture in semi-arid West Africa

The semi-arid zone of West Africa (Figure 1.1) is characterized by an average annual rainfall of 300─800 mm and a ratio of annual rainfall to annual potential evapotranspiration of 0.2─0.65 (Bationo and Buerkert, 2001). About 41% of Sub-Saharan farming lands are in the semi-arid zone. Only 2% of the arable lands are irrigated, which means that rain-fed agriculture is the main source of food for the increasing populations in that zone (Parr et al., 1990). However, in semi-arid regions, rain-fed agriculture is coping with unreliable rainfall and recurrent droughts with subsequent production failures (Stroosnijder, 2003).

Two major factors characterize the agriculture in the Sahel: (1) the erratic climatic conditions with frequent periods of water shortage (Sivakumar and Wallace, 1991; Stroosnijder and Van Rheenen, 2001) and (2) the presence of large areas of inherently low fertile and crust prone soils (Morin, 1993; Breman et al., 2001). This situation is particularly worsened by continuous cultivation with low input, overgrazing and trampling by cattle (Stroosnijder, 1996; Sanchez et al., 1997, Mando et al., 2001). The effects of these factors have resulted in severe human-induced land degradation in the Sahel (IFAD, 1992; Roose, 1994). Indeed, Oldeman et al. (1991) indicated that in Africa, 40% of agricultural lands were affected by human induced-land degradation.

In order to curtail further degradation and to increase food production, several research studies have been done in this zone to understand the soil degradation phenomena and the processes of their rehabilitation (Hien, 1995; Albergel et al., 1995; Pontanier et al., 1995).

Most important soil degradation processes in the region are: water and wind erosion, hard setting and crusting, nutrient depletion, acidification, and salinization. Among soil degradation processes, nutrient depletion, surface sealing/crusting and soil erosion are the most prominent ones (Morin, 1993). The formation of soil surface crusts increases runoff (Hoogmoed, 1999), which leads to severe water loss through runoff.

In the Sahel, the main constraint to crop production is inadequate water supply (Somé, 1989; Lal, 1991). However, this is not due to rain shortage but to loss of water through runoff and evaporation (Morin, 1993; Fox and Rockström, 2003). Indeed, subsurface degradation results into an increased water loss through runoff and evaporation (Hoogmoed and Stroosnijder, 1984; Mando, 1997; Zougmoré et al., 2000). Because of low soil infiltration and high rainfall intensity, runoff is responsible for severe soil loss despite the gentle slopes in the region (Roose, 1994). Thus, to improve water use efficiency for crop production in this zone requires the increase of Green Water, which is defined by Ringersma (2003) as the fraction of rainwater that infiltrates into the rooted soil zone and that is used, through the process of transpiration, for biomass production. According to the same author, the green water use efficiency (GWUE), expressed as the fraction of transpiration and the annual rainfall, ranges from 5-15% in dryland systems of West Africa. This would consist in maximizing the productive flow of water such as plant transpiration whereas minimizing the non-productive water flows, including soil evaporation, runoff and percolation beyond the root zone (Stroosnijder, 2003). Stone rows or grass strips are SWC measures that could reduce loss of rainwater through runoff and therefore could play an important role in non-productive water flows reduction. However, several studies have shown that these soil and water conservation practices induce limited effects on soil fertility improvement, which is a prominent factor affecting GWUE (Penning de Vries and Djitèye, 1982; Breman and de Ridder, 1991). Indeed, in semi-arid West Africa, cultivated lands are nutrient depleted soils, especially for N and P (Sédogo, 1981; Bationo and Mokwunye, 1991; Bado et al., 1997). This is continuously being worsened by negative nutrient balances of most cropping systems. In Burkina Faso, average negative budgets of 22 kg ha^{-1} of nitrogen, 7 kg ha^{-1} of phosphorus and 18 kg ha^{-1} of potassium per year were reported by Stoorvogel and Smaling (1990). This implies that nutrient replenishment has to be assured in addition to soil and water conservation. In the Sudano-Sahelian zone of West Africa, compost, animal manure and urea are organic or fertilizer sources of nutrients that are recognized to greatly increase crop growth and yields particularly in the low fertile soils of smallholder farming system (Bationo et al., 1998).

Water and nutrients thus interact in limiting crop growth and thereby need to be tackled in synergy to improve crop yields in the Sahel. Integrated soil management, which includes water, nutrients and biomass management, should therefore be addressed in order to reduce runoff and soil erosion, increase water infiltration, and nutrient availability for intensified crop production (Hudson, 1991; Roose, 1994; Breman et al., 2001). This will be the central point of the work reported in this thesis.

1.2 Study area

A large part of Burkina Faso is situated in the semi-arid zone of Sub-Saharan West Africa (Figure 1.1). The increasing population (2.4% annually) is mainly rural and nearly 80% of the population are farmers.

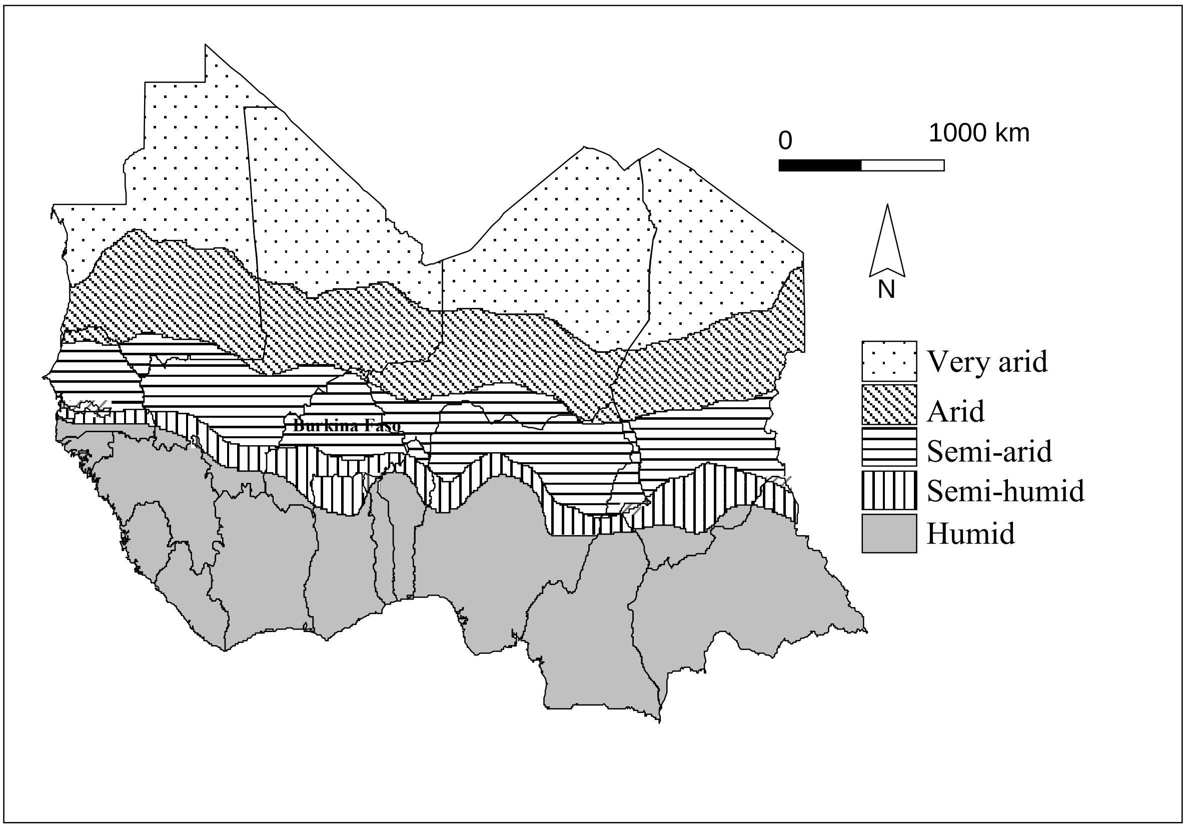

Figure 1.1: Agro-climatic zones in Sudano-Sahelian West Africa (After Bationo and Buerkert, 2003)

Agriculture drives economic growth in Burkina Faso and accounts for 37.1% of the gross domestic product (World Bank, World development Indicators database 2003). Cereal crops (millet, sorghum, maize) cover 80% of the cultivated areas. Cash crops are more productive, mainly cotton which is the country's most important resource. Groundnut is the second most important cash crop. Food security is low, due to the low and variable yields of staple crops. In addition to the constraints mentioned above, the performance of the agricultural sector is poor and greatly influenced by low labor and input productivity (Breman et al., 2001).

The annual rainfall ranges from 300 mm in the North to 1100 mm in the South (Figure 1.2). Several drought periods can occur during the only one rainy season, some time compromising seriously the crop production. Our study covered two climatic zones (Figure 1.2): the first experimental site was located at Kirsi village in the Sahelo-Sudanian climate zone, with an average annual rainfall of 600 mm, occurring in four months (June-September). The second site was located at Saria agricultural research station in the North Sudanian climate zone, with an average annual rainfall of 800 mm occurring in 6 months (May-October).

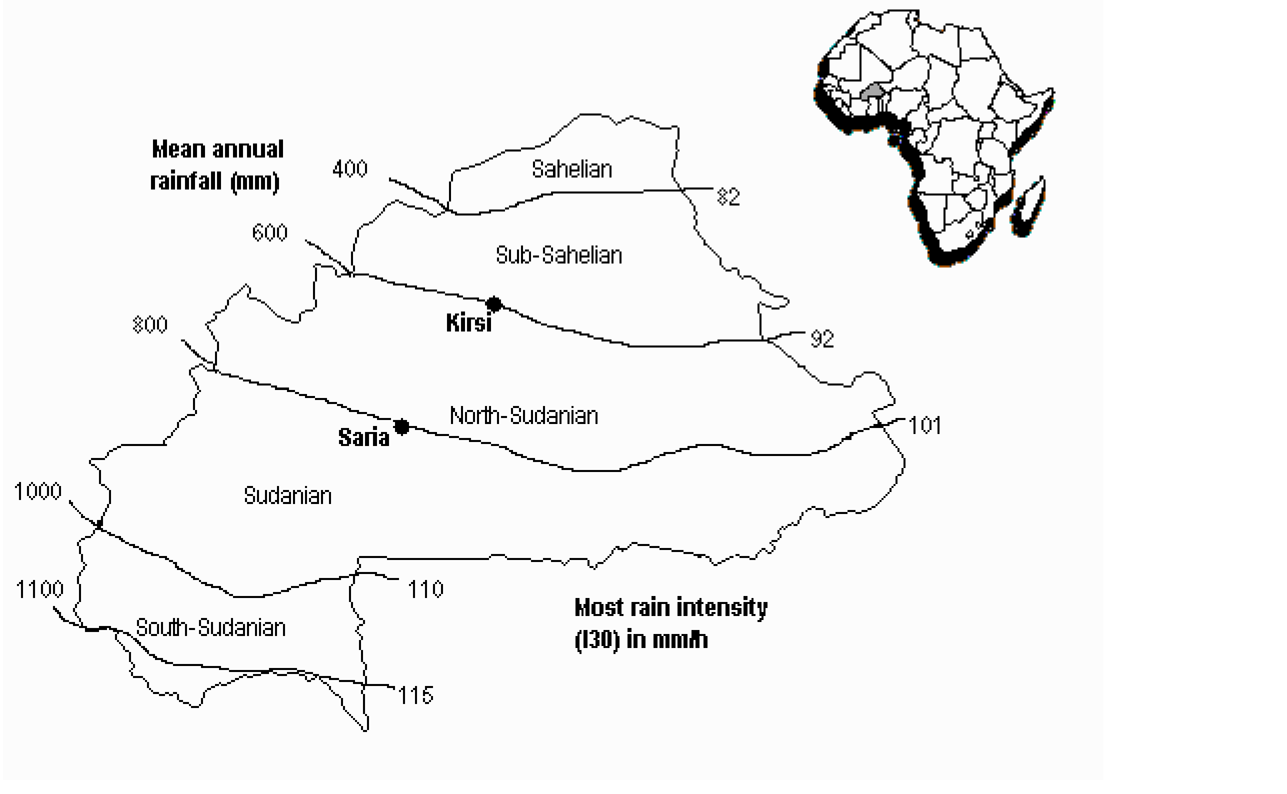

Figure 1.2 Agro-climatic zones of Burkina Faso (After Guillobez, 1996)

The major soils types in the country are Lixisol, Cambisol, Vertisol and Lithosol. These soils are characterized by low native soil fertility, low water holding capacity and soil surface crusting that do not allow water to easily infiltrate into the soil. This, in addition to the high rainfall intensities, makes the soils very sensitive to soil erosion despite the gentle slope (< 3%). The Central Plateau is the most eroded zone due to the high pressure of the population on natural resources, particularly on arable lands (Figure 1.3a). Guillobez (1996) showed in a comparison of erosion state in 1985 and in 1995 that through several interventions (Extensions services, projects, NGO's, Agricultural research, etc.), the magnitude and severity of soil erosion was decreasing throughout the whole country (Figure 1.3b). This indicates that technologies of soil and water conservation promoted by extension services are accepted by farmers which was not the case some decennia before. However, the low soil fertility remains a serious constraint that limits the efficient use of the improved soil moisture conditions for crop intensification.

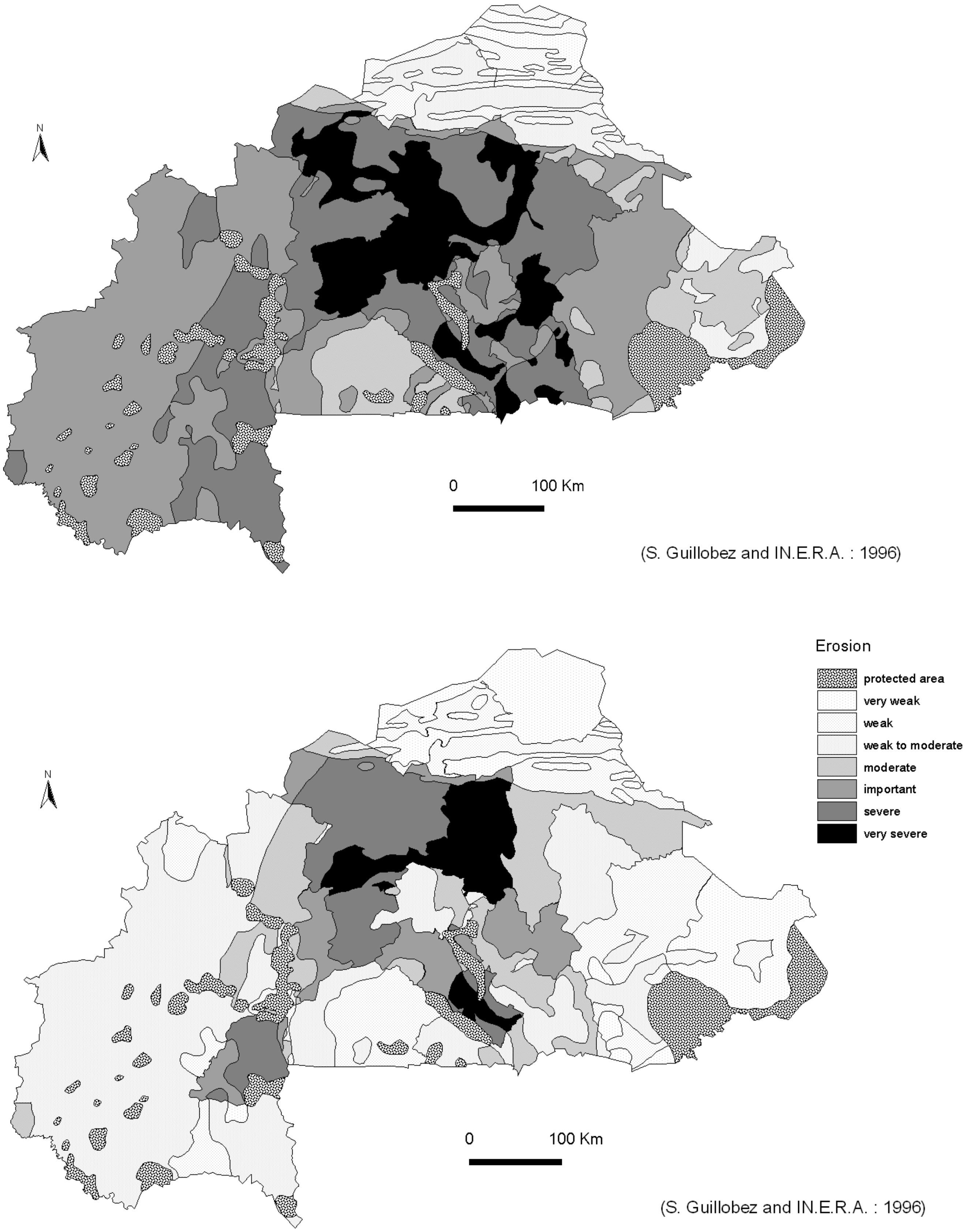

Figure 1.3: Magnitude of soil erosion from 1985 (a) to 1995 (b) in Burkina Faso: impact of soil and water conservation practices (After Guillobez, 1996)

1.3 Aim of the study and thesis outline

This study aims to enhance biomass production in dry tropical zones by improving sorghum cropping systems, with technically appropriate, socio-economically acceptable and environmentally sound approaches in a landscape where soil physical properties and soil fertility deterioration limits crops yield levels.

The main objectives of this study were (1) to assess the effect of stone rows on runoff, soil moisture and soil fertility under continuous sorghum cropping, which is the main agricultural system in the study zone; (2) to evaluate alternative barriers to stone rows such as grass strips; (3) to study the effect of soil and water conservation measures on plants nutrient use efficiency and crop production under continuous sorghum cropping system. The first objective was mainly carried out in the site of Kirsi while objectives 2 and 3 where handled at Saria agricultural research station.

Following the present introductive chapter, Chapter 2 and 3 present the effects of stone rows and their spacing on runoff and sorghum performance. The effect of stone rows on soil chemical characteristics under continuous sorghum cropping is discussed in Chapter 4. Chapter 5 deals with the combined effect of water and nutrient management on runoff and sorghum performance and Chapter 6 analyzed the soil-plant water balance in response to soil water and nutrient managements. The effect of integrated water and nutrient management on soil erosion and nutrient loss is presented in Chapter 7 and nitrogen flows and balances resulting from different soil water and nutrient managements are analyzed in chapter 8. Chapter 9 presents the economic benefits of combining soil and water conservation measures with nutrient management and Chapter 10 summarizes the main conclusions on integrated water and nutrient management in the Sahel.

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Chapter 2

Runoff and sorghum performance as affected by the spacing of stone rows in the semi-arid Sahelian zone

Zougmoré, R., Guillobez, S., Kambou, N.F., Son, G., 2000. Runoff and sorghum performance as affected by the spacing of stone lines in the semi-arid Sahelian zone. *Soil and Tillage Research 56: 175-183.*

Abstract

Crop yields are primarily water-limited in dryland production systems in semi-arid regions. This study was conducted in a catchment located in the "plateau central" of Burkina Faso to assess the impact of the space between stone rows on runoff and crop performance. The experimental design consisted in four plots in which stone rows were installed. The spacing between the rows was 100 m in the first plot, 50 m in the second, 33 m in the third, and 25 m in the last plot. The soil was a Ferric Lixisol and the slope, which is characteristic of the area, was about 1─3%. Subplots placed at regular and fixed distances from the rows were used to monitor soil water content and crop yield. Runoff from all plots was measured using a water discharge recorder. It was found that 31% of rainfall was lost through runoff in plots without stone rows. The efficiency of stone rows in checking runoff and in improving soil water storage increased with reduced stone row spacing (runoff was reduced by an average of 12% on plots where the space between the rows was 33 m but was reduced by 23% when the stone row spacing was 25 m). Soil water content decreased with increasing distance from the stone row. Sorghum (*Sorghum bicolor* (L.) Moench) performance was greatly affected by stone row and plant straw and grain yield were doubled in plots with stone rows compared with those of plots without stone rows. At an area of about 6 m from the stone rows (upslope), where organo-mineral sediments were collected, sorghum grain yields was 60% greater than that obtained at 19 m from stone rows. The stone row technique seems to be a sound option to mitigate water stress during dry spells.

Keywords: Runoff; Stone rows spacing; Water conservation; Sorghum; Sahel

2.1 Introduction

Erratic rainfall and loss of water through runoff are major agriculture problems in the Sahel. The loss through runoff is caused by the high intensity of the rainfall, the low organic matter content of the soils and the extent of soils with surface crusts and seals (Roose, 1981). In the Sahelian zone, the combined effects of climatic conditions, soil quality and human activities has resulted in soil degradation, due to crusting, sealing, erosion by water and wind (Casenave and Valentin, 1989; Zougmoré, 1991; Mando et al., 1999) and the loss of nutrients through erosion and runoff (Roose, 1981; Stroosnijder and Hoogmoed, 1984). Because of the degradation phenomenon, crop production and animal production are at risk (Mando and Stroosnijder, 1999).

To solve the degradation problem, farmers have developed a range of measures, including runoff control, soil structure improvement, and nutrient management (Delwaulle, 1973). Soil and water conservation extensionists have put emphasis on the implementation of the stone row technique to check runoff and to control erosion (Rochette, 1989; Mando et al., 2001). On-farm research has shown that stone rows are efficient in increasing soil water status and in reducing soil erosion and downward particle transport (Lamachère and Serpantié, 1991; Van Duijn et al., 1994). Empirical models using slope data as input were used to design stone row structures (Guillobez, 1990; Roose, 1994) and linear programming was used to study the socio-economic benefits of stone rows (Maatman et al., 1998). However, few data on the role of the spacing between stone rows on the efficacy of the stone row technique are available.

The aim of this study was to establish the effect of the space between stone rows on runoff, on soil water content and on crop performance. This is a prerequisite for the use of stone rows for crop production and environmental protection.

2.2 Material and methods

2.2.1 Environmental setting and experimental design

The experiment was conducted in Kirsi village, which is at about 150 km northwest of Ouagadougou (13°3’ North and 1°54’ West). The average slope was about 0.8% and the major soil type, which covers 70% of the country, was a Ferric Lixisol (FAO, 1976; FAO-UNESCO, 1989). The usual depth of the soil equaled or exceeded 60 cm and plinthite sometimes occurred at the 60 cm depth. The topsoil was sandy-loamy (470 g kg^{-1} sand, 280 g kg^{-1} silt, and 250 g kg^{-1} clay). Soil structure was moderately developed and pH (H_2O) was less than < 6. The soils had a strong tendency to seal and crust (Casenave and Valentin, 1992). The soil had a low organic matter content (< 10 g kg^{-1}), low nitrogen content (< 0.5 g kg^{-1}), and low available phosphorous (< 0.03 g kg^{-1}).

The vegetation type was bush savannah (UNESCO, 1973) and the main woody plants were *Acacia* spp., *Combretum* spp. and *Butyrospermum paradoxum*. The herbaceous component was dominated by *Loudetia togoensis* and *Schoenfeldia gracilis*.

The climate was of Sahelian soudanian type (Fontes and Guinko, 1995) and the mean annual rainfall amount was about 600 mm, with pronounced rainy and dry seasons. The main characteristic of the rainfall was irregularity in time and space.

The field had been subjected to 15 years continuous sorghum cropping. Early maturing variety of sorghum was used (110 days). The main agricultural operations during the cropping season were ploughing at depth 10–15 cm depth in July using horsepower, sowing, and weeding (three times). It takes 25 hours to plough one hectare of land.

The experiment consisted of four plots (P1, P2, P3 and P4) each 100 m x 25 m. Stone rows were installed on each plot; detailed information on the stone rows is presented in Table 2.1. Each plot was isolated from the surrounding area by an earth bund 60 cm high. The stone rows consisted of two rows of stones placed in a furrow along a contour line. The upslope row of stones consisted of large blocks of stones when the downslope row consisted of small stones placed so as to stabilize the first row. The height of a stone row was about 20–30 cm and the weight of stone was about 80 to 90 kg m^{-1}.

Table 2.1 Characteristics of the experimental plots at Kirsi

Plots	Number of stone rows	Spacing (m)
P1	1	100 (control)
P2	2	50
P3	3	33
P4	4	25

2.2.2 Data collection

On each plot, equipment was installed to collect and store runoff. This equipment consisted of a drainage system, which drained the water into a concrete container of 1.3-m^3 volume. Each container was equipped with a water discharge recorder (OTT model, X-type), to record runoff amount per unit time. Rainfall intensity was recorded with a rain gauge installed at the site. Each plot was divided into 12 subplots of 8 m x 3 m in 1992. In 1993, 12 subplots were added in each plot. There were in total 24 subplots in each treatment. The subplots were located at 96, 87, 79, 71, 62, 54, 46, 37, 29, 21, 12, and 4 m respectively, from the downslope border of each plot (Figure 2.1). These subplots were used to measure soil water content and estimate sorghum yield, which was harvested in November.

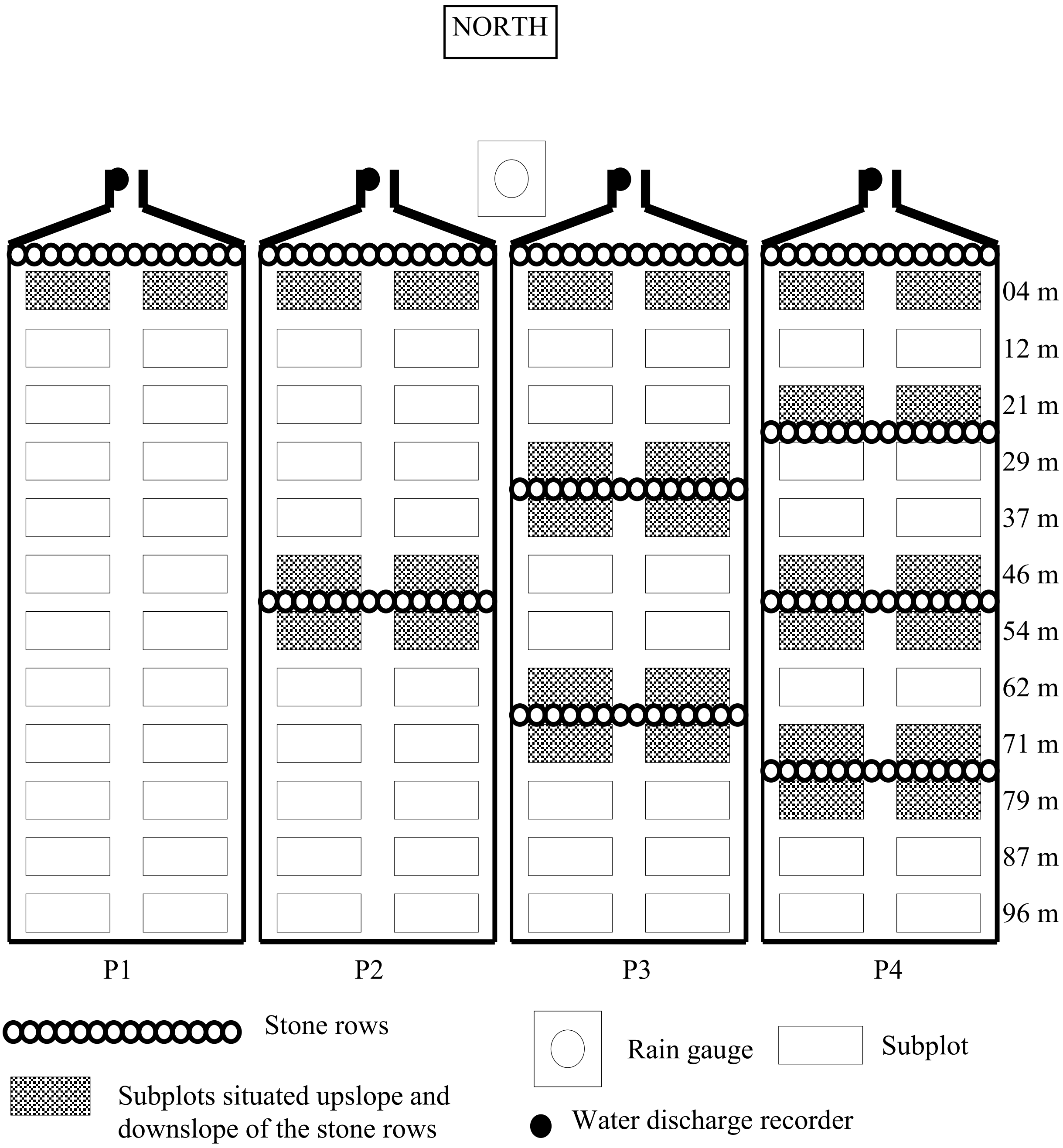


Figure 2.1 Experimental design. P1: Plot with 100 m stone row spacing; P2: plot with 50 m stone row spacing; P3: plot with 33 m stone row spacing and P4: plot with 25 m stone row spacing.

Grain and straw yields were obtained after sun drying and weighing plant material and grain from each subplot during three weeks. The gravimetric method, based on one composite soil sample taken from each subplot, was used to measure soil water content from 0–10, 10–20, and 20–40 cm depths. The measurements were made at the end of the rainy season (September 21, 1993), three days after a 18-mm rain and after a total of 649 mm of rain fell on the field.

2.2.3 Data analysis

Runoff was analyzed on single event basis in 1992 but in 1993, runoff was analyzed using cumulative runoff data. The rain event of August 31, 1992, was used to analyze the effect of the treatments on runoff. It was the most intense rainfall of 1992 (48 mm h^{-1} intensity) and it occurred after the tillage mediated soil roughness had declined. In 1993, 32 rain events were used for runoff analysis.

The Genstat (General statistics) package was used for statistical analyses of soil water content and sorghum yields data, including ANOVA and Newman-Keuls test for significant differences between treatments at $p < 0.05$. To handle the statistical analysis, the experiment was considered as a randomized block design using the four runoff plots as blocks and the 12 selected positions located at 96, 87, 79, 71, 62, 54, 46, 37, 29, 21, 12, and 4 m respectively, from the downslope border of each plot as treatments.

2.3 Results

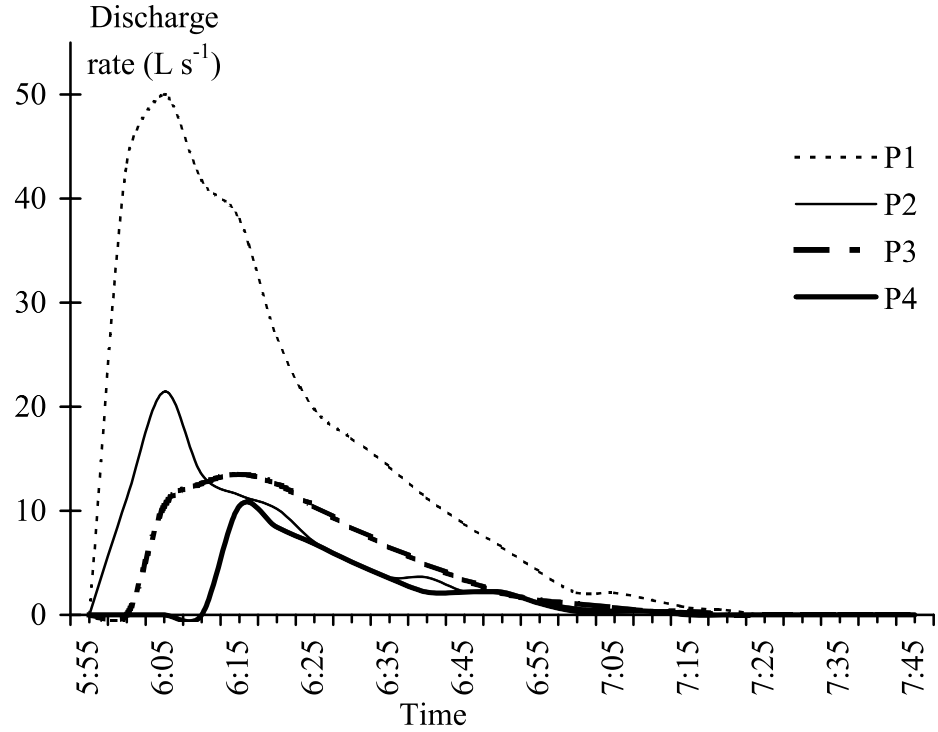
2.3.1 Rainfall

In 1992, 470 mm of rain fell at the site. This was below the mean annual rainfall of 600 mm during the last decade. Three major dry spells occurred during 1992: 11 days in the first half of July, 10 days in August, and 20 days in September. In 1993, 664 mm rain fell at the site. The rainfall distribution was more even in 1993 than in 1992. The most erosive rain of the two cropping seasons was recorded on August 31, 1992. The total amount was 46 mm and the maximum 15-min intensity was 64 mm h^{-1}, the maximum 30-min intensity was 48 mm h^{-1}. This event had two phases, the second phase started 15 min after the first one (Figure 2b).

2.3.2 Runoff

In 1993, the runoff from 32 showers, with a cumulative rainfall of 627 mm was 195 mm for P1, 165 mm for P2, 122 mm for P3 and only 50 mm for P4 (Figure 2.3). Runoff decreased when the plots were hoed, but the effect of soil disturbance (i.e., increased soil roughness) by hoe disappeared after only two rains. The treatments had a significant effect on the hydrology of the plots (Figure 2.2a). Runoff started 5 min after the beginning of rainfall on P1 and P2 and started 5 min later on P3 and 10 min later on P4 (Figure 2.2a).

(a)



(b)

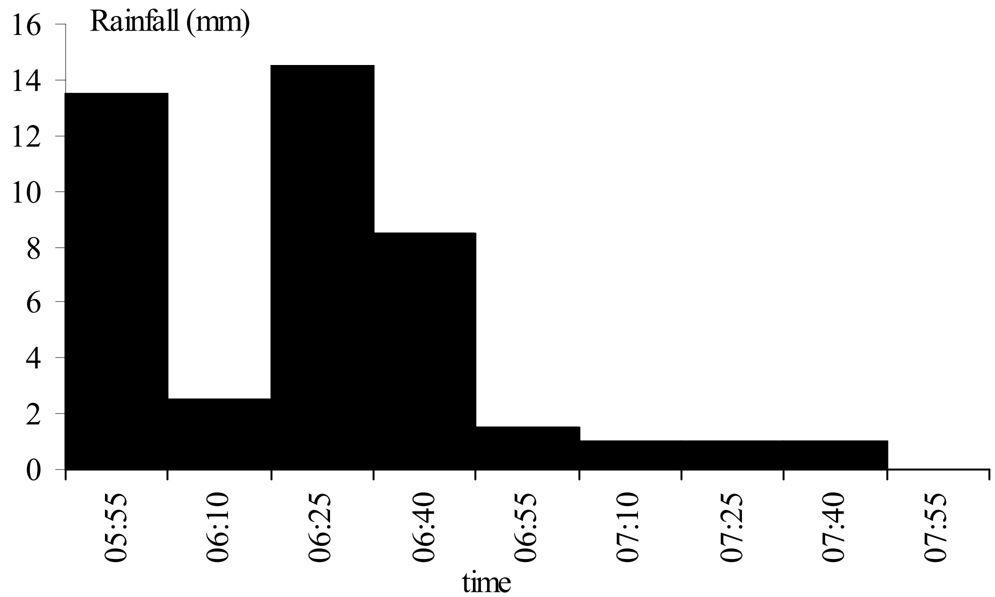


Figure 2.2: (a) Runoff hydrograph and (b) rainfall hyetograph for the event of 31.08.1992.

P1: Plot with 100 m stone row spacing; P2: plot with 50 m stone row spacing; P3: plot with 33 m stone row spacing and P4: plot with 25 m stone row spacing.

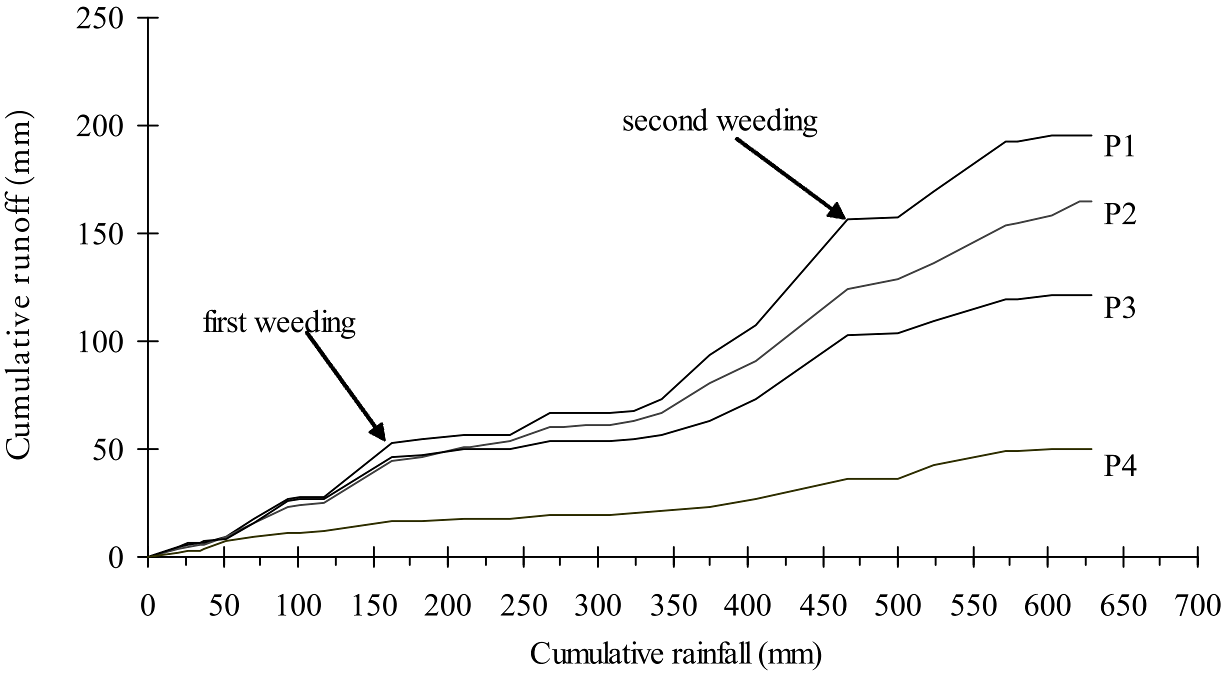


Figure 2.3 Cumulative runoff as a function of cumulated rainfall in 1993

P1: Plot with 100 m stone row spacing; P2: plot with 50 m stone row spacing; P3: plot with 33 m stone row spacing and P4: plot with 25 m stone row spacing.

The flooding time was also affected by the treatments; the smaller the space between the stone rows, the shorter was the flooding time. The flooding time was 1 h 30 in P1 (control), 1 h 25 in P2 (50 m spacing between stone rows), 1 h 20 in P3 (33 m spacing between stone rows) and 1 h 5 min in P4 (25 m spacing between stone rows). The maximal discharge rate was 43.5 liters per second (L s^{-1}) in P1, 21.5 L s^{-1} in P2, 12.6 L s^{-1} in P3 and 10.5 L s^{-1} on P4. Runoff amount was 34 mm in P1. Runoff was 6 times greater on P1 than in P4 (5 mm) and was three times greater in P1 than on P2 (10 mm) and P3 (11 mm). Runoff increased with increasing space between stone rows.

2.3.3 Water content

The differences in water content between plots at 10, 20, and at 40-cm depths were significant (Table 2.2). At all depths, soil water content increased with decreasing stone row spacing and increased with increasing soil depth. Water content in the 0–10 cm layer was 121 g kg^{-1} in P1, 127 g kg^{-1} in P2, 148 g kg^{-1} in P3, and 144 g kg^{-1} in P4. Similarly, water content in P1 was 121g kg^{-1} for 0–10 cm layer, but increased to 133 g kg^{-1} in the 10-20 cm layer and to 150 g kg^{-1} in the 20–40 cm layer.

Table 2.2 Effect of stone rows spacing on soil water content on 21 September 1993 (g kg^{-1})

Depth	0-10 cm		10-20 cm		20-40 cm	
P1	121	d	133	d	150	b
P2	127	c	138	c	153	b
P3	148	a	166	a	176	a
P4	144	b	158	b	175	a
ESE	1.5		2.6		4.0	
Probability	0.003		0.007		0.038	
SED	2.1		3.7		5.6	
Nb of samples	24		24		24	
CV (%)	1.6		2.5		3.4	

P1: plot with 100 m stone row spacing; P2: plot with 50 m stone rows spacing; P3: plot with 33 m stone row spacing; P4: plot with 25 m stone row spacing. Treatments with the same letter are not statistically different at p= 0.05; ESE: standard error of the means; probability: probability F; SED: standard error of differences of means; CV (%): coefficient of variation; nb. of samples: number of samples.

Differences were also observed between points at various distances from the stone rows (Figure 2.4). In all plots, the highest water content was observed behind the stone row (upslope). This situation was most evident behind the most downslope row and particularly on plots where the space between rows was large (P1 and P2).

Figure 2.4 Water content of soil at different distances from the stone row (P1): error bars indicate standard deviation.

2.3.4 Crop performance

Stone row spacing had a significant effect on crop performance (Table 2.3). In the 1992 rainy season, where rainfall amount was lower than the mean rainfall amount of the last decade, crop production on plots with stone rows doubled compared to the production on the control plot. The difference in crop yield between the control plot and plots with stone rows in 1993, where rainfall amount was higher than the mean rainfall of the site, was not impressive (0.007 to 0.41Mg ha-1). In 1992 the highest yield was recorded with P4 whereas the highest yield was recorded with P3 in 1993 (Table 2.3). Crop performance was greater in the area upslope from the row than in the area downslope and decreased with increasing distance from the row. In 1992, when many dry spells occurred, crop yield with P4 was 0.025 Mg ha-1 at 94 m from the stone row whereas the yield was 0.25 Mg ha-1 in the same plot at 6 m from the stone row (data not shown). With P4 where the space between the stone rows was the smallest, crop yield was rather homogeneous in all the sampling points of the plot. Sorghum-straw yields had the same trends as grain yield and the ratio of straw to grain yield was 0.25 in all plots. Straw (shoot) yield was 0.55 Mg ha-1 on the control plot and 1.46 Mg ha-1 on P4 plot in 1992 (dry year). However, in 1993 when rainfall was well distributed, straw yield was 2.9 Mg ha^{-1} on the control plot and 3.7 Mg ha-1 on P4 plot (25 m spacing between rows).

Table 2.3 Effect of stone rows spacing on crop performance in 1992 and 1993 (Mg ha^{-1}).

	Grain yield		Straw yield	
	1992	1993	1992	1993
P1	0.12 d	0.56 c	0.55 d	2.86 c
P2	0.19 c	0.57 c	0.86 c	3.03 c
P3	0.25 b	0.97 a	1.10 b	4.58 a
P4	0.53 a	0.88 b	1.46 a	3.75 b
ESE	0.023	0.060	0.061	0.191
Probability	0.003	0.030	0.007	0.022
SED	0.032	0.085	0.087	0.269
Nb of samples	16	24	16	24
CV (%)	11.8	11.6	8.5	7.6

P1: plot with 100 m stone row spacing; P2: plot with 50 m stone rows spacing; P3: plot with 33 m stone row spacing; P4: plot with 25 m stone row spacing. Treatments with the same letter are not statistically different at p= 0.05; ESE: standard error of the means; probability: probability F; SED: standard error of differences of means; CV (%): coefficient of variation; nb. of samples: number of samples.

2.4 Discussion

2.4.1 Runoff

Stone rows reduced runoff and the time to onset of runoff depended on the space between the stone rows (Figure 2.2a). The smaller the space between the stone rows, the greater the reduction in runoff velocity, which increased infiltration into the soil (Casenave and Valentin, 1989). It is known that overland flow reaches its maximum velocity after water has flooded for some distance (Guillobez, 1990). Therefore, the optimum spacing of stone rows would be one that prevents overland flow from reaching an erosive velocity. This is consistent with the results of Lamachère and Serpantié (1991), who observed that stone rows kept water upslope and, therefore, modified the characteristics of overland flow by delaying the time to the onset of the flood and by slowing down the velocity of the discharge. The flooding time is shorter when the spacing between stone rows is smaller (runoff time was 25 min longer in P4 than in P1). Guillobez (1990) using a modeling approach showed that overland flow is dependent to soil surface roughness (overall roughness of the interplay between soil and the overflow) and thus related to the presence of barriers on the soil surface. In our experiment, the main factors influencing the velocity of the overland flow were the length of the plot, rainfall intensity, and the surface roughness (i.e., soil disturbance due to tillage) in the plots. Rainfall intensity and surface roughness are, therefore, the dynamic factors determining the velocity of overland flow. Runoff data in 1993 provided evidence that stone rows reduce water loss through runoff. The data indicated that more than 31% of rainfall was lost through runoff on control plots when only 8–28% of rainfall was lost in plots with stone rows, depending on the spacing of the rows. Runoff was 23% less from the plot with stone rows having a 25-m spacing than from the control plot. However, runoff was only 5% less from the plot with stone row spacing of 50 m than from the control plot. In sandy soils, Lamachère and Serpantié (1991) found that 20-m spaced stone rows reduced runoff by about 13% compared with that of the control plot.

From Figure 2.3, it is clear that the disturbance of the soil surface through any tillage has an influence on runoff. However, such influence lasts only for a short time. The influence of soil tillage is due to the modification of soil surface roughness, which provides many tiny barriers to runoff and in the disruption of the soil crust. This improves water storage (Eimberck, 1990; Zougmoré, 1991). As shown in Figure 2.3, tillage permitted the absorption and the storage in soil of all water from 50 mm of rain. This is consistent with Hoogmoed (1999) and Zougmoré et al. (2000).

2.4.2 Soil water content

There was a large increase in soil water content at the 40-cm depth in plots with stone rows compared with that in the control plots. This was probably the result of the increase in infiltration through the delay in the onset of runoff and the decrease in water flow velocity due to the barriers formed by stone rows. Furthermore, the stone rows collect water upslope, which spreads the water downslope and upslope. Such distribution is greater when the spacing of the rows is smaller (Hien, 1995). This accounts probably for the higher water content in P3 and P4 compared with P1 and P2. Water content was higher upslope from the stone row (Figure 2.4) and the spacing of the stone rows had a significant effect on water content at all measured depths (Table 2.2). Under the sandy-loamy soil conditions of our experiment, crusting that greatly reduces infiltration (Chevalier and Valentin, 1984) is a common phenomenon. In such circumstances, the combination of stone rows and techniques that improve soil structure such as tillage, mulching, or pitting could be an alternative strategy for water conservation.

2.4.3 Grain and straw yield

In 1992, the increase in grain yield was 58% in plot with 50-m spacing of stone rows, 109% in plots with 33-m spacing of stone rows, and 343% in plot with 25-m spacing of stone rows. The increase in sorghum-straw yield had the same trend. These results were attributed to the improved water content due to the stone rows. In 1992, rainfall was below the mean amount for the region and, therefore, water was a limiting factor. The pattern of variability of water distribution in the plots and that of the crop performance in the plots was similar. This is further evidence that the increased crop production was due to the improved water content of the soil. Our results are consistent with those of Lamachère and Serpantié, (1991) and Mieton, (1986), who found an increase in crop yield of 30–90% due to stone rows. These studies also found a relationship between the yield and the increase in water storage in deep layers due to stone rows. It was hypothesized that the water stored in deep layer diffuses upwards during dry periods and is then used by the crop. Furthermore, it is known that water availability increases nutrient uptake and nutrient use efficiency and this could also account for better crop performance on plots with stone rows. Stone rows, because they slow down runoff, also result in the deposition of organo-mineral particles (sediments), which provide nutrients upslope from the stone rows (Hien, 1995; Spaan and Van Dijk, 1998).

In 1993, rainfall was above the mean of the region and constraints due to water were less important than in 1992. During this year, the increases in crop yield due to stone rows were less than in 1992. The increase was only 1% in the 50-m spacing plot (P2), 73% in the 33-m spacing plot (P3), and only 56% in the 25-m spacing plot (P4). This indicated that water logging was starting to hinder crop growth in P4. Field observations indicated that the crop in the first two rows near the row upslope suffered from water logging. These results again are consistent with Lamachère and Serpantié (1991) who have found that during wet years the impact of stone rows is not impressive and could even be negative (they measured a 20% loss in production behind stone rows). This indicates that stone rows are technologies, which would mainly help to mitigate the effect of drought, and therefore, to minimize the risk of crop failure during dries spells. The major process involved in the improvement of crop performance through stone row is the increase of soil water content. Where water is limiting, we would agree with Reij et al. (1988) that the judicious use of stone row techniques and soil fertility management is a sound means for the improvement of agriculture production in semi-arid zones.

2.5 Conclusion

The study clearly showed that under water limiting conditions, the stone rows technique was efficient in improving soil water content through runoff control. Under water limiting conditions, crops in plots with stones rows could yield two to three times more than crops in control plots, but under heavy rain conditions, stone rows could be harmful to crop production as they can create waterlogging conditions. The effect of stone rows on soil water content depends on the space between the stone rows. The larger the spacing, the less their effects. It is useful to explore the interaction effect of stone row technique and soil fertility management such as compost or fertilizer application in order to enhance and sustain crop production in the semi-arid regions.

Acknowledgements

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A farmer showing how to trace contours with a triangle, Kirsi village, Burkina Faso

A farmer materialising grass strip position upslope a stone row, Kirsi village, Burkina Faso

Youngsters repairing a stone row, Zon village, Burkina Faso

Runoff collection device of the experimental plots at Kirsi village, Burkina Faso

Experimental plot with sorghum crop at Kirsi village, Burkina Faso

Chapter 3

Optimal spacing of soil conservation barriers: example of stone rows in Burkina Faso

Zougmoré, R., Kaboré, D., Lowenberg-Deboer, J., 2000. Optimal Spacing of Soil Conservation Barriers: Example of Rock Bunds in Burkina Faso. *Agronomy Journal 92: 361-368.*

Abstract

Though construction methods vary widely, use of physical or biological barriers to conserve soil and water is common throughout the world. Rock or earthen bunds are common physical barriers. Strips of perennial grass, shrubs or trees serve as biological barriers. Often these barriers are arranged on a slope in roughly parallel contour bands. The spacing between barriers has important economic consequences because distance from the barrier may create patterns of soil fertility and water availability that influence crop yields and because the spacing determines land available for cropping. The objective of this study was to develop a method for determining the optimal economic spacing of conservation barriers and apply that method to spacing of stone rows in Burkina Faso. The steps in the optimization method include estimating a continuous yield response to distance between barriers, developing a mathematical expression to describe how costs change as spacing is altered, and optimization using calculus. The method is general and can be applied to determining spacing of any conservation technique that is applied in bands. For example, this method could be adapted to spacing of grass strips, hedges, windbreaks, or terraces. This analysis suggests that the economically optimal spacing of stone rows on the Central Plateau of Burkina Faso depends on the type of construction, materials transport cost, and how labor is organized.

Key words: Stone rows; Economic spacing; Net present value; Sorghum; Burkina Faso

3.1 Introduction

Though construction methods vary widely, use of physical or biological barriers to conserve soil and water is common throughout the world (Erdmann, 1993; Lutz et al., 1994; Hudson, 1995; Roose, 1996). Rock or earthen bunds are common physical barriers. Strips of perennial grass, shrubs or trees serve as biological barriers. Often these barriers are arranged on a slope in roughly parallel contour bands. The spacing between barriers has important economic consequences because distance from the barrier may create patterns of soil fertility and water availability that influence crop yields and because the spacing determines land available for cropping. Walle and Sims (1999) and Kambou et al. (1994) provide evidence of the soil fertility gradients behind such barriers. Spacing the barriers too widely leaves some areas unprotected and does not allow farmers to achieve yield potential. Barriers are costly to create, so spacing bunds too closely wastes precious resources. The objective of this study was to develop a method for determining the optimal economic spacing of conservation barriers and apply that method to spacing of stone rows in Burkina Faso.

In both industrialized and developing countries, the spacing of the conservation barriers has been based mainly on physical criteria, such as slope, soil characteristics and rainfall patterns (FFTC, 1995; FAO, 1988; Schwab and Frevert, 1985). In mechanized agriculture, the width of equipment is often a determining factor in the spacing of conservation barriers. The yield effects of windbreaks as a function of spacing are well documented (Kort, 1988), but methods for incorporating that yield response into the design of windbreaks are not well developed.

Initial economic evaluation of these conservation techniques focused on the value of benefits over the life of the physical or biological barrier for a fixed spacing. As information on crop response has accumulated, a few studies have looked at the effect of the spacing between parallel barriers on economic returns. In Nebraska, Brandle et al. (1992) compared windbreak spacing of 193.6 m, 128.0 m and 66.5 m. They found that the more widely spaced windbreaks provided higher returns, mainly because they required less land to be taken out of crop production. Shively (1996) estimated maize response to hedgerow spacing in the Philippines as a quadratic function. He found that the spacing required to maximize either yield or profits is somewhat wider than the spacing that minimizes erosion.

On the Central Plateau of Burkina Faso, constructing stone rows on the contour is one of the most effective techniques for reducing erosion and increasing water infiltration, while improving yields. About 24% of arable land in Burkina Faso is severely degraded (Kambou et al, 1994). Most of this degraded land is on the Central Plateau, where population pressure has led farmers to cultivate marginal lands and reduce fallow periods. Kaboré et al. (1994) estimate that on average fields protected by stone rows have 11% higher sorghum (*Sorghum bicolor* (L.) Moench) yields than unprotected fields. Wright (1985) reported a 47% increase in average sorghum and millet (*Pennisetum glaucum* (L.) R.Br.) yields with bund spacings varying from 10 to 50 meters. Vlaar (1992) reports doubling of yields in some cases when stone rows are constructed. Hulugalle et al. (1990) and Maatman et al. (1998) indicate that the impact of stone rows is substantially enhanced when combined with other soil and water conservation techniques such as tied ridges and *zaï*, which is an intensive manure management method.

The objective of this paper is to outline a method for determining the net present value (NPV) maximizing spacing for stone rows and to provide an application of this method using the data gathered by the Water, Soil Fertility, Irrigation and Mechanization Program (ESFIMA) of the National Institute of Agricultural Research (IN.E.R.A.) of Burkina Faso. The method is intended to be used in the design stage of conservation projects by planners who determine the spacing to be used by project staff when they are involved in building barriers and in training farmers to do their own construction. Yield response is estimated as a function of bund spacing. Calculus is used to optimize bund spacing. The NPV maximization is assumed as a first approximation of farmer objectives.

Several methods are used for stone row construction in Burkina Faso but all are based on the principle of slowing rainfall runoff with rock barriers. Water is held on the field longer, increasing infiltration. Sediments are deposited behind the row. On the Central Plateau, stone rows are usually preferred to earth bunds because they are permeable. Water is trapped behind earth bunds and may flood crops. Stone rows slow runoff, but allow some water to pass. Kaboré et al. (1994) provide an overview of the primary stone row construction techniques in Burkina Faso.

This paper is divided into two primary sections: the theoretical optimization model and use of that model with data from the Kirsi site on the Central Plateau in Burkina Faso. The final section includes conclusions and implications for research.

3.2 Theoretical Model

In fields protected by stone rows, it is generally observed that yield is a function of distance upslope from the row. Yield is highest immediately behind the row where sedimentation is greatest and where water is collected even after small rains. For the purpose of this analysis, it will be assumed that yield declines monotonically as distance increases and that at some point the stone row effect becomes negligible (i.e., expected yield beyond a certain distance from the row is the same as in a field without stone rows, see Figure 3.1). In an effort to focus on the stone row spacing, this model abstracts from the other factors that might affect yield, including micro variation in soil quality, slope differences, stone row construction and maintenance problems that might induce flooding behind the row, interaction of stone rows and soil fertility enhancement with manure or fertilizer, and interaction of bund spacing and yield over time (e.g., it might take several years for the full yield effect to be observed, because it takes time for sediment to build up behind the row). The analysis assumes a uniform slope and microsoil variation that is independent of stone row spacing.

This analysis will apply standard response function analysis (Dillon and Anderson, 1990). A model of continuous response to stone row spacing is developed assuming information is available on yield-distance relations. This model is optimized using ordinary calculus (Thomas and Finney, 1980). This analysis will assume a quadratic response function to distance, because it is the simplest function that yield effects decrease nonlinearly, dropping off rapidly in the first few meters and then gradually leveling out.

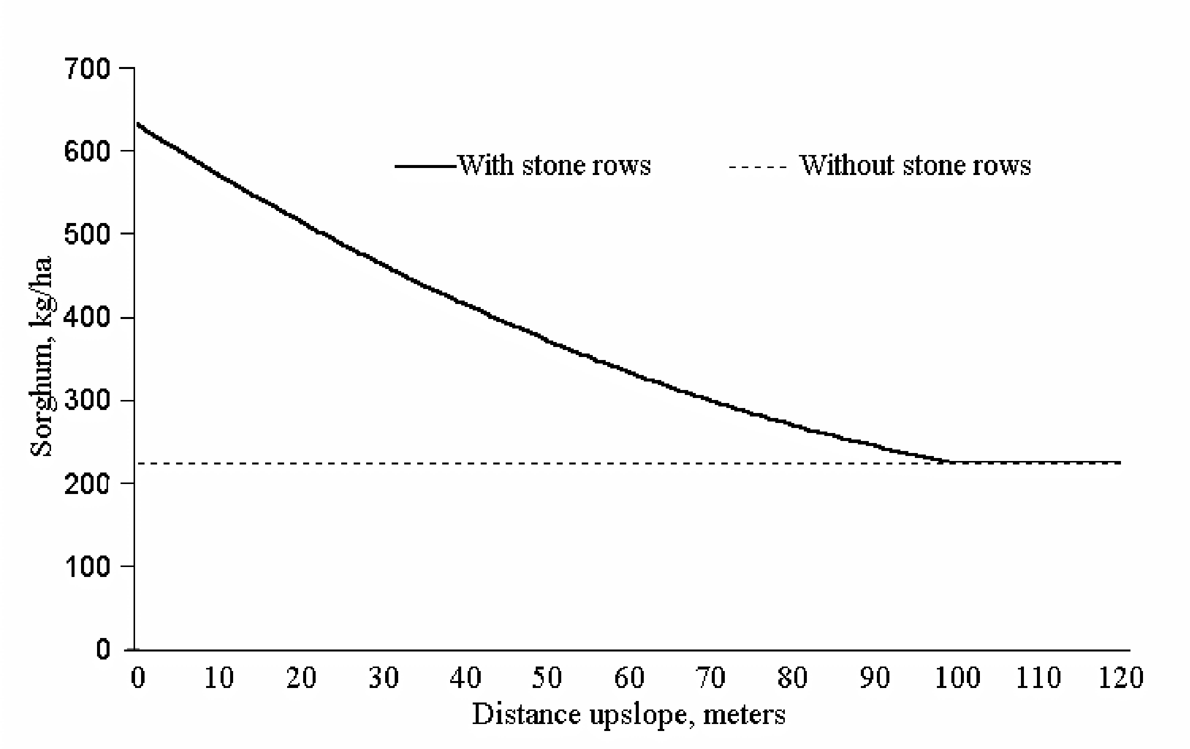

Figure 3.1 Sorghum yield as a function of distance upslope from stone rows, Kirsi, Burkina Faso

A linear response would assume that the yield improvement is strictly proportional to distance. The method outlined below works with a linear or any polynomial function. Other functional forms could be handled similarly, but the mathematics may be more complicated. In particular, closed form solutions to the integration over distance may not always be available and numerical solutions may be required.

Assume the yield response to distance upslope from a well-constructed stone row is:

$$Y = a_0 + a_1D + a_2D^2 \quad [1]$$

where: Y = yield (kg/ha), D = distance (m), and a_i = coefficients ($a_1<0$, $a_2>0$, $a_1+2a_2D < 0$) for D=0 to M.

This relationship is assumed for distances 0 to M. Beyond M, the yield is constant at:

$$Y = a_0 + a_1M + a_2M^2 \quad [2]$$

The economic variable of interest is the spacing of the rows. The average yield over a parcel protected by stone rows might be estimated as the average over all distances represented. If the spacing is less than M, the approximation would be:

$$X = \sum_{D=0}^{S} (a_0 + a_1 \text{ x } D + a_2 \text{ x } D^2)/S, \; S \leq M \quad [3]$$

where: X = average yield given row spacing S (kg/ha) and S = distance from one row to the next (m).

Because the yield response to distance is assumed to be continuous, the units of distance can be made very small. The variable X can be written as the integral over the distance from 0 to S:

$$X = (1/S) \int_0^S (a_0 + a_1 \text{ x } D + a_2 \text{ x } D^2)/dD \qquad [4]$$

This integral has a closed form solution:

$$X = (1/S)[a_0S + (a_1/2)S^2 + (a_2/3)S^3] = a_0 + (a_1/2)S + (a_2/3)S^2 \qquad [5]$$

3.2.1 Economic Benefits

The NPV maximization approach is necessary because stone rows can have effects over many crop seasons. Farmers everywhere have multiple objectives. In Burkina Faso, these objectives include maximizing profits and NPV, managing risk, maintaining food self-sufficiency and protecting the environment. This analysis uses NPV as a first approximation of the farmer's objectives. Profit maximization in any one season would not tell the whole story. By discounting future cost and benefit flows in NPV, all flows can be put in terms of value at the time of stone row construction. Risk, food self-sufficiency and environmental protection are important, but beyond the scope of this analysis. Typically, science proceeds in small increments. In economics, it is common to first solve the simpler deterministic problem of maximizing profits or NPV before tackling more complex risk and environmental issues. The general form of the NPV would be:

$$V = \sum_{t=1}^{T} [P \text{ x } (a_0 + (a_1/2) \text{ x } S + (a_2/3) \text{ x } S^2) - C - K \text{ x } 10000/S]/(1 + r)^t - I \text{ x } 10000/S \qquad [6]$$

where V = net present value of production from time 0 to T, P = the product price, C = the variable cost of production, (African Financial Community Francs [FCFA]/ha), K = stone row maintenance cost (FCFA/m), r = discount rate, and I = stone row construction cost (FCFA/m).

The FCFA exchange rate was about 500 FCFA/US$ in 1995. The term (10000/S) is the number of meters of stone row per hectare.

Theoretically, all of the variables might change over time. Prices might trend up or down. Stone row yield effect and maintenance may change as the row ages. To focus on the economics of stone row spacing it is useful to consider the case of constant expected prices, costs and coefficients. The net present value takes the form:

$$V = W[P(a_0 + (a_1/2) \text{ x } S + (a_2/3) \text{ x } S^2) - C - K \text{ x } 10000/S] - I \text{ x } 10000/S \qquad [7]$$

where $W = [1-(1 + r)^{-T)}]/r$

The term W is often called an *annuity factor*. It gives the present value of a uniform series of benefits over a given period (Barry et al., 1983).

The interior extreme maximum and minimum points occur when the first derivative is equal to zero. These stationary points may be either maximums or minimums:

$$dV/dS = W\{P[(a_1/2) + (a_2 2/3)S] + K10000/S^2\} + I \times 10000/S^2 = 0 \qquad [8]$$

The first order conditions (FOC) can be interpreted by noting that the first term, $WP[(a_1/2) + (a_2 2/3)S]$, is negative in the neighborhood of the NPV maximizing spacing. The term represents the present value of the marginal decline in the value of production as spacing is increased. The second term, $W \times K \times 10000/S^2$, is the present value of marginal decrease in the cost of maintenance as spacing is increased. The third term is the decrease in construction cost as spacing is increased.

As it is stated, optimization requires that at the spacing that maximizes NPV, the value of yield loss from increased spacing will be exactly offset by the gain from reduced maintenance and construction cost. Because of the form of the response function (i.e., yield declines as the variable input is increased), the signs of the marginal product and marginal cost terms are the opposite of the usual crop response case, but the interpretation is the same.

The FOC are necessary, but not sufficient conditions for a maximum. The second order conditions (SOC) check the second derivatives around the stationary point. If slope is decreasing, the point is a maximum:

$$d^2V/dS^2 = W[P(a_2 2/3) - K \times 10000/S^3] - I \times 10000/S^3 < 0 \qquad [9]$$

If the response takes the form in Figure 3.1, the first term in the SOC is positive and the stationary point of the NPV expression will be a maximum only if the cost terms are large relative to the quadratic term ($WPa_2 2/3$).

Solving the FOC for S will provide the interior solution for NPV-maximizing stone row spacing. A complete analysis also should check the corner solution of no stone rows and the yield given by Eq [2].

This analysis assumes that no crop area is lost by building stone rows. For the Central Plateau that is a reasonable simplifying assumption. The stone rows are narrow and with manual labor, crops can be planted very close to the stones. For those cases in which stone rows are stabilized with grass strips or hedgerows, it is necessary to multiply the yield in the NPV expression by the proportion of land that remains in crop production (1-w/S, where w= the width of the grass strip or hedge row). In this case, there will be a third cost term in the FOC reflecting land removed from production that would increase optimal spacing.

3.3 Empirical Application

Yield response to stone rows was estimated with 3 years of data from the village of Kirsi. Data of sorghum production were monitored at various distances from stone rows during the 1992, 1993 and 1994 crop seasons. The soil type is Ferric Lixisol. The 2500 m^2 site has a uniform slope of 1%. The site was protected from upslope runoff by an earthen bund along the top and sides of the area. Four stone row spacings were implemented in this area. P1: One stone row along the lower edge of the plot, P2: A stone row along the lower edge and another spaced at 50 m upslope, P3: A stone row along the lower edge, one at 33 m and one at 66 m and P4: A stone row along the lower edge, one at 25 m, another at 50 m and a 4th one at 75 m.

In 1993 and 1994, yields were measured at the following distances upslope from the lower edge of the plots for all spacings: 4 m, 12 m, 21 m, 29 m, 37 m, 46 m, 54 m, 62 m, 71 m, 79 m, 87 m, and 96 m. In 1992, P1, P2 and P4 yields were measured at 6 m, 19 m, 31 m, 44 m, 56 m, 69 m, 81 m, and 96 m, while the P3 yields were measured at 6 m, 27 m, 39 m, 60 m, 72 m, and 93 m. In 1993 and 1994, two yield measurements were taken for each spacing. In 1992, two measurements were taken for P1, P2 and P4, but three yield measurements were taken for P3. The local variety of sorghum was planted and traditional agronomic practices were used. No fertilizer was applied.

3.3.1 Response function

A quadratic response function was estimated with dummy variables for seasons and for the location on a given slope (Table 3.1). The dummy variables are specified so that the coefficients give the difference between the mean yield for a given category and the overall mean. For example, the 1993 dummy variable coefficient is the difference between the mean yield in 1993 and the mean for the 3 yr data period. A *t* test with the null hypothesis that the coefficient is zero indicates whether mean yields for the year or location differ from the overall average. The location dummy was tested because of a hypothesis that having one or more stone rows upslope may have beneficial effects because it protects crops from flooding and sedimentation. The estimation assumed that all distances in the data set were less than M (i.e., that the stone row had some effect at all distances for which yields were measured).

The OLS regression estimates are given in Table 3.1 for the full model and a model without the location dummy variables. Both models are significant at the 1% level of the overall *F* test. The R^2 is acceptable given use of on-farm data. The location dummies are not individually significant. A joint *F* test of the three location dummies is also not statistically significant ($F_{3250} = 1.80$). It should be noted that the impact of protection from upslope rows might have been reduced by the earthen dike that protected the entire site from upslope runoff. The dike limited upslope runoff to that which was generated within the plot. The estimated distance-yield coefficients have the hypothesized signs. The season dummies are statistically significant at the 1% level. The distance-yield coefficients are similar with or without the location dummies. The linear coefficient is negative and statistically significant at the 5% level.

Table 3.1 Estimated sorghum response to distance upslope from a stone row, Kirsi, Burkina Faso, 1992-1994

Independent variables†	Model 1		Model 2	
	Coefficient	T stat	Coefficient	T stat
Distance	-6.30*	-2.07	-6.81*	-2.25
Dissquared	0.02	0.65	0.02	0.56
Dum 93	209.77*	7.19	209.74*	7.16
Dum 94	-187.05*	-6.41	-187.08*	-6.39
2nd	42.95	1.07	-	-
3rd	-19.47	-0.40	-	-
4th	47.34	0.71	-	-
Intercept	631.69		623.30	
R^2	0.29		0.28	
Number of observation	258		258	
F	14.68**		24.22**	

† Independent variables are defined as: Distance = distance upslope from a stone row, ms; Dissquared = distance squared; Dum 93 = dummy variable for the 1993 season, 1 if 1993, -1 if 1992, 0 if 1994; Dum 94 = dummy variable for the 1994 season, 1 if 1994, -1 if 1992, 0 if 1993; 2nd = dummy variable for location downslope from a row, 1 if there is a row upslope, 0 otherwise; 3rd = dummy variable for location downslope from 2 rows, 1 if there are 2 rows upslope, 0 otherwise; 4th = dummy variable for location downslope from 3 rows, 1 if there are 3 rows upslope, 0 otherwise; * Statistically significant at the 5% level; ** Statistically significant at the 1% level.

The quadratic terms are positive in both models, but not statistically significant at conventional 5% or 1% levels. The estimated quadratic coefficients will be retained for the economic analysis because econometric theory strongly encourages model specification based on previous knowledge of the process being modeled. The regression statistical tests assume that the functional form is known. Econometric theory discourages ad hoc models based on the particular data set being analyzed because such models are difficult to interpret and because the significance levels in conventional statistical tests do not take into account errors that may occur in the iterative process of model development.
Alternative models were estimated for linear, square root and logarithmic functional forms. Judging from the R^2, the alternative models did not provide a better fit than the quadratic.

3.3.2 Optimization

The NPV of returns to sorghum production (V) was maximized with respect to stone row spacing for three scenarios using estimated stone row construction and maintenance costs. Sensitivity testing was done on the opportunity cost of labor and the discount rate. Only results for model 2 are reported; spacing estimates for model 1 are very similar.

The NPV is calculated for returns to family resources with traditional production techniques, including local varieties with seed saved by the farmer, no chemical fertilizer and all family labor. Thus, all variable inputs are supplied out of family resources and the variable cash costs term (C) is zero. A more complete analysis would jointly optimize stone row spacing with fertilizer-improved varieties and other inputs. Unfortunately, such interactions cannot be tested with available data; the Kirsi trial used traditional inputs.

Stone row construction costs vary widely depending on the type of transportation and how labor is organized. In this section, optimization is carried out for three cost examples to show how optimal row spacing would vary with cost.

3.3.2.1 Community land management projects

The usual objective of such projects is to protect a substantial portion of the land in a given village or watershed. Because large quantities of rock are required, they must often be transported some distance. Local people work together to gather rocks and build the stone rows in community workdays. People may not be working on their own land. Typically, the community workdays are full days (roughly 8 hours) to make efficient use of trucks and other equipment.

3.3.2.2 Farmer with NGO assistance

The farm family is working to protect its own fields, but rocks must be transported from a distance. In the case cited by Kaboré et al. (1994), the non governmental organization (NGO) helped with training in contour tracing and with truck transportation. To use the truck efficiently, full day workdays are planned for hauling.

3.3.2.3 Farmer with rocks nearby

The farm family is working to protect its own fields using rocks found close to the fields. In the case studied by Kaboré et al. (1994), the farmer laid the contours himself and transported the rock with a wheelbarrow that he already owned. This is a relatively rare situation, but it is included to show the full range of costs levels. The farm family does the heavy work of stone gathering, transport and laying during the cooler early morning hours.

The cost estimates per meter of stone row are shown in Table 3.2 assuming farm family labor has an opportunity cost of 50 FCFA/hr in the dry season (Lowenberg-DeBoer et al., 1994). A sensitivity test will be done assuming the legal minimum wage of 143 FCFA/hr. The cost estimate for the community land management projects is higher mainly because of greater labor use. The Vlaar labor estimate gives a range of 80─160 person days/ha. Table 3.2 estimates assume 8 hours per day and the midpoint of the range. Kaboré et al. (1994) hypothesize that the greater labor use in community projects is related to the lack of motivation when individuals are not working on their own fields and the full day work schedule. Most stone row construction occurs during the hot season when temperatures may reach 45 °C in the afternoon and work efficiency is low. It should be noted that this cost estimate does not include the expenditures on the survey team that traces the contours or, administrative costs for the project. Surveying and administrative costs are potentially important in estimating the overall net benefit, but they are fixed costs that do not change much with different row spacings. Similarly, the cost of the earthen bund upslope and to the sides of the Kirsi site was not included in the cost analysis because such protection bunds are not usually used on farms and if they were used, they would be a fixed cost that would not affect spacing.

Available data indicates that when farmers work on their own fields, less labor is needed for stone row construction (Kaboré et al., 1994). Thus, the cost estimate for a farmer with NGO assistance has a lower stone row construction cost estimate. This estimate includes labor for tracing the contours, which is done by the farmer and a neighbor trained by the NGO, but it does not include the cost incurred by the NGO in providing the training, the hand tools provided by the NGO or administering the project.

Table 3.2 Stone row construction cost in Burkina Faso under differing conditions.

Item and Type of Construction	Units	Quantity	Price (FCFA)	Amount (FCFA)
Community projects †				
Truck rental	Ha	1	26300	26300
Farmer labor	Hours	960	50	48000
Cost per hectare				74300
Cost per meter ‡				248
Individual farmer with NGO assistance §				
Truck rental	Ha	1	18840	18840
Farmer labor	Hours	432	50	21600
Cost per hectare				40440
Cost per meter ¶				81
Individual farmer with rocks close to field §				
Farmer labor	Hours	97	50	4850
Cost per hectare				4850
Cost per meter ¶				10

† Estimate from Vlaar (1992) assuming the midpoint value of the range of labor times, truck rental, and mid point value for meters of stone row/ha; ‡ Assuming 300 m/ha of stone row; § Estimate from Kaboré et al (1994); ¶ Assuming 500 m/ha of stone row.

The farmer with rocks close to the field has the lowest cost. In the case cited by Kaboré et al. (1994), the farmer used tools already on the farm and traced the contours without assistance. It is hypothesized that the labor times are low because the farm family is working only on their own land and only in the cooler early morning hours.

Parameters needed for the optimization include the sorghum price the discount rate, annual maintenance costs, and the useful life of stone rows. The average harvest time market price of sorghum in the area was 59 FCFA/kg during the period 1992-1994. The annual maintenance costs are assumed to be 5 FCFA/m. The useful life of stone rows has not been well studied; for the purpose of these examples, the T in Eq. [6] is assumed to be 10 years.

The appropriate discount rate depends on the decision maker's opportunity cost of capital. Lowenberg-DeBoer et al. (1994) indicate that private opportunity cost of capital for Burkinabé farmers is at least 50% annual. The high discount rate has been linked to poorly developed financial institutions and a chronic shortage of capital. A 10% cost of capital was used as the social discount rate for the donor and NGO-assisted scenarios, reflecting the great availability and lower cost capital in the industrialized countries. The discount rate sensitivity test assumed that the social discount rate was 6% and the farmer rate 100% annually. For the social rate, this was based on the argument that the rate should reflect a long-term social discount rate. For the farmer discount rate sensitivity test, 100% was chosen based on studies which indicate that some Sahelian farmers have opportunity costs of capital of 100% annually or more (Lowenberg-DeBoer et al., 1994).

Optimization was carried out using the FOC described above and a Quattro Pro spreadsheet. The Quattro Pro command /TOOLS/SOLVE was used to solve the FOC for the NPV maximizing distance. The SOC are negative for all the solutions discussed here.

Results are given for the three cost scenarios in Table 3.3. The NGO scenario is considered from both the social cost angle and the farmer's private cost perspective. The NGO social cost analysis includes all costs and a 10% baseline discount rate. The NGO farmer cost analysis includes only the farm family labor and used a 50% baseline discount rate.

Using baseline discount rates and an opportunity cost of labor of 50 FCFA/hr, the NPV-maximizing spacing ranges from 23 m to 40 m (Table 3.3). With the higher costs in the community land management scenario, the NPV-maximizing solution is not to build stone rows because yield increases do not cover costs. The 23 m spacing is optimal for the scenario in which the farm has rock close to the field and can construct the stone rows with existing farm tools.

If the opportunity cost of labor is 143 FCFA/hr, with baseline discount rates, optimal spacing rises to 33m for the scenario of the farm with rocks nearby. Under the NGO scenario, stone row construction is beneficial for society at large, but not the individual farmer. For community projects, stone row construction cannot be justified by economic benefits alone.

Except for the scenario of a field with rocks nearby, these spacings are greater than the approximately 30-meter spacing that is suggested based on physical criteria alone. This is consistent with the usual production economics result that less of an input (in this case meters of stone row per hectare) is used when maximizing economic returns than when maximizing physical yield.

Breakeven construction costs and spacing were calculated using the spreadsheet. For the baseline social cost scenarios, the maximum construction cost is 191 FCFA per meter of stone row and the spacing at this cost would be 47 meters. For the baseline farmer cost scenarios, the maximum construction cost would be 61 FCFA per meter and the optimal spacing would be 47 meters. Discount rate sensitivity testing modifies the maximum allowable construction cost, but the spacing at those maximum costs remains 47 m. With the 6% discount rate community project could support a cost up to 229 FCFA/m. At the 100% discount rate the maximum construction cost for farmers is 31 FCFA/m.

Table 3.3 NPV maximizing spacing for stone rows using estimated sorghum response functions, Kirsi, Burkina Faso.

	Social cost of capital scenarios		Farmer cost of capital scenarios	
Discount Rates and Labor Cost	Community projects	Farm with NGO help	Farm cost NGO help	Farm with rock nearby
FCFA/hr				
	m			
Base line discount rates				
50	No Stone row†	32	40	23
143	No Stone row†	43	No Stone row†	33
Discount rate sensitivity‡				
50	No Stone row†	30	No Stone row†	29
143	No Stone row †	43	No Stone row†	

† The NPV maximizing solution is to construct no stone rows when the NPV from sorghum production without stone rows is greater than the NPV at the spacing which satisfies the FOC; ‡ Baseline discount rates are: Donors, 10%; Farmers, 50%. Sensitivity testing uses discount rates of: Donors, 6%; and Farmers 100%.

Figure 3.2 shows how NPV changes as spacing is increased. The level of the NPV curve is higher for the community and farm/NGO scenarios because of their lower discount rate. The NPV surfaces beyond a 30-m spacing are relatively flat and as a consequence, the NPV difference between a 30 m and the 47 m maximum spacing (suggested by the breakeven analysis) is relatively small. Because of the lower labor productivity in the community scenario, the NPV maximizing spacing is wider than for the other scenarios.

If the response is estimated without the distance-squared term and optimization is carried out with linear estimates, NPV maximizing stone row spacings are within 1 meter for the scenarios in Table 3.3. This suggests that in this case, maintaining the econometric assumption of a known functional form and retaining the quadratic coefficient estimates, even if they are not statistically significant, has little impact on the economic results. If the assumption that the row takes no land out of production is relaxed and a 1 m band is taken out of crop production by the row, optimal spacings are 3 to 6 meters wider.

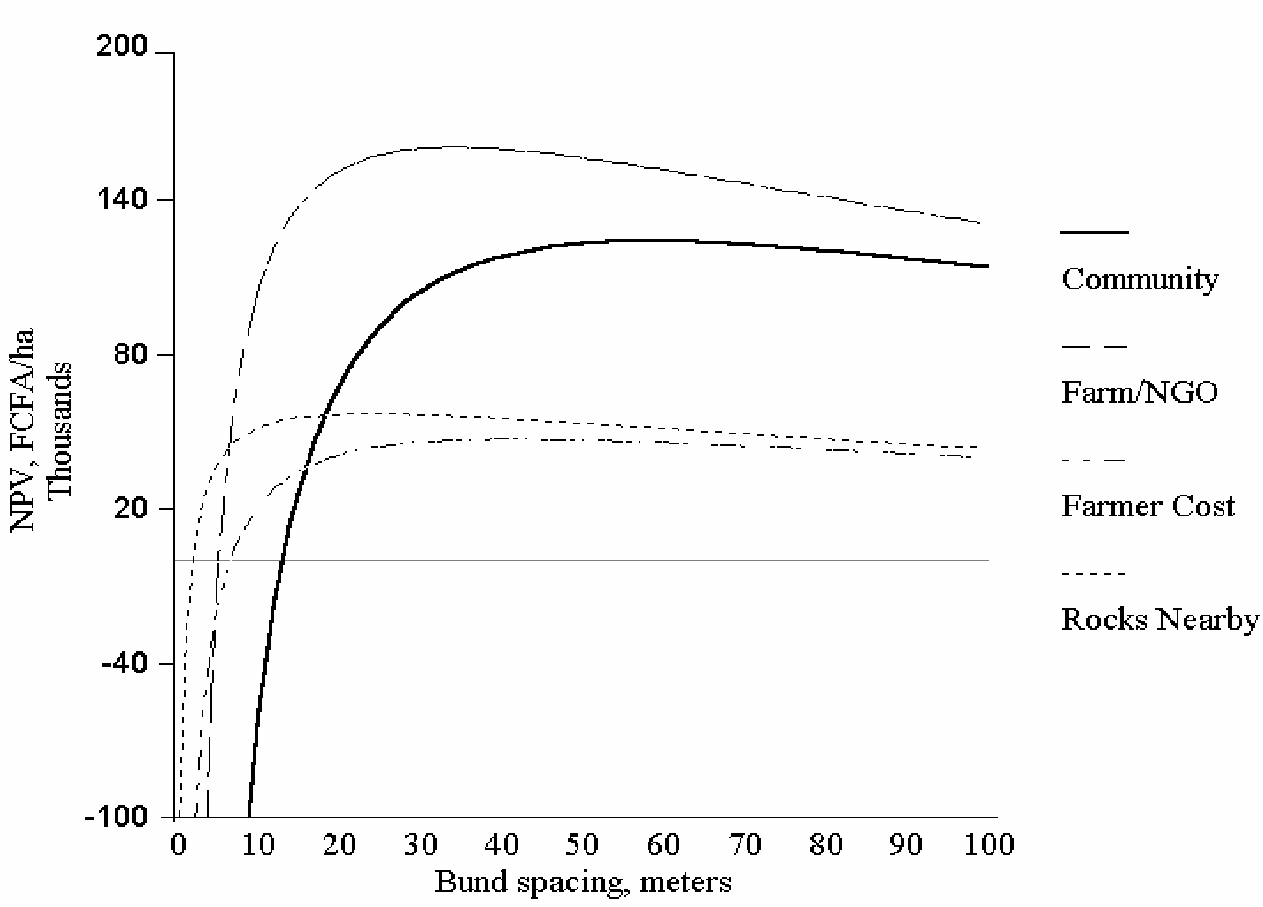

Figure 3.2 The net present value (NPV) per hectare of sorghum production as a function of stone rows spacing, for the baseline scenario at Kirsi, Burkina Faso.

3.4 Conclusions

This paper describes a method for estimating the optimal spacing for conservation barriers. The steps include estimating a continuous yield response to distance between barriers, developing a mathematical expression to describe how costs change as spacing is altered, and optimization using calculus. The method is general and can be adapted to fine tune spacing of any conservation technique that is applied in bands. For example, this method might be applied to spacing of grass strips, bunds, hedges, windbreaks, or terraces.

This analysis suggests that the NPV-maximizing spacing of stone rows on the Central Plateau of Burkina Faso depends on the type of construction, transport cost and how labor is organized. Because of high labor inputs, yield increases do not cover stone row construction costs for the community project scenario; environmental and other benefits not considered here may still justify this type of project.

For the conditions of the Kirsi site, the optimal spacing for a farmer who can construct stone rows with farm tools from rocks available close to the field is between 23 m and 45 m. The more common case of a farmer who works with an NGO to trace contours and transport rock has a NPV maximizing spacing of 30 to 43 m. Except for the community scenario, the NPV surface rises sharply for initial increases in distance up to about 30 m, but it is relatively flat in the neighborhood of the maximum. This suggests that in the Kirsi case, not much is lost by using the 30-meter spacing based on physical criteria if farmers are working on their own fields with or without the help of an NGO. Those planning stone row projects using community labor should consider wider spacing.

Further research in this area should relax some of the stringent assumptions made in this first approximation. Risk and environmental aspects should be incorporated in the theoretical model. For Burkina Faso, an effort should be made to include in the analysis the age of the stone rows and soil characteristics. Interactions of stone rows with fertilizer, improved genetics and other inputs, need to be examined. Empirical results need to be derived for a range of slopes, soil conditions and rainfall patterns. With these additional research results, it would be possible to develop extension information that would guide barrier spacing according to local conditions, including the cost of construction, slope, and soil type.

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Chapter 4

Effect of stone rows on soil chemical characteristics under continuous sorghum cropping in semi-arid Burkina Faso

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Abstract

In the semi-arid Sahel, farmers commonly lay stone rows in fields to disperse runoff. This study was conducted in northern Burkina Faso to assess the chemical fertility of a soil under a permanent, non-fertilized sorghum crop, which is the main production system in this area, five years after laying stone rows. The experimental design consisted of four plots in which stone rows had been laid. The spacing between the rows was 100 m in the first plot, 50 m in the second, 33 m in the third, and 25 m in the fourth. To determine soil chemical characteristics in relation to the stone row spacing patterns studied, soil samples were taken from subplots at regular and fixed distances from the rows at the start of the trial and then five years later. Under the continuous non-fertilized sorghum cropping system, the beneficial effect of stone rows on soil fertility was limited. Five years after installing stone rows, soil organic C, total N, available P and Na concentrations and soil pH had decreased. Within the plots, these same variables were higher upslope than downslope of stone rows, probably because of water storage and sediment accumulation in front of the stone rows. In plots where stone rows were relatively close together (< 33 m), the decrease in soil fertility was less. It is concluded that in Sahelian zones, stone rows alone are not sufficient to insure the conservation of soil fertility. Combining soil and water conservation techniques with soil fertility management practices are needed to sustain soil productivity.

Keywords: Stone rows; Runoff; Soil fertility; Sorghum; Sahel.

4.1 Introduction

Agricultural production in the Sahelian zone of Burkina Faso (600 mm annual rainfall) is under serious threat from soil erosion and depletion of soil fertility (Roose, 1994). Several erosion control methods have been used successfully in this region in the past 15 years (Rochette, 1989). Among them, laying stone rows in fields is now well known and is widely practiced by farmers in sub-Saharan West Africa (Lal and Stewart, 1990; Morin, 1993; Zougmoré et al., 2000a). As a result, various government and non-government are promoting the large-scale introduction of the technique and providing technical and logistical backup for collecting and transporting stones (Rochette, 1989). Several studies have demonstrated the benefits of filterable obstacles such as stone rows and live hedges on soil water balance (Lamachère and Serpantié, 1991; Perez et al., 1998). The technique is particularly efficient in reducing runoff and improving rainwater infiltration (Zougmoré et al., 2000b); it also reduces fine sediment transport by runoff (Mando et al., 2001).

Many claims have been made about soil and water conservation techniques improving soil fertility, but objective results are scarce (Walle and Sims, 1999). Indeed, few studies have looked at the effect of such techniques on soil chemical fertility in the Sahelian zone. Some, for instance by Penning de Vries and Djitèye (1982) and Breman and De Ridder (1991) contended that soil and water conservation techniques play a minor role in improving soil fertility. Some studies (Morin, 1993; Roose, 1994; Sessay and Stocking, 1995) have shown that the lack of water and nutrients remains the main constraint for soil rehabilitation. Lal (1997) pointed out two conditions for soil rehabilitation: (1) ensuring effective water infiltration and storage in the soil and (2) re-establishing nutrient cycling. Zougmoré et al. (2000b) demonstrated the efficacy of stone rows in improving soil moisture and sorghum crop yield. In this study, we set out to evaluate the chemical fertility of a soil under unfertilized continuous sorghum (*Sorghum bicolor* (L.) Moench) cropping five years after stone rows had been laid. Our aim was to assess whether laying stone rows alone would be sufficient to maintain soil fertility under continuous sorghum cropping.

4.2 Materials and methods

4.2.1. Site description and experimental design

The trial was set up on-farm on a plateau at Kirsi, a village ca. 150 km northwest of Ouagadougou, 13°3’ N and 1°54’ W. The average slope (S→N) was 0.8% and the major soil type, which covers 70% of the country, was a Ferric Lixisol (FAO-UNESCO, 1989). The topsoil was sandy loam (470 g kg^{-1} of sand, 280 g kg^{-1} of silt and 250 g kg^{-1} of clay). The soil was acid (pH < 6), highly susceptible to surface sealing with an index greater than 2 (Casenave and Valentin, 1992), and relatively low in organic C (< 6 g kg^{-1}), N (< 0.5 g kg^{-1}) and Bray II available P (< 30 mg kg^{-1}).

The natural vegetation was bush savannah (UNESCO, 1973), with the following main species: *Acacia* spp., *Combretum* spp., and *Butyrospermum paradoxum*. The herbaceous understory was dominated by *Loudetia togoensis* and *Schoenfeldia gracilis*.

The climate is Sudano-Sahelian (Fontes and Guinko, 1995). Mean annual rainfall is 600 mm, with a dry season and a rainy season that varies in time and space.

The production system during the five years was monoculture sorghum with tillage by horse-drawn plough. Sorghum was sown in rows at a density of 27 500 plants ha^{-1} (0.6 m x 0.6 m). There were usually three hoeing rounds for weed control. Ploughing and sowing were each year in June, and the three hoeing rounds in July, August and September. No fertilizers were applied. The average ploughing depth was 10-15 cm, and sorghum had been grown continuously on the site for 15 years before the experiment.

The trial comprised four adjacent plots 100 m long and 25 m wide, with their long axes aligned along the maximum gradient, which was S→N (Figure 2.1). Stone rows had been laid in February 1992 along contour lines at four spacings: P1 with stone rows spaced at 100 m (1 stone row), P2 with stone rows spaced at 50 m (2 stone rows), P3 with stone rows spaced at 33 m (3 stone rows), and P4 with stone rows spaced at 25 m (4 stone rows). Each row consisted of two rows of laterite rocks placed in a furrow dug with a subsoiler or pick. The upslope row was of large blocks (35 cm x 25 cm) of stones partly buried (5 cm depth) in the soil while the downslope row consisted of small stones (15 cm x 15 cm) placed so as to stabilize the first row. The earth excavated from the furrow was replaced along the stones to fill up remaining holes in the soil. The heap of stones weighed about 80–90 kg m^{-1} and was about 20-30 cm high from the soil surface.

4.2.2 Sampling and analysis

In each plot, 16 subplots measuring 8 m × 3 m were marked out in 1992. To measure soil water content and sorghum yields at various distances from the stone rows, this number was increased to 24 in 1993. The subplots were located at the same distances in the four plots respectively: 96, 87, 79, 71, 62, 54, 46, 37, 29, 21, 12 and 4 m, from the downslope border of each plot (Figure 2.1). In each plot, 16 soil samples were collected with an auger at 0-20 cm depth to determine soil chemical and physical characteristics at the start of the trial (April 1992). Each soil sample was a composite of 3 cores taken from the center of each subplot. Similarly, in April 1996, 24 soil samples were taken from each plot at 0-20 cm depth to determine the same characteristics five years after laying the stone rows. Organic C was measured using the Walkley and Black method, N using Kjeldahl method, available P using the Bray II method, exchangeable bases by cobalt hexamine extraction and pH (H_2O) by potentiometric method (Baize, 1988). Methods were the same for soil collected in 1992 and 1996.

4.2.3 Data analysis

Data were analyzed statistically using the Genstat (General statistics) package. Analysis of variance and Newman-Keul's tests were used to establish significant differences between the treatments at $p < 0.05$. The experiment was considered a randomized block design using the 4 plots as blocks and the 12 selected positions located at 96, 87, 79, 71, 62, 54, 46, 37, 29, 21, 12 and 4 m, respectively from the downslope border of each plot as treatments. The means per plot for 1992 and 1996 were compared (data pooled for each year) and were also used in 1996 to determine the differences depending on position in the field. To this end, immediate adjacent upslope and downslope subplots to stone rows in each plot were compared (Figure 2.1). There was no subplot downslope from the only stone row in plot P1.

4.3 Results

4.3.1 Initial properties of plots in 1992

There were no significant differences among plots in any of the chemical characteristics in 1992 when the trial was initiated (Table 4.1). From this analysis, we concluded that the four plots had similar initial soil characteristics and the experimental block was homogeneous. The pH (H_2O) was slightly acid for all four plots. The soil was very poor in organic C (6.0-7.2 g kg^{-1}). All four plots had very low N concentration (0.4-0.6 g kg^{-1}). Available P was also low (20-30 mg kg^{-1}). Calcium concentration was average for the region, as were those for Mg and K. The soils were relatively rich in sodium. Total exchangeable bases was low (4.13-4.51 cmolkg^{-1}), suggestive of poor fertility (Baize, 1988).

Table 4.1 Initial soil chemical characteristics of the plots (1992)

Plot	pH (H2O)	C:N	SOC	N	P_2O_5	K	Mg	Ca	Na	SEB
		ratio	g kg^{-1}		mg kg^{-1}	cmol kg^{-1}				
P1	5.9	14.3	5.7	0.40	20	0.03	1.3	2.9	0.09	4.3
P2	5.6	13.7	6.3	0.46	30	0.04	1.7	2.6	0.09	4.4
P3	6.2	13.0	7.2	0.55	30	0.06	1.5	2.5	0.09	4.1
P4	6.3	14.7	6.5	0.44	30	0.05	1.5	2.9	0.07	4.5
Sig.	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

Plots with stone rows spaced at 100 m (P1), 50 m (P2), 33 m (P3), and 25 m (P4); ns: not significant at $p < 0.05$; SEB: sum of exchangeable bases.

4.3.2 Changes in soil characteristics between 1992 and 1996

Soil pH (H_2O), organic C and N concentrations decreased from 1992 to 1996 (Table 4.2). Available P was identical for the two dates, but the C:N ratio was higher in 1996 than in 1992. Regarding exchangeable bases, Na was the only element that changed with time. The sum of exchangeable bases (SEBs) did not change significantly with time. Overall, nutrient concentrations decreased between 1992 and 1996, suggesting a decline in soil chemical fertility.

Table 4.2 Comparison of soil chemical characteristics in 1992 and 1996

Year	pH	C:N	SOC	N	P_2O_5	K	Mg	Ca	Na	SEB
	(H_2O)	ratio	g kg^{-1}		mg kg^{-1}	cmol kg^{-1}				
1992	5.9 a	13 b	6.4 a	0.46 a	26 a	0.04 a	1.5 a	2.7 a	0.08 a	4.3 a
1996	5.4 b	16 a	6.1 b	0.39 b	29 a	0.05 a	1.4 a	3.3 a	0.03 b	4.8 a

Years with the same letter are not statistically different at p= 0.05; SEB: sum of exchangeable bases.

4.3.3 Effect of laying stone rows on soil chemical fertility (1996)

In 1996, unlike in 1992, there were significant differences in chemical characteristics among the four plots (Table 4.3). Soil organic C, total N and available P concentrations and C:N ratio differed significantly at $p < 0.05$. On average, soil organic C, N and P_2O_5 concentrations were higher in plots P3 and P4 than in P1 and P2, implying that the narrower the spacing, the greater the improvement in soil chemical characteristics.

Table 4.3 Effect of stone rows on soil chemical characteristics (1996)

Plot	pH	C:N	SOC	N	P_2O_5	K	Mg	Ca	Na	SEB
	(H_2O)	ratio	g kg^{-1}		mg kg^{-1}	cmol kg^{-1}				
P1	5.4 a	15.5 c	5.1 d	0.33 c	24 d	0.05 a	1.2 a	3.2 a	0.02 d	4.5 a
P2	5.1 a	15.2 c	5.5 c	0.36 b	34 a	0.04 a	1.5 a	3.3 a	0.03 c	4.9 a
P3	5.1 a	15.8 b	7.1 a	0.45 a	27 c	0.06 a	1.5 a	3.6 a	0.04 b	5.1 a
P4	5.8 a	17.4 a	6.4 b	0.37 b	32 b	0.05 a	1.3 a	3.2 a	0.11 a	4.7 a

Plots with stone rows spaced at 100 m (P1), 50 m (P2), 33 m (P3), and 25 m (P4); Plots with the same letter are not statistically different at p= 0.05; SEB: sum of exchangeable bases.

The values for pH (H_2O) were higher upslope than downslope stone rows (Table 4.4). The same was true for Organic C, total N, available P and exchangeable K concentrations. Though not significant, the SEBs was numerically higher below the stone rows than above them. These observations apply to all four plots.

Table 4.4 Comparison of soil chemical characteristics upslope and downslope of stone rows

Position	pH	SOC	N	P_2O_5	K	Mg	Ca	Na	SEB
	(H2O)	($g\ kg^{-1}$)		($mg\ kg^{-1}$)	($cmol\ kg^{-1}$)				
Upslope	5.7 a	7.4 a	0.42 a	39.7 a	0.07 a	1.2 a	3.1 a	0.05 a	4.5 a
Downslope	5.3 b	6.4 b	0.35 b	29.4 b	0.05 b	1.4 a	3.3 b	0.06 a	4.8 a

Positions with the same letter are not statistically different at p= 0.05; SEB: sum of exchangeable bases.

4.4 Discussion

Nutrient balances obtained in several studies in semi-arid Sahelian zones have shown that soil fertility inevitably declines in cropping systems without fertilizers (either organic or inorganic) (Arrivets, 1976; Wetselaar and Ganry, 1982). Indeed, export and loss of nutrients due to erosion and leaching result in gradual soil exhaustion. This exhaustion can be quantified by the variation in (1) physico-chemical regulation systems (soil acidity), (2) reserves of major production factors (nutrients and organic C), and (3) soil structure. In our study, the variations in pH and organic C concentration between 1992 and 1996 (Table 4.2) showed that cropping for five successive years without applying fertilizers or additional organic matter had negative effect on soil chemical properties.

The drop in soil pH (H_2O) between 1992 and 1996 (Table 4.2) reflected an increase in soil acidity. According to Piéri (1976), under a continuous cropping system the soil acidity increases due to the gradual replacement of basic cations by aluminium. This acidification was interpreted as a type of soil exhaustion, generally resulting in reduced yields and nutrient bioavailability to plants (Piéri, 1989).

Organic matter is an excellent indicator of the changing fertility of cultivated soils, since concentrations co-vary with soil physical, chemical and biological characteristics. The decline in organic C from 1992 to 1996 (Table 4.2) was likely from mineralization (Sessay and Stocking, 1995; Bado et al., 1997) and soil erosion (Morin, 1993; Roose, 1994). The most marked losses in organic C and N were observed in plots P1 and P2, which suggests that the greater number of stone rows in plots P3 and P4 helped to limit losses by controlling water erosion. Although wind erosion would have been less active than water erosion in this zone, organic C and N losses could have also occurred from loose crop residues blowing away from plots. We can also assume that given the greater humidity in plots P3 and P4, particularly during dry periods (Zougmoré et al., 2000b), mineralization would have been more active and rapid in those plots. Ganry and Cissé (1994) stressed that in cultivated ferruginous soils in the dry tropics, organic C in the topsoil is crucial in relation to water balance and nutrient mobility.

Total N in soil is very closely linked to that of organic C, and particularly to its net mineralization (Piéri, 1989). In our case, the drop in N concentration was more marked than the drop in organic C, as is often seen in traditional cereal cropping systems without fertilizer applications (Van der Pol, 1991). The organic C and N changes were similar to the results obtained by Pichot et al. (1981), who recorded a 30% drop in organic C reserves and 10% drop in total N reserves after 19 years of continuous cropping.

Available P did not vary with time. This maintenance of reserves of exchangeable P may be due to a balance resulting from chemical retrogression of P (Piéri, 1989). As there are often very considerable internal exchanges between the available and mobilizable reserves (Frissel, 1978), the variations in exchangeable bases concentrations cannot be considered as changes in reserves. Instead, the concentration of exchangeable elements should be seen more as an indication of the nutritional potential of a soil. Provided the soil is not exhausted, this potential oscillates around a stable value (Piéri, 1989). For K, the maintenance of the exchangeable reserves is due to internal K redistribution within the soil (Piéri, 1982). However, we observed an increase in exchangeable Ca reserves after five years of cropping. This result was similar to that obtained by Sarr (1981) in Senegal after 17 years of cropping without fertilizers on a sandy soil. Likewise, Piéri (1985) observed an increase in Ca in a millet crop in Bambey. This pattern may be due to soil desaturation, i.e., a gradual liberation of cations, particularly Ca (Soltner, 1995).

Soil total N, organic C, available P, Na and K concentrations, and pH (H_2O) were higher above than below stone rows. The opposite was true for Ca. This result is consistent with the results of Hien (1995) obtained in 1991 and 1992 at Yabo village (same type of climate as Kirsi village) with earth bunds laid on a Ferric Lixisol. These differences can be linked to the fact that the area above the rows is where water and also sediments from further up the plots accumulate. This is consistent with Meyer et al. (1995) who found that contour barriers of grass or stone promote sediment deposition by slowing runoff velocity and trapping sediments. Studies by Hien (1995) and Zougmoré et al. (2000b) showed that soil water varied depending on position relative to stone rows. Erosion and runoff from upslope contribute to the increase in water and nutrients upslope of stone rows.

4.5 Conclusion

This study suggests that in unfertilised continuous sorghum cropping systems in Sahelian zones, stone rows will have a limited effect on improving soil fertility. Five years after laying the stone rows, a drop in soil pH and organic C, N, P and Na concentrations was observed. However, soil fertility was improved above stone rows. Water and sediment that had accumulated above stone rows made this area the most fertile. In plots in which stone rows were relatively close together (< 33 m apart), depletion of soil organic C, N, P and Na concentrations was less. We conclude that in Sahelian zones, stone rows alone are not sufficient to insure the conservation of soil fertility. Combining soil and water conservation techniques with soil fertility management practices is essential to improve the efficiency of these measures, and thus to sustain soil productivity.

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Chapter 5

Effect of combined water and nutrient management on runoff and sorghum performance in semi-arid Burkina Faso

Zougmoré, R., Mando, A., Ringersma, J., Stroosnijder, L., 2003. Effect of combined water and nutrient management on runoff and sorghum yield in semi-arid Burkina Faso. *Soil Use and Management* 19: 257-264

Abstract

In the semi-arid 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 of 2000 mm y^{-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 two replications of nine 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 to 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 properly managed to alleviate shade and other negative effects of the bunds on adjacent crops.

Keywords: Stone rows; Grass strips; Nutrient input; Sorghum, Burkina Faso

5.1 Introduction

Soil degradation is a major issue for arid and semi-arid tropics (Ryan and Spencer 2001), where the combined effect of depletion of soil organic matter (SOM), mismanagement of the fragile ecosystem and the harsh climatic conditions has 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% rain-fed (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 and 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 semi-permeable obstacles such as stone rows and live hedges (Lamachère and Serpantié 1991; Perez et al., 1998). The technique is particularly effective in reducing runoff and in 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 and Sims 1999; Zougmoré et al., 2002). This implies that there is no effective 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.

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 in Sub-Saharan Africa is to use adequate amount 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 managements geared to land use practices that are ecologically sound and economically viable remains the key factors for the sustainability of agricultural systems in West Africa (Buerkert et al., 2002).

The objective of the study we describe here 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 hypothesised that soil and water conservation measures could improve sorghum water and nutrient use efficiency under semi-arid conditions.

5.2 Materials and methods

5.2.1 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 and 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 may reach 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 and Guinko 1995). The soil type is a 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 depth. Average bulk density is 1.7 at 0-15 cm layer. 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 nitrogen input. The experimental design was a randomized block with nine treatments and two replications coded as follows (Figure 5.1): 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 + fertilizer N, T_{GSU}: grass strips + fertilizer N, T_0: no SWC measures, no nitrogen supply (control plot).

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) and T_U (Urea applied without SWC).

Each plot (100 m by 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 in each plot were collected from a 100 m by 1 m subplot. A metal sheet was used to direct runoff into a 6-m3 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) 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 by 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.

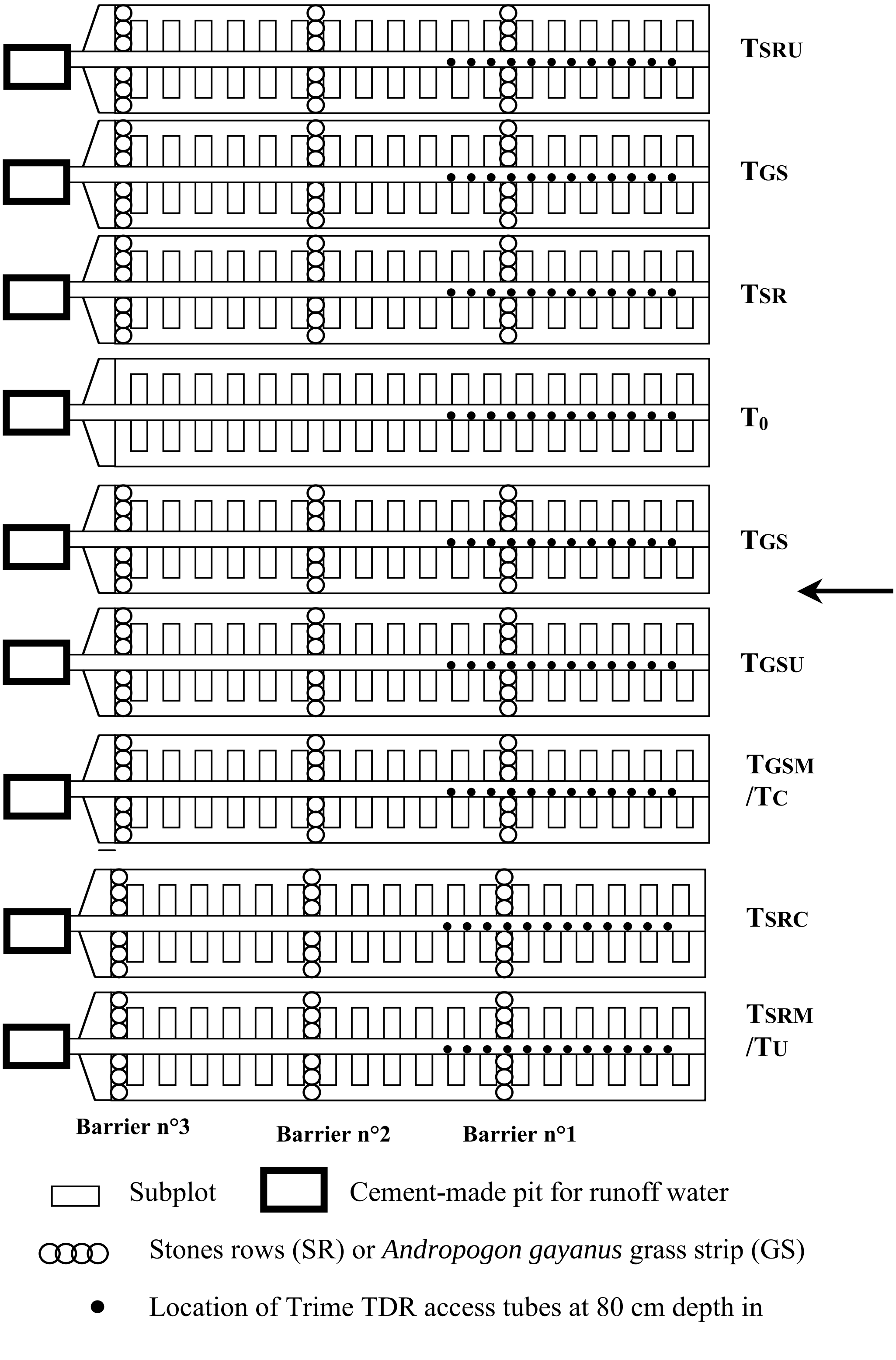

Figure 5.1 Experimental design at Saria agricultural station, Burkina Faso. T_{SR}: stone rows, no nitrogen supply; T_{GS}: grass strips, no nitrogen supply; T_{SRC}: stone rows + compost; T_{GSC}: grass strips + compost; T_{SRM}: stone rows + manure; T_{GSM}: grass strips + manure; T_{SRU}: stone rows + 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.

Previous studies showed that for the more common case of farmers working with an NGO to trace contours and transport rocks, the economic optimal spacing of stone rows 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 31250 seedlings per hectare (0.8 m x 0.4 m). The plots were tilled with hand hoes twice a year for weed control, 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 to 7 t ha^{-1} of manure or compost, thus consistent with the recommended minimum application of organic amendment in Burkina (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.

5.2.2 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 gravimetrically on August 6 and October 18 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 seven days with time domain reflectometry method (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, 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.

5.2.3 Data analysis

Runoff was analyzed from 10 erosive rain events for the 2000 rainy season, 9 rain 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 its harvest) of each year was related to cumulative rainfall to assess the ratio of annual runoff (Table 5.1). Hydrograph parameters defined by Reid and Parkinson (1984) and successfully exercised by Twomlow et al. (1990) were used to analyze runoff in relation to rainfall distribution and intensity. To better cope with runoff and rainfall behaviors 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, peak discharge: Q_p) have been related to the time at which rainfall started (Lamachère and 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. STATITCF package (Gouet and Philippeau 1986) was used for statistical analyses of soil water content and sorghum grain yields. Newman-Keuls test was used for mean separation at $P < 0.05$.

5.3 Results and discussion

5.3.1 Rainfall characteristics

Figure 5.2 shows the cumulative rainfall patterns over the 3 years, 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, 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 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 5.5). A drought of 13 days occurred early in September 2000 (Figure 5.2), 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.

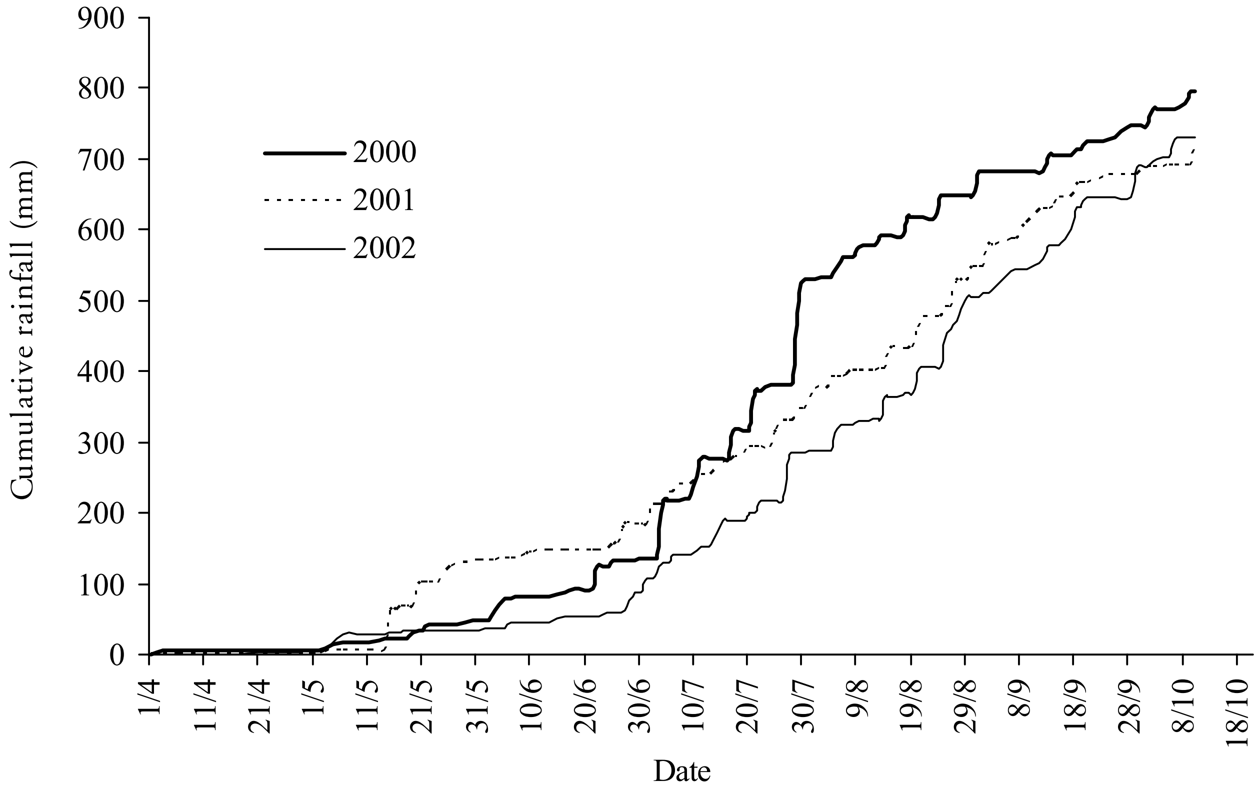

Figure 5.2 Daily cumulative rainfall for the 2000, 2001 and 2002 rainy seasons at Saria, Burkina Faso.

5.3.2 Runoff

Figures 5.3a and 5.3b show runoff hydrographs for selected major rainfall events. The associated hyetographs give the rainfall distribution over time. Time to start of the hydrograph rise (t_s) for rain event of 27.07.2002 were below 30 min but reached 50 min for those of 02.07.2001. 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 02.07.2001 started at a very low intensity during the first 50 min before rising to its highest level. This was not the case of 27.07.2002 rainfall event, which started readily with very high rain intensity. Time to peak discharge (t_c) was very much influenced by rainfall intensity: for the 27.07.2002 event, which maximum half-hourly rainfall intensity reached 82 mm h^{-1}, average t_c was shorter (35 min) than that of 02.07.2001 rainfall events (70 min). The latter rainfall intensity was 36 mm h^{-1}. Hydrographs also showed that treatments had a significant effect on the runoff process.

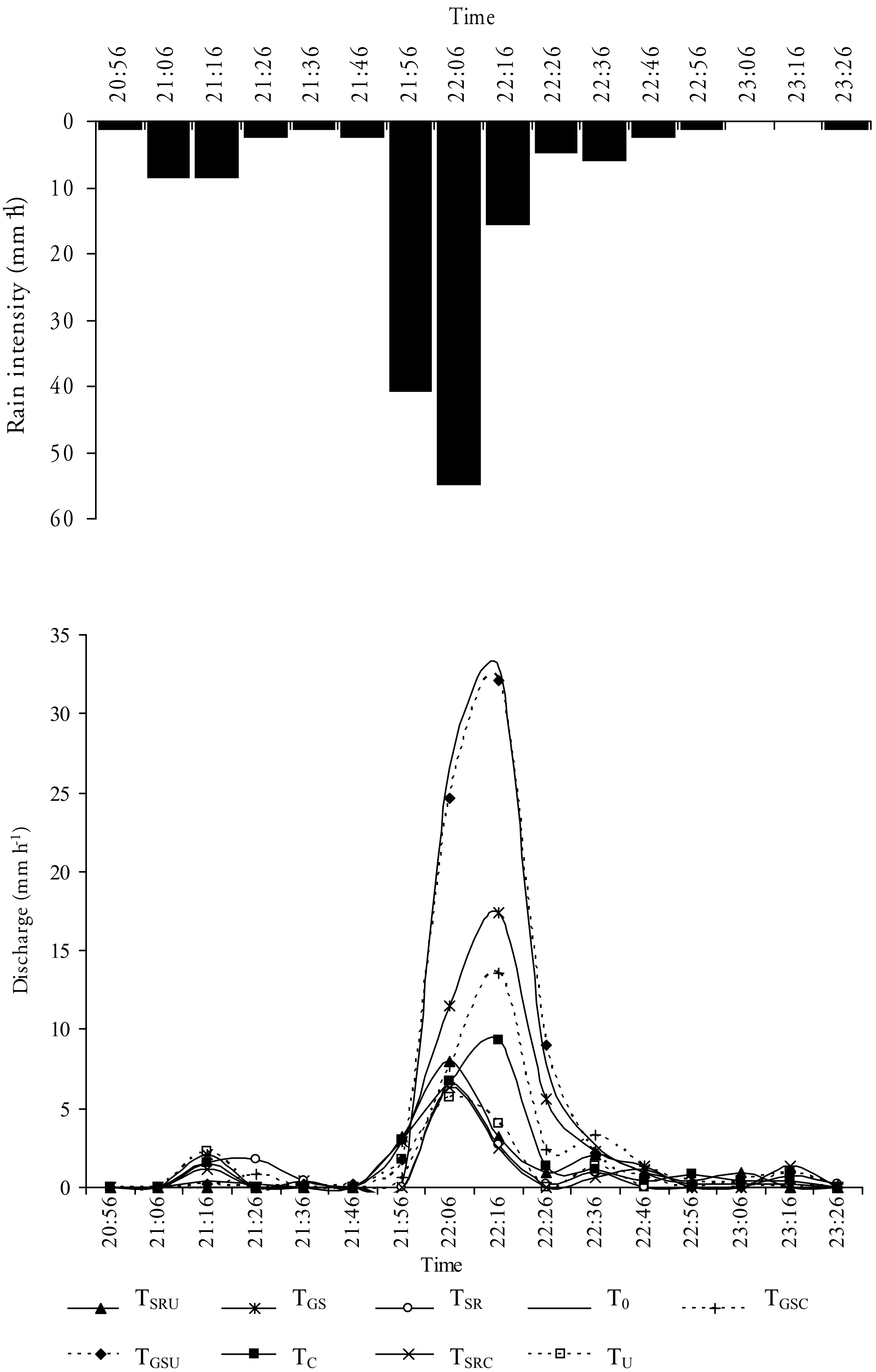

Figure 5.3a. Rainfall hyetograph and runoff hydrograph for major rain event of 02 July 2001 (28 mm) at Saria, Burkina Faso. Treatments explained in Figure 5.1.

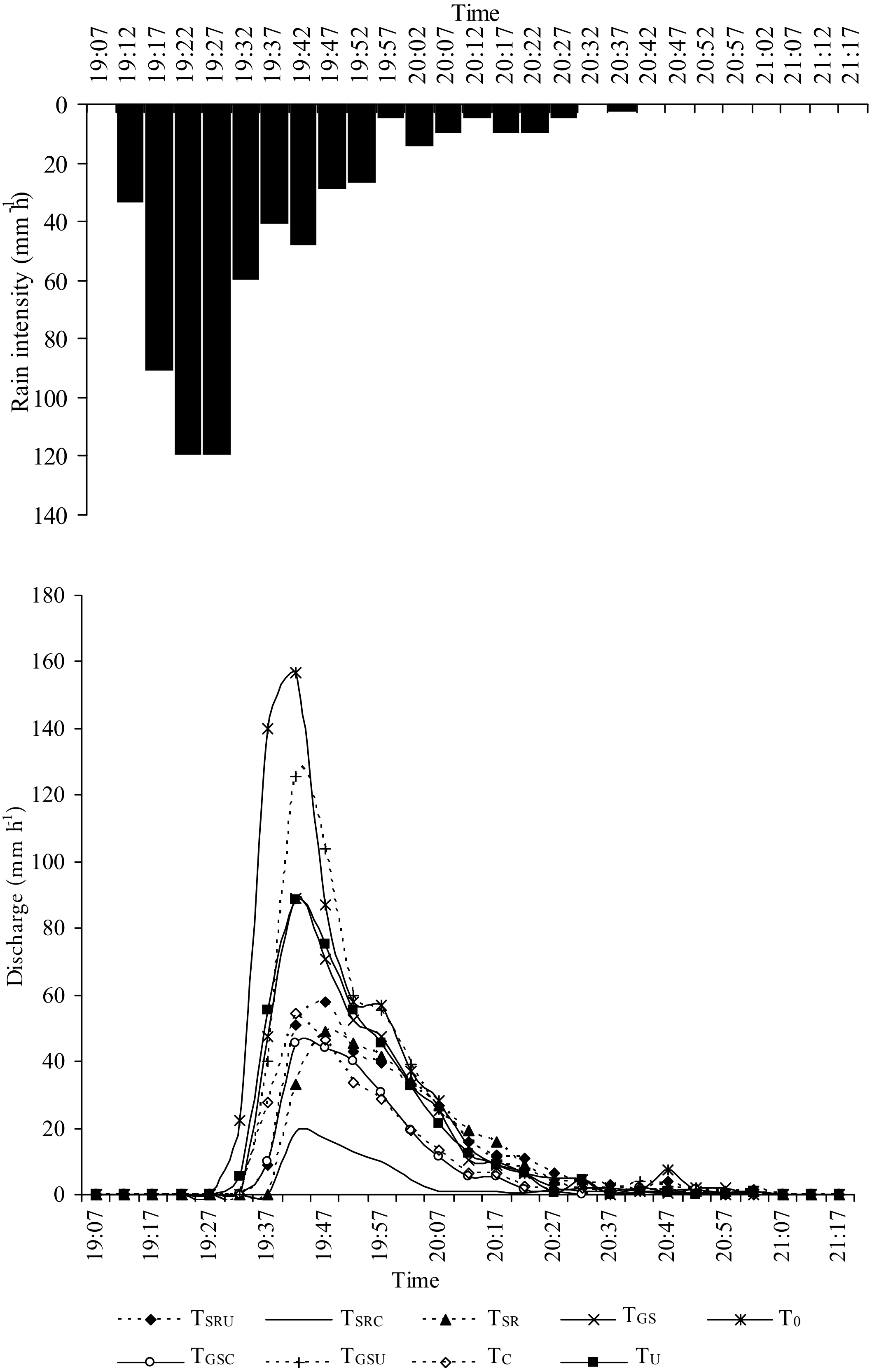

Figure 5.3b. Rainfall hyetograph and runoff hydrograph for major rain event of 27 July 2002 (52 mm) at Saria, Burkina Faso. Treatments explained in Figure 5.1.

On Figure 5.3b, t_s for plots with fertilizer N and without fertilization (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 5.3b were two to four times those of treatments with organic input. The greater Q_p with grass strip treatments when compared in pairs to stone rows 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 the control treatment (Table 5.1). 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 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 5.1). Overall in 2000, T_{SRC} and T_{GSC} had the least runoff, followed by T_{SR}, T_{SRM}, T_{GSM}, T_{GS}, T_{SRU}, T_{GSU} and T_0.

Table 5.1 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 explained in Figure 5.1.

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 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) 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 5.1). 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 semi-arid 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 (Figures 5.3a, 5.3b); 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 to vegetation bunds is attributable to the difference in architecture between the two types of barriers. The second row 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 and need about one month of re-growth after the inhospitable dry season 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 and Serpentié (1991) and Zougmoré et al. (2000a) in similar climatic zones.

5.3.3 Soil loss

All treatments reduced soil loss compared to the control plot (Table 5.2). In the rainy season of 2002, two exceptionally heavy rain events occurred and 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 2000 rainy season, stone rows reduced soil erosion by 55%, whereas the reduction by grass strips was about 31% compared with the control plots. 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 to 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 5.2). 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.

5.3.4 Soil moisture

Statistical analyses revealed significant differences of soil water content between treatments (Table 5.3). However, these slight differences were mainly observed during wet periods, soon after the rain events had induced runoff (06 August 2000 and 27 August 2001). This could be explained by the fact 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 plot 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 the control treatment but drier than treatments with stone rows (T_{SR}) 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 15.07.2002. 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. In addition, given that organic amendments improve soil drainage (Roose 1981; Mando 1997), this 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 5.2 Effect of treatments on soil loss in the rainy seasons of 2000, 2001 and 2002 at Saria, Burkina Faso.

	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

Treatments explained in Figure 5.1.

Table 5.3 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

Treatments with the same letter are not statistically different at $P = 0.05$. Values in brackets: ± standard deviation. Treatments explained in Figure 5.1.

Table 5.4 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 near 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.

5.3.5 Sorghum production

The treatment effect on sorghum grain and straw yields was statistically significant over the three years (Table 5.5). 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 5.5) suggested that nutrient supply, through both organic and fertilizers, more than water retention by the barriers, increased yields in combined SWC and nutrient plots. 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 5.5 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 matter production was obtained from plots receiving compost. Studies by Bielders and 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 5.6). 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 well distributed). That sorghum production was less near the grass strips than further away from them was probably due to the shading from the grass and competition for nutrients and water. As stones do not compete with plants, the opposite trend was observed with stone rows.

Table 5.4 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), Saria Burkina Faso.

		T_{SRU}	T_{GS}	T_{SR}	T_0	T_{GSC}	T_{GSU}	T_C	T_{SRC}	T_U
27.08.2001	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
	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
15.07.2002	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
	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

Positions with the same letter are not statistically different at P= 0.05. Values in brackets: ± standard deviation. Treatments explained in Figure 5.1.

Table 5.5 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})			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) ab
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) c	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) c	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) d	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) d	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) d	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) b	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

Treatments with the same letter are not statistically different at P= 0.05. Values in brackets: ± standard deviation. Treatments explained in Figure 5.1.

Table 5.6 Sorghum grain yield for different positions upslope of the barriers in 2000, 2001 and 2002 at Saria, Burkina Faso

	2000		2001		2002	
	Grain yield upslope barriers (kg ha^{-1})		Grain yield upslope barriers (kg ha^{-1})		Grain yield upslope barriers (kg ha^{-1})	
	1m	17m	1m	17m	1m	17m
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

Treatments with the same letter are not statistically different at P= 0.05. Values in brackets: ± standard deviation. Treatments explained in Figure 5.1.

5.4 Conclusions

The semi-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 semi-permeable barriers resulted in a substantial increase of 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 properly to alleviate shading and other effects of competition on crops near to the strips. In the Sahel, the use of animal manure in smallholder cereal-based farming systems is sometimes limited by its availability, but the additional crop residues produced with these combined practices allows the production of the required quantity of organic amendment. However, given the difficulty of managing crop residues by the smallholders, the wide adoption of such practices would be more 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 of great interest to establish the most sustainable options under semi-arid conditions.

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Andropogon gayanus grass strip at early stage of the rainy season, Saria, Burkina Faso

Sorghum crop beside a grass strip, Saria, Burkina Faso

Andropogon gayanus grass strip and sorghum crop at maturing stage, Saria, Burkina Faso

Andropogon gayanus grass strip after sorghum harvest, Saria, Burkina Faso

Andropogon gayanus grass strip during the dry season, Kirsi, Burkina Faso

Chapter 6

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

Zougmoré, R., Mando, A., Stroosnijder, L., 2003. Effect of soil and water conservation and nutrient management on soil-plant water balance in semi-arid Burkina Faso. *Agricultural Water Management, accepted.*

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 mineral treatments. 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 fertilizers could improve the 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

6.1 Introduction

In Sahelian countries where land and vegetation are seriously degrading, there is an urgent need to develop sound technologies for resource management that optimize 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 Bare, 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 fertilizer 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.

6.2 Materials and methods

6.2.1 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). 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 6.1). 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 to 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.*

Table 6.1 Physical characteristics of the experimental plots at Saria agricultural station, Burkina Faso.

	Clay (<2µm)	Silt (2-50µm)	Sand (50-2000µm)	Gravel (>2mm)	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.	n.s.	n.s.	s	n.s.	n.s.

Where there are significant differences, treatments with the same letter are not statistically different at p= 0.05; **s**: significant at the 0.05 level of probability; n.s.: not significant; UAW: useful available water. 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.

6.2.2. Experimental design

The trial started in 2000 and consisted of a randomized Fisher block design with nine treatments in two replications (Figure 5.1); Treatments were as follows: 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 and T_0: no SWC measures, no nitrogen supply

In 2001, T_{GSM} and T_{SRM} were replaced by respectively T_C (compost application with no 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., 3 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 stabilize 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 per m^2. Oxen were used to plough to 15-cm depth, and to 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.

6.2.3 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 by 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[1]) that

[1] Eijkelkamp, Giesbeek, The Netherlands

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 by 2 m were delimited, to measure sorghum yield. These subplots were located in pairs at the following distances (in 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 August 6 and October 18 at depths of 0–10 cm, 10–20 cm, 20–30 cm, 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[2]) at depths of 0–20 cm, 20–40 cm, 40–60 cm 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 seven days from July to November, three readings were made per position.

6.2.4 Data analysis

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

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

where P is precipitation, I is irrigation, ET is evapotranspiration, D is drainage below the root zone, R is runoff and ΔS is 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), equation (1) could be simplified as:

$$Inf - \Delta S = ET + D, \text{ where Inf is infiltration.} \qquad (2)$$

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 (Inf - ΔS) over the terms ET and D we used the following reasoning, based on the magnitude of (Inf - ΔS). Two cases may occur (Mando, 1997):

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

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

[2] Eijkelkamp, Giesbeek, The Netherlands

where PET is 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 (Inf - ΔS) < 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.).

Therefore, in 2000, P and R were measured and ET, D and ΔS were derived from calculations. All variables are expressed in mm. 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 measured and simulated data for year 2001 also showed good correlations for ET, soil water storage and soil drainage below 80-cm depth (Figure 6.1).

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:

$$ETc = k_c \times PET \qquad (5)$$

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 ET:ETc > 0.75. Water deficiency is moderate if 0.3 < ET:ETc < 0.75, and very severe if 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 $p < 0.05$.

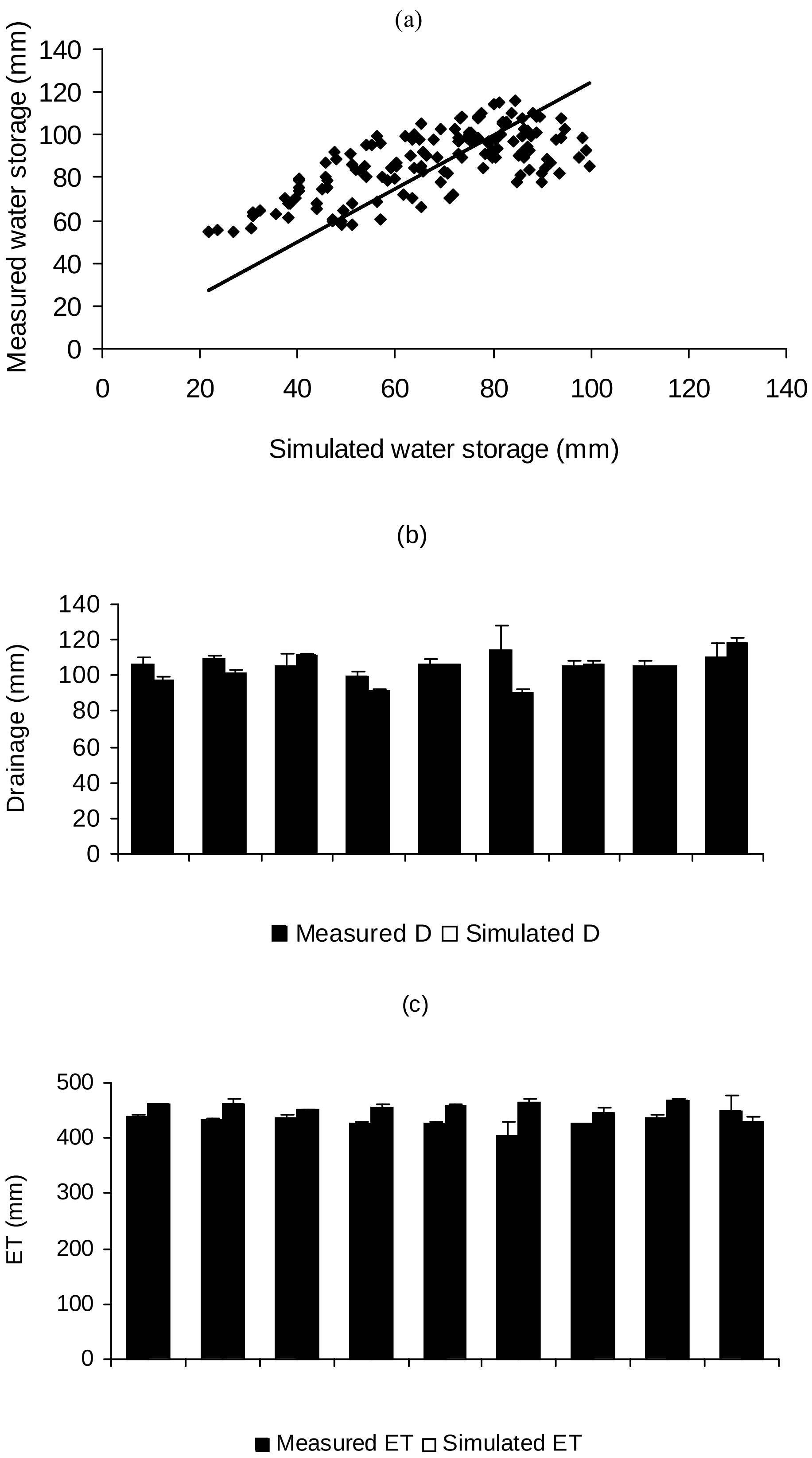


Figure 6.1 Comparison between measured and simulated data in 2001 at Saria, Burkina Faso; (a) soil water storage at 0–80-cm depth, (b) cumulative soil drainage below 80-cm depth, (c) cumulative ET.

6.3 Results

6.3.1 Rainfall characteristics

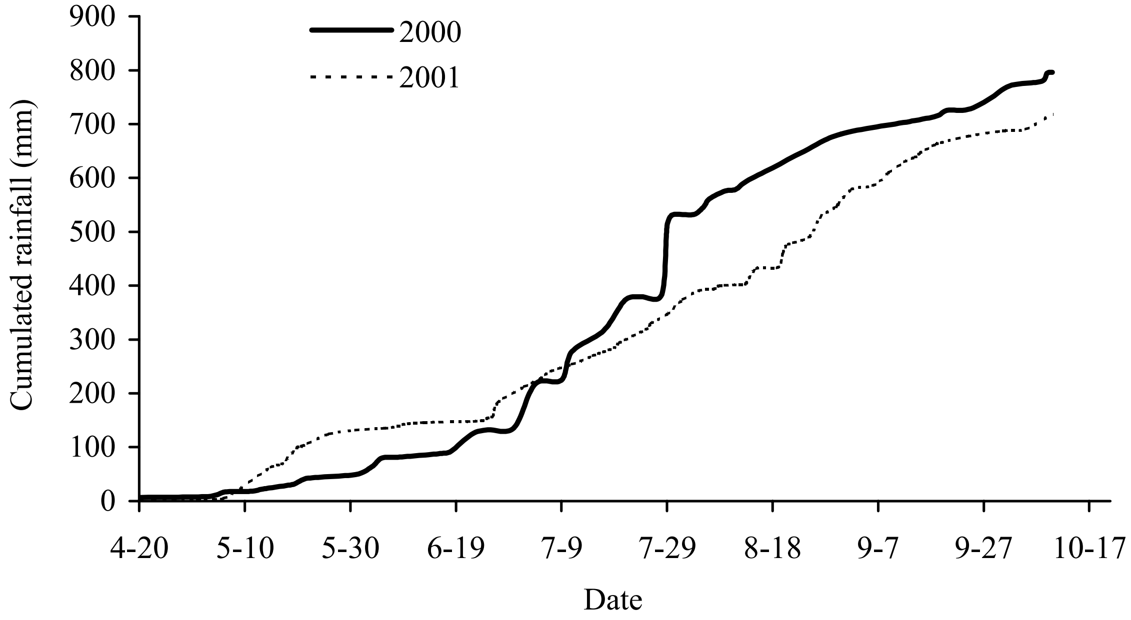
The rainfall was 796 mm in 2000 and 719 mm in 2001 (Figure 6.2a). Rainfall for year 2001 was below the average annual rainfall in the region (800 mm). Table 6.2 shows the rainfall in different size classes. In 2000, there were 43 rain events, 4 of which were exceptional (53 mm, 56, 81 and 127 mm) and 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}. Figure 6.2b shows the rainfall characteristics per 10-day period for the two 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.

Table 6.2 Rainfall distribution over size classes at Saria in 2000 and 2001

	2000 Rainfall: 796 mm			2001 Rainfall: 719 mm		
Class of rainfall	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	-

I_{30}: highest rainfall intensity during the 30 most rainy minutes

(a)



(b)

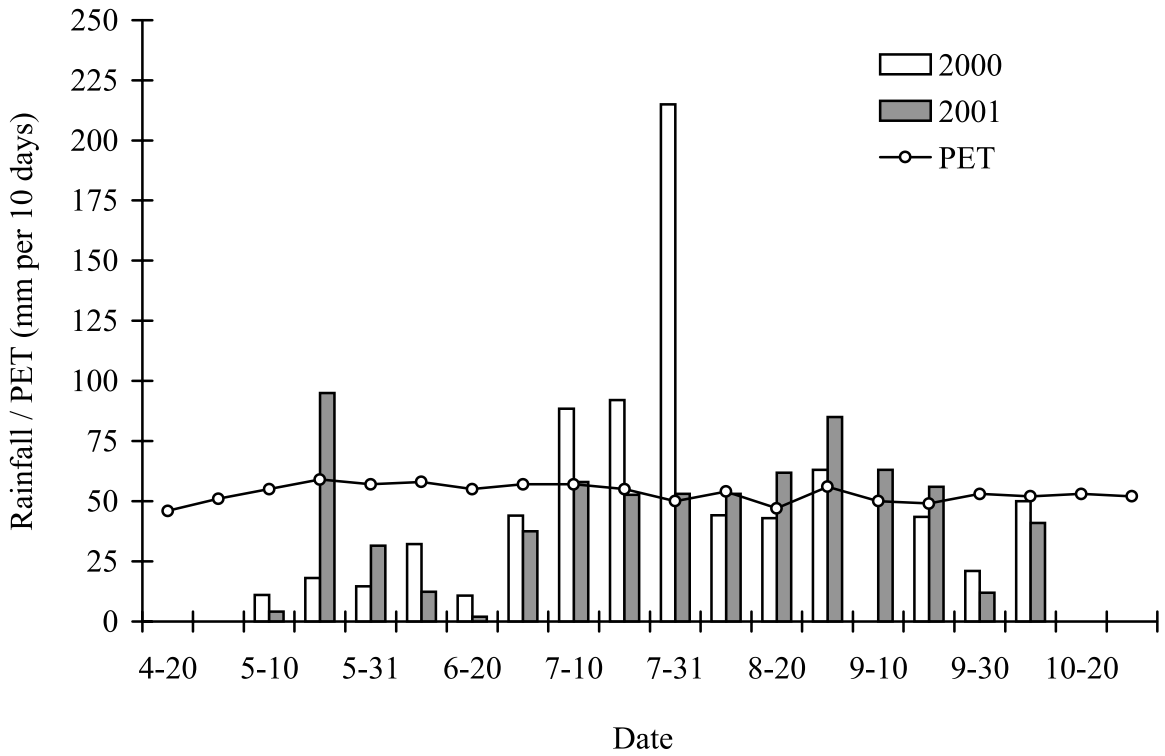


Figure 6.2 Rainfall and PET per 10 days for the 2000 and 2001 rainy seasons at Saria, Burkina Faso; (a) Cumulative rainfall, (b) Potential evapotranspiration and rainfall per 10-day period.

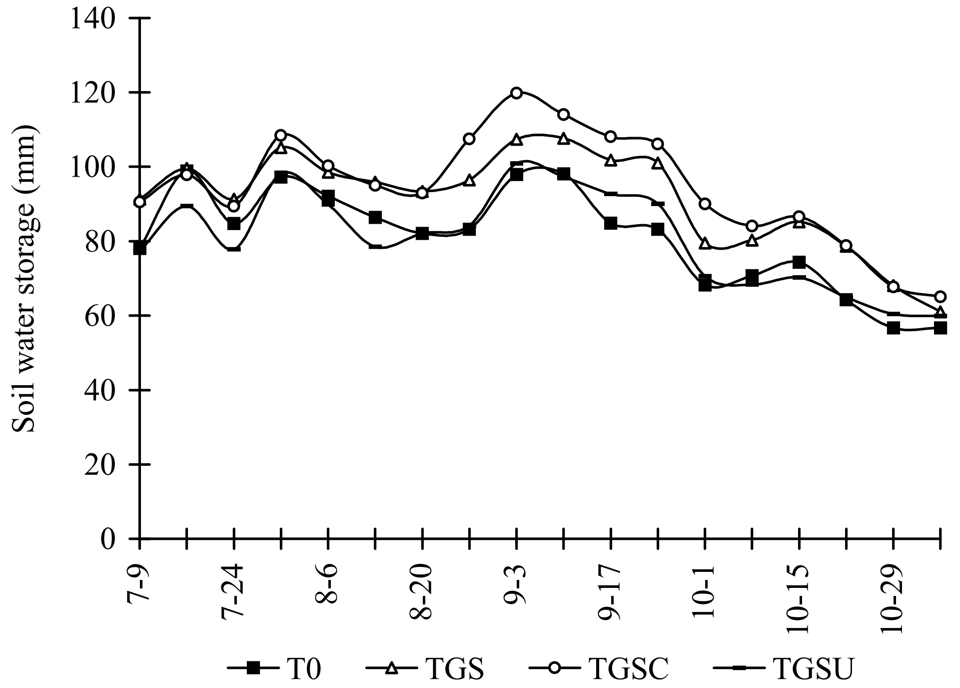
6.3.2 Soil water storage

In 2001, the soil water storage (S) over the 0–80 cm layer was less in the control treatment than in other treatments (Figure 6.3a–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 (Figure 6.3a). The compost effect was also observed when comparing T_C with T_U. Among treatments with compost, the decreasing S order was T_{GSC}, T_C, and T_{SRC} (Figure 6.3c). S was greater in T_{SRU} than in T_{SR}, indicating the positive effect of mineral input (Figure 6.3b). More water was stored in T_{SRU} than in T_{GSU} and T_U (Figure 6.3d).

Figure 6.4 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, except for the treatment T_{SRM} (stone rows + manure) that had very little useful available water (Table 6.1). The highest S was observed in treatments T_{SRC} (stone rows + compost) and T_{GSU} (Grass strips + mineral nitrogen), followed by 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). Overall in 2000, S was lower in organic treatments (T_{GSC}, T_{GSM}, T_{SRM}) than in treatments with mineral nitrogen (T_{SRU}, T_{GSU}). 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 two 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, application of compost induced a better S than urea 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.

(a)



(b)

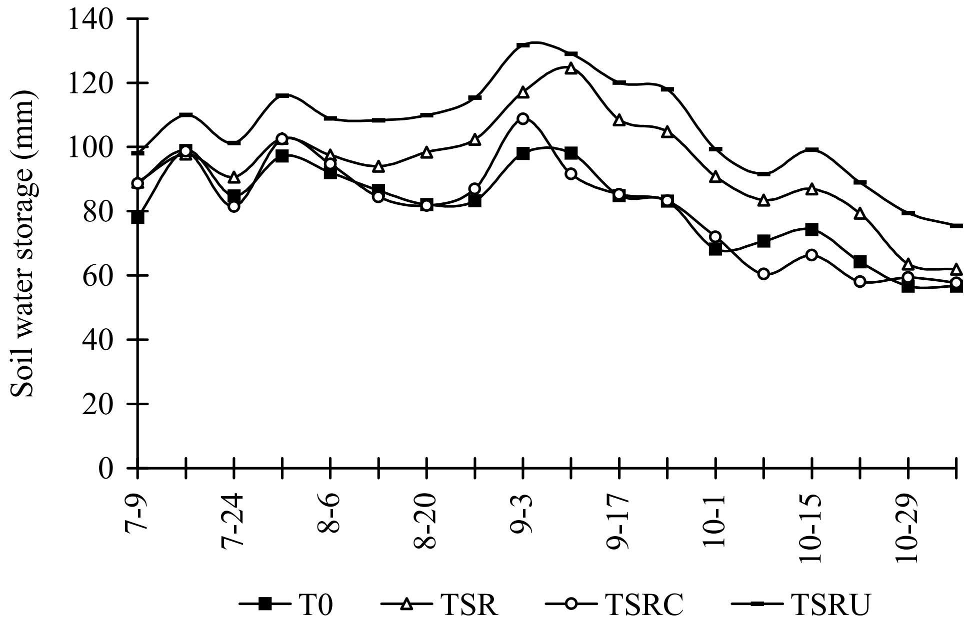
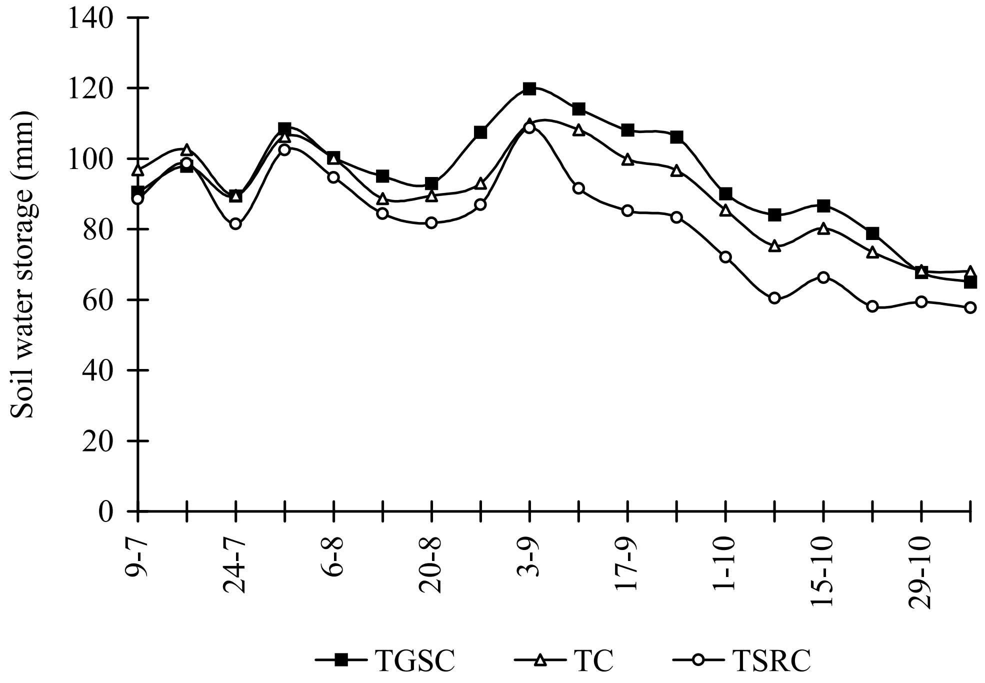


Figure 6.3 Dynamics of measured soil water storage during the sorghum cropping period in 2001 at Saria, Burkina Faso; (a) grass strip treatments, (b) stone row treatments.

(c)



(d)

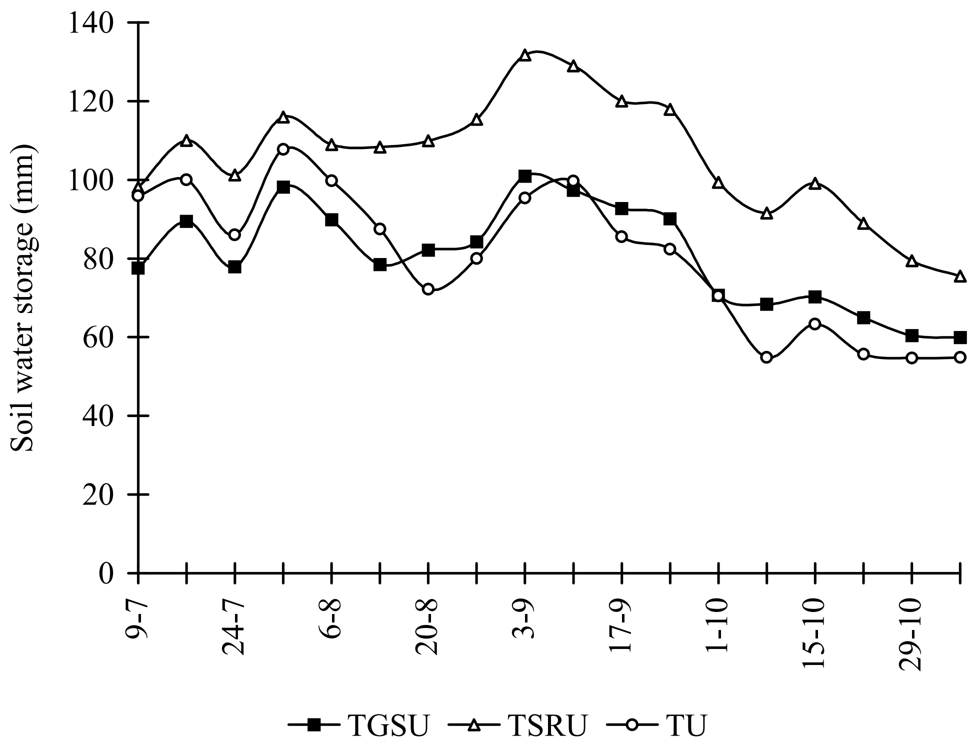


Figure 6.3 Dynamics of measured soil water storage during the sorghum cropping period in 2001 at Saria, Burkina Faso; (c) organic treatments, (d) mineral input treatments.

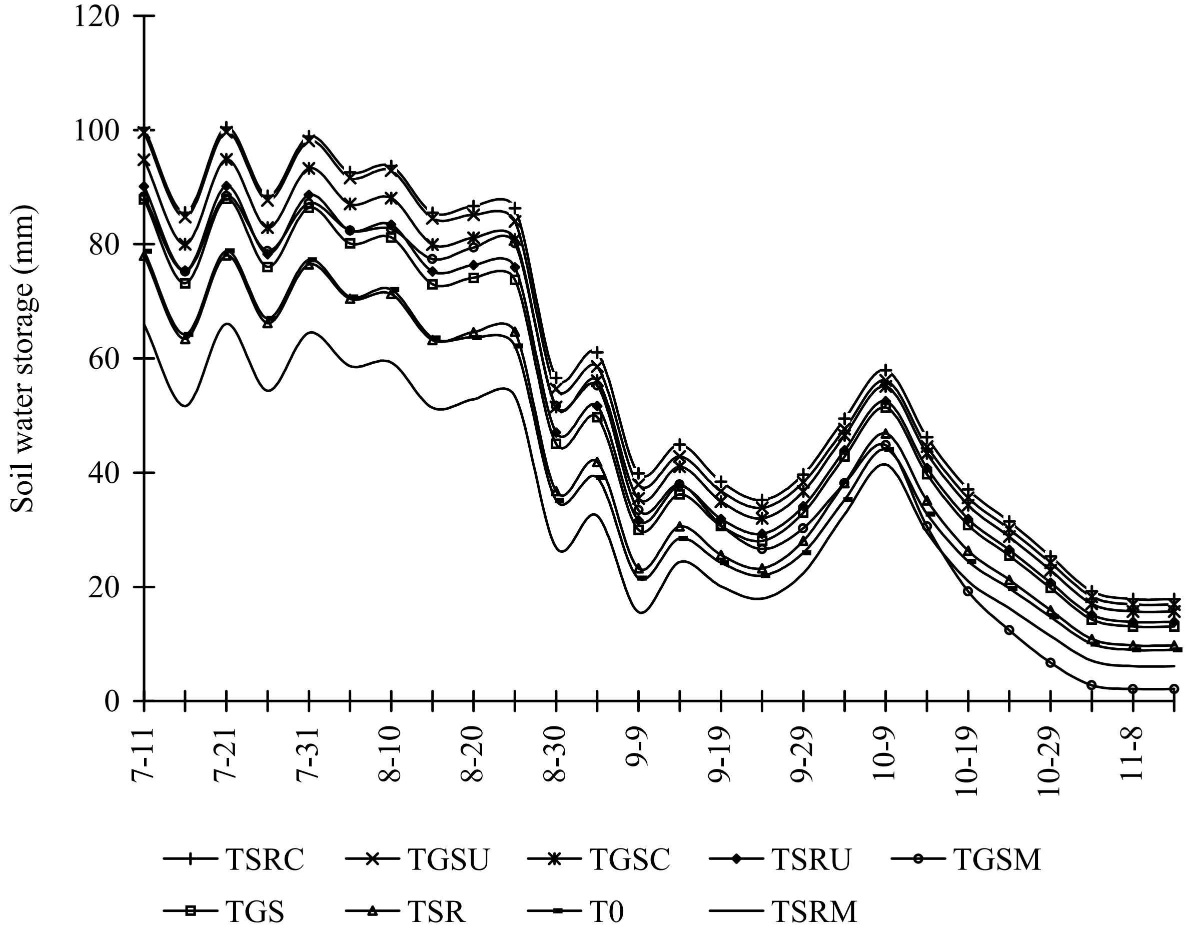


Figure 6.4 Dynamics of soil water storage during the sorghum cropping period in 2000 (simulated data) at Saria, Burkina Faso.

6.3.3 ET and soil drainage

In 2001, the ET values were not significantly different between treatments (Table 6.3). However, the highest ET was for the T_U plot that had been the T_{SRM} plot in 2000. The mean 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 6.3). 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 (Figure 6.2b), the mean values of ET were higher than those recorded in 2000. In both years, the control plots recorded the least soil drainage.

Table 6.3 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.

	Cumulative ET (mm)		Cumulative D below 80 cm depth (mm)		Annual runoff rate (% ΣP)	
	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
	s	n.s.	s	n.s.	s	s

Where there are significant differences, treatments with the same letter are not statistically different at p= 0.05; ΣP: cumulative rainfall; s: significant at the 0.05 level of probability; n.s.: not significant. Treatments explained in Table 6.1.

6.3.4 Plant water demand

In 2001, crop water demand was satisfactory (ET:ETc > 0.75) during the vegetation and maturation stages of sorghum (Figure 6.5a). 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 treatments and T_{GSU}-T_{GSC}-T_{GS} (Figure

6.5a) 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 (Figure 6.5b). 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.

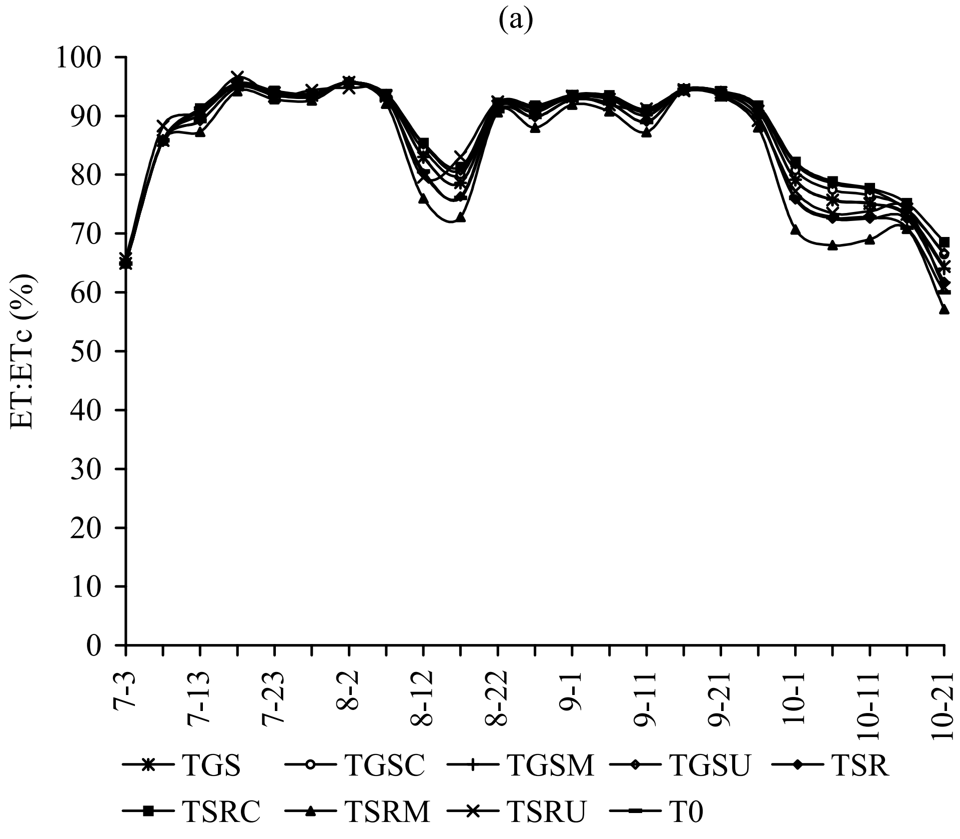


Figure 6.5a Plant water demand satisfaction rate (ET:ETc ratio) for the sorghum crop in year 2001 at Saria, Burkina Faso.

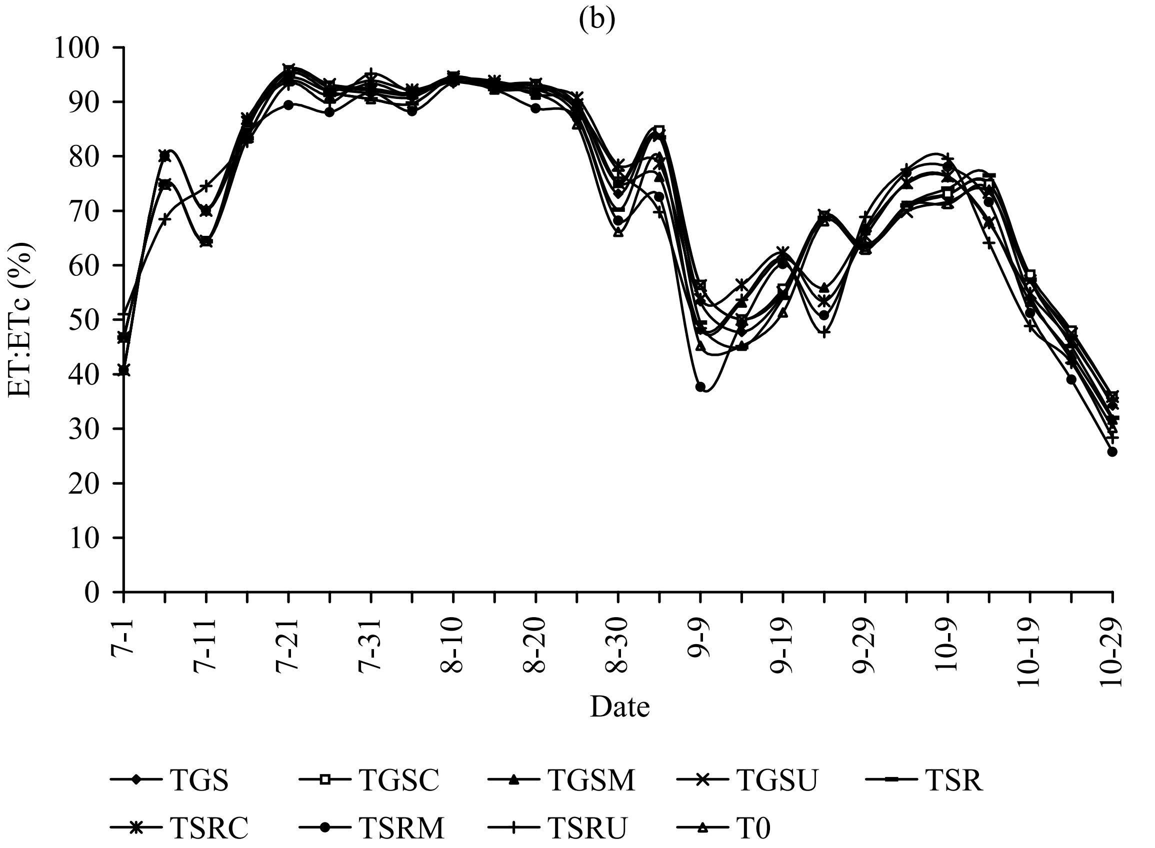


Figure 6.5b Plant water demand satisfaction rate (ET:ETc ratio) for the sorghum crop in year 2001 at Saria, Burkina Faso.

6.4 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 characterized 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 6.4), the soil water consumption by the sorghum crop was higher than in non-organic plots (Table 6.3). According to Vetterlein and Marschner (1994), an important relationship between nutrient supply and soil water balance is the increase in plant shoot sizes 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 that in 2001 (Table 6.3) because of the exceptional rain 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 6.3) 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 (Pieri, 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 6.3). 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 one 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 Figure 6.5, 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 needs (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 fertilizer was supplied. This is confirmed by the sorghum performance and IUE during 2000 and 2001 (Table 6.4), 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 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 fertilizers, there is probably greater loss of nutrients through runoff or drainage than from plots given organic input.

Table 6.4 Sorghum performance and infiltration water use efficiency (IUE) for 2000 and 2001 at Saria, Burkina Faso.

	Grain yield ($kg\ m^{-2}$)		Total biomass ($kg\ m^{-2}$)		IUE ($kg\ m^{-3}$)	
	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 c	0.62 ab	0.62 ab	0.85 abc	0.91 ab
T_{SRM}/T_U	0.17 b	0.21 b	0.61 ab	0.62 ab	0.84 abc	0.92 ab
T_{GSU}	0.09 cd	0.15 c	0.43 bc	0.54 ab	0.61 bcd	0.84 ab
T_0	0.08 cd	0.11 d	0.41 bc	0.43 ab	0.61 bcd	0.68 ab
T_{SR}	0.07 d	0.12 d	0.37 bc	0.46 ab	0.50 cd	0.66 ab
T_{GS}	0.06 d	0.09 d	0.33 c	0.32 b	0.46 d	0.48 b

Treatments with the same letter are not statistically different at p= 0.05; IUE: Infiltration water use efficiency= Annual total biomass (Straw + panicle)/Annual infiltrated water. Treatments explained in Table 6.1.

6.5 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. 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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Chapter 7

Effect of integrated water and nutrient management on soil erosion and nutrient loss in semi-arid Burkina Faso

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Abstract

Soil erosion by water is one of the main factors accounting for negative nutrient balances in most agriculture systems in West Africa. A field experiment was carried out from 2001 to 2002 at Saria agricultural research station to assess the effects of soil and water conservation barriers (stone rows or grass strips of *Andropogon gayanus* Kunth cv. *Bisquamulatus* (Hochst.) Hack.), the sole use of organic (compost) or mineral (urea) nitrogen and the combined use of soil and water conservation barriers and organic (compost) or mineral (urea) nitrogen on soil fertility erosion. The trial was on a Ferric Lixisol, 1.5% slope and consisted in two replications of 9 treatments in which the runoff barriers were put along contours. Carbon and nutrients losses through runoff and sediments were monitored during two consecutives rainy seasons. Soil losses from plots with stone rows and grass strips were respectively 30% and 42% of the losses from control plots. The application of compost leads to the reduction of soil loss by 52% in plots without barriers and by 79% when applied in plots with stone rows as compared to the losses in control plots. The application of urea in plots with and without soil conservation barriers also resulted into significant decrease in soil loss but this decrease was 25% less important than the loss in plots with compost. Eroded sediments were richer than the parent soil for organic C (3─7 times), N (4─10 times), P (2─5 times) and K (1─3 times). 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 through runoff and therefore could play a major role in sustaining crop production in Sahelian smallholder farming systems.

Keywords: Stone row; Grass strip; Compost; Urea; Soil fertility erosion; Enrichment ratio

7.1 Introduction

Soil degradation is a major global issue because of its adverse impact on the sustainability of agricultural production (Lal, 1998). In the semi-arid zone of West Africa, soil degradation due to 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 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). Pierce and Lal (1994) indicated that low levels of N, P, K, and low cation exchange capacity are among the most important chemical and nutritional constraints accentuated by soil erosion; which means that in the long term, fertility erosion affects considerably soil productivity mainly in semi-arid West Africa, where major soils, due to their low soil organic matter content are highly sensitive to erosion by water (Roose, 1981).

To mitigate the food shortage problem that is very acute in the region, effort should include tough measures to control erosion-induced loss of soil nutrients. Indeed, Stoorvogel and Smaling (1990) indicated that in 2000, under low input cereal cropping system, 10 kg N ha^{-1}, 2 kg P ha^{-1}, and 6 kg K ha^{-1} were lost through erosion in Burkina Faso. 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 erosion (Sanchez et al., 1997; Quansah, 1999).

Studies by Zougmoré et al. (2003) in this region indicated that semi-permeable soil and water conservation (SWC) barriers such as stone rows and grass strips of *Andropogon gayanus* combined with compost or animal manure application induced significant reduction of runoff. The present study assessed the effect of combined soil and water conservation barriers and organic or mineral sources of nitrogen on soil fertility erosion with emphasis on organic carbon (OC), N, P and K losses.

7.2 Material and methods

7.2.1 Site description and experimental design

The experimental field was 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). Over the last 30 years the average annual rainfall was 800 mm. Rainfall is mono-modal, lasts 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 may reach 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. The soil type was Ferric Lixisol (FAO-UNESCO, 1994) with an average slope of 1.5% and a hardpan at a depth of 70 cm. 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% at 10 cm depth. Average bulk density is 1.7 g cm^{-3} at 0-15 cm layer. There are very low contents of organic C (< 6 g kg^{-1}), N (< 0.5 g kg^{-1}), exchangeable K (< 46 mg kg^{-1}) and available P (< 15 mg kg^{-1}) in the 0-30 cm depth. Analyses revealed a poor CEC (2–4 cmol kg^{-1}) and a base saturation ratio that falls from 70% in the topsoil to 30–50% at 80 cm depth, in line with the pH (H_2O), which decreased from 5.3 to 4.9.

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

The trial combined two linear SWC measures with three types of nitrogen input. The experimental design was a randomized Fisher block with nine treatments and two replications. Treatments were: 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_{SRU}: stone rows + urea-N, T_{GSU}: grass strips + urea-N, T_0: no SWC measures, no N input, T_C: compost-N, no SWC measures and T_U: Urea-N, no SWC measures.

Each plot (100 m long, 25 m wide) was isolated from the surrounding area by an earth bund 0.6 m high. Due to their great dimensions that make collection of runoff from the whole 2500 m^2 plots difficult, one twenty fifth part of total runoff and sediments in each plot was collected using a subplot of 100 m long by 1 m large. A metal sheet was used to direct runoff in a cement-lined pit of 6 m^3. The pits were dug at the downhill part of each plot and designed to cope with an exceptional 120 mm rain event. They were covered with metal sheet to avoid incursion of rainwater. Each pit was equipped with a water level recorder (TD-diver, Eijkelkamp, Giesbeek, The Netherlands) that recorded the overland flow hydrograph. These runoff collection devices were set in the 9 plots of the first replication. Rainfall intensity was recorded using an automatic rain gauge (tipping bucket). Stone rows and grass strips had been installed in 1999, spaced 33 m apart (i.e., 3 barriers per plot) along the contours as recommended by previous studies (Zougmoré et al., 2000a; Zougmoré et al., 2000b). Each stone row consisted of two rows of stones placed in a furrow. The upslope row of large stones was stabilized by the down part row of small stones. Each stone row was about 0.2–0.3 m high. 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 in rows perpendicular to the slope. The plots were completely tilled with hand hoes twice a year for weed control. Ox-drawn ploughs at 15-cm depth were done on 29.06.2001 and 04.07.2002 to incorporate compost and urea. Compost and urea were applied each year at a dose of 50 kg N ha^{-1}. The amount of compost derived from this N-dose corresponds to about 5 to 7 t ha^{-1} of compost (Table 7.1), thus consistent with the recommended minimum application of organic amendment in Burkina (Sédogo, 1981). Urea was applied one half during first hand hoeing (21 days after planting) and one half during 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 as a factor in the experiment.

Table 7.1 Chemical characteristics of applied compost for 2001 and 2002 rainy seasons at Saria, Burkina Faso

	Organic C (g kg^{-1})	N (g kg^{-1})	P (mg kg^{-1})	K (mg kg^{-1})	C:N ratio	Applied quantity (kg ha^{-1})
In 2001	188	12.0	2594	21878	15.8	4800
In 2002	149	8.9	2408	16254	16.7	5600

7.2.2 Data collection

When rainfall was high enough to generate overland flow, runoff was quantified by pumping out and measuring the water collected in each runoff-pit but also by recording runoff volume with the TD-divers placed in the 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 collected coarse sediment. For each treatment, a fraction (1/SF) of the coarse sediment was added to the dried fine sediment per rain event, thoroughly mixed and sampled for N, P and K analysis. Runoff water was analyzed for dissolved NO_3^--N and NH_4^+-N contents. Soil core samples were taken each year at depths 0–15 cm and 15–30 cm in triplicate at the onset of the rainy season from each treatment to determine content of OC (Walkley and Black method), N, P (automatic colorimetric method), and K (flame photometric method).

7.2.3 Data analysis

Soil loss was analyzed from 9 erosive rain events for the 2001 rainy season and 16 such events for the 2002 rainy season. Cumulative soil loss was compared per treatment to assess the effect of treatment on soil erosion during the two study years. Enrichment ratio (ER) was calculated for each plot to give the magnitude of fertility erosion. It is given by the concentration of nutrients in the eroded sediment divided by the concentration of nutrients in soil from which eroded sediment originated.

Data were statistically analyzed using Genstat (General Statistics) and STATITCF packages (Gouet and Philippeau, 1986), including ANOVA and Newman-Keuls test for significant differences between treatments at $p < 0.05$.

7.3 Results

7.3.1 Soil loss in 2001 and 2002

All treatments reduced soil loss compared to the control treatment, which showed the average highest soil loss of 236 kg ha^{-1} in 2001 and 32711 kg ha^{-1} in 2002 (Figure 7.1). 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 (Figure 7.1a, 7.1b). 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}.

In 2002, it was clearly observed that treatments with compost-N application reduced soil loss more than treatments with urea-N and without fertilization (Figure 7.1b). Indeed, soil loss reduction compared to the control reached 98% for T_{SRC} and 94% for treatments T_{GSC} while the reduction rate was only 70% for T_{GSU}, 73% for T_U and 89% for T_{SRU}. On average, stone rows reduced soil loss 19% more than grass strips did when the two SWC measures are combined with urea but only 4% when combined with compost.

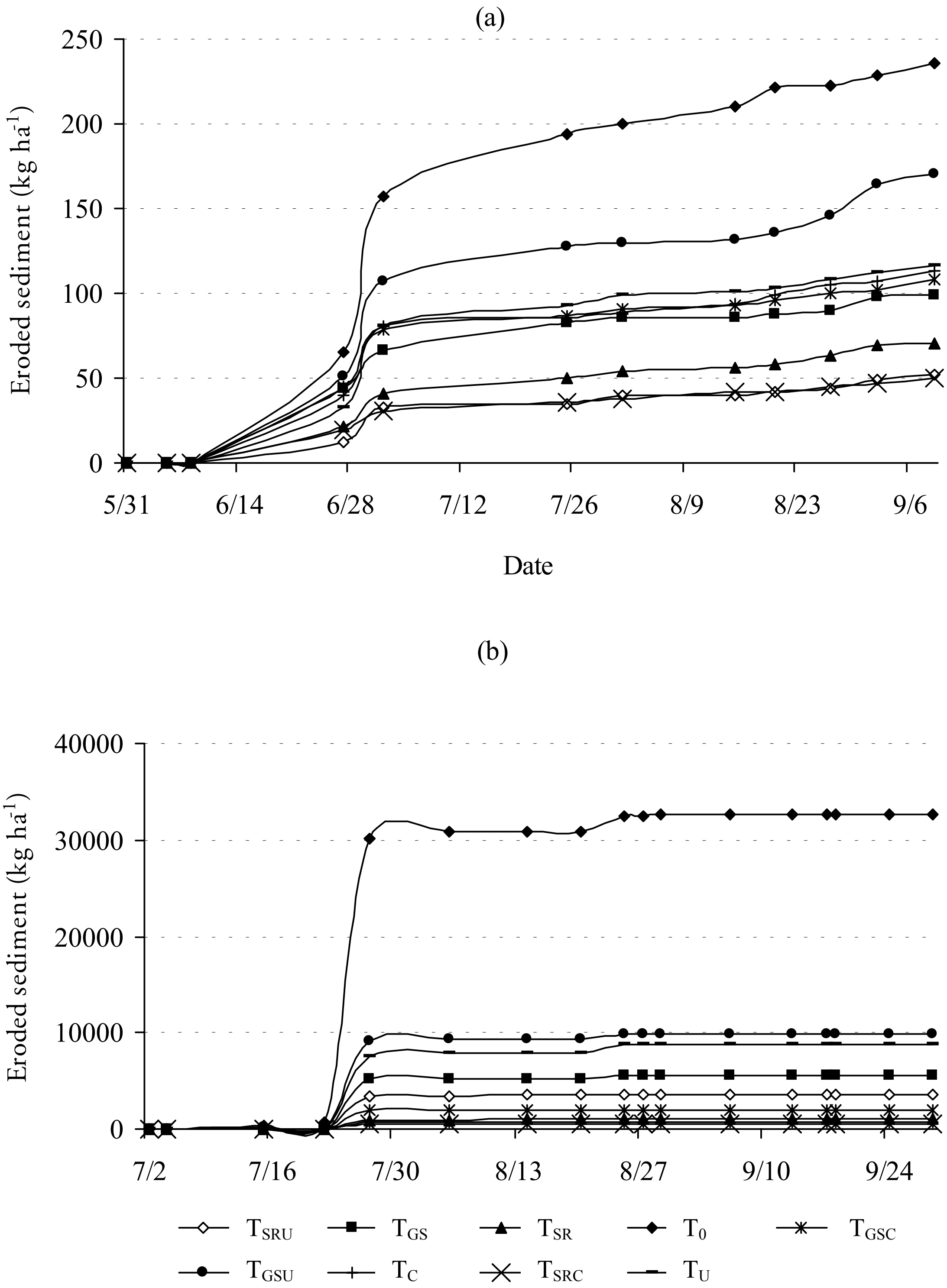

Figure 7.1 Cumulative soil loss as affected by SWC measures and nutrient inputs at Saria, Burkina Faso; (a) 2001, (b) 2002.

T_0: no SWC measures, no N input; T_C: compost-N, no SWC measures; T_U: Urea-N, no SWC measures; T_{GS}: grass strips, no N input; T_{GSC}: grass strips + compost-N; T_{GSU}: grass strips + urea-N; T_{SR}: stone rows, no N input; T_{SRC}: stone rows + compost-N; T_{SRU}: stone rows + urea-N.

In 2002, soil loss in the control treatment was very high and represented 3 to 30 times that of the other treatments. An exceptional heavy rain event (rainfall: 65 mm, intensity I_{30}: 82 mm h^{-1}) occurred on 27 July 2002 and accounted for 80% of annual soil loss. This rainfall event occurred at the onset of the rainy season after the soil was ploughed and when the crop was not fully developed to provide a good coverage of the soil.

7.3.2 Organic C, N, P and K contents in sediment and runoff

Organic C, N, and K contents in eroded sediments were significantly different among treatments (Table 7.2). In 2001, mean annual OC and N contents in treatments T_{SRC} and T_{SRU} were higher than in the other treatments. Sediment OC and K contents in plots with stone row alone (T_{SR}) and the control treatment (T_0) were also high in this year. In 2002, treatments T_U and T_{SRU} showed the highest OC contents of sediment while the greatest N contents were observed for sediments from treatments with compost (T_{GSC}, T_C and T_{SRC}). Average contents of P were not statistically different among treatments. Mean P contents of sediments per treatment ranged from 318─412 mg kg^{-1} 2001 and from 516─709 mg kg^{-1} in 2002.

Eroded sediments from heavy rainfall events were less rich in N, P and OC than sediments from less intensive and small rainfall events as shown on Figure 7.2.

OC, N, P and K enrichment ratios (ER) for all plots were greater than 1, indicating that eroded sediments were richer than the parent soil (Table 7.3). Indeed, concentrations of OC in eroded sediments were 3─7 times greater than in the 0─10 cm layer of the parent soil. Results of the two years showed significant differences between OC enrichment ratios of treatments and the control, which showed the highest ratio. The least OC enrichment ratios were observed in treatment T_{GSC} in 2001 and in treatments T_{GSC}, T_{SRC}, and T_C in 2002. Enrichment ratios for N, P and K didn't show significant differences between treatments. N concentrations in eroded sediments were 4─10 times that of N content in the parent soil. P enrichment ratios ranged from 2 to 4.7 while this was between 1 and 3 for K.

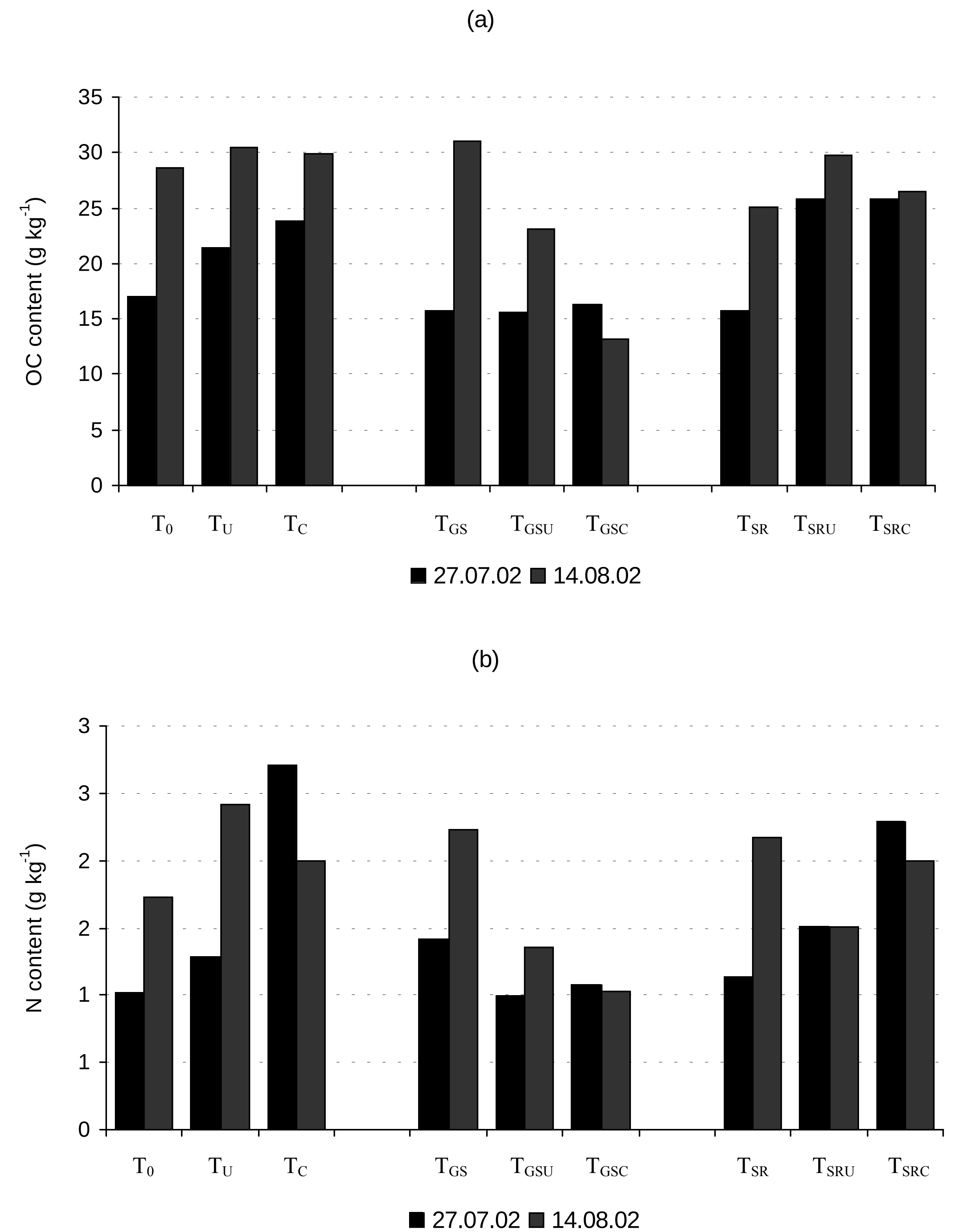

Figure 7.2 Effect of treatments on organic C and N contents in eroded sediments for two different rainfalls at Saria (Heavy rain event of 27.07.2002: 65 mm, I_{30}: 82 mm h^{-1}, highest soil loss: 29 t ha^{-1}; Small rain event of 14.08.2002: 33 mm, I_{30}: 43 mm h^{-1}, highest soil loss: 22 kg ha^{-1}); (a) Organic C content, (b) N content. Treatments explained in Figure 7.1.

Table 7.2 Effect of treatments on organic C, N, P and K contents in eroded sediments during 2001 and 2002 at Saria, Burkina Faso

	OC ($g\ kg^{-1}$)		N ($g\ kg^{-1}$)		P ($mg\ kg^{-1}$)		K ($mg\ kg^{-1}$)	
	2001	2002	2001	2002	2001	2002	2001	2002
T_0	24 a	25 ab	1.67 ab	1.93 d	410 a	604 a	1058 a	424 bc
T_C	14 b	24 ab	1.02 d	2.53 b	332 a	638 a	536 b	497 bc
T_U	19 ab	29 a	1.43 bc	2.34 bc	364 a	709 a	958 ab	845 a
T_{GS}	17 ab	27 a	1.39 bc	2.37 b	412 a	705 a	644 ab	477 bc
T_{GSC}	17 ab	20 b	1.22 c	3.73 a	318 a	684 a	489 b	408 c
T_{GSU}	18 ab	21 b	1.41 bc	1.49 d	342 a	516 a	714 ab	342 c
T_{SR}	19 ab	26 a	1.72 ab	2.39 b	347 a	644 a	668 ab	495 bc
T_{SRC}	25 a	26 a	2.01 a	2.42 b	401 a	653 a	1001 ab	727 ab
T_{SRU}	24 a	27 a	2.14 a	2.32 bc	398 a	567 a	809 ab	561 bc
Probability	0.010	0.002	0.002	0.007	0.289	0.299	0.009	0.017
SE	7.1	4.7	0.6	0.6	103	173	376	131

Treatments with the same letter are not statistically different at p= 0.05; SE: standard error. Treatments key in fig. 7.1.

Table 7.3 Effect of treatments on organic C and N, P, K enrichment ratios for years 2001 and 2002 at Saria, Burkina Faso

	C		N		P		K	
	2001	2002	2001	2002	2001	2002	2001	2002
T_0	6.74 a	5.31 a	8.10 a	7.38 a	4.68 a	2.47 a	1.74 a	2.25 ab
T_C	4.48 ab	3.65 b	4.63 a	4.79 a	3.70 a	2.37 a	0.83 a	1.87 ab
T_U	5.48 ab	5.07 ab	6.80 a	4.53 a	3.89 a	2.47 a	0.99 a	1.68 ab
T_{GS}	3.76 ab	5.30 a	5.41 a	7.58 a	3.70 a	3.29 a	1.12 a	2.02 ab
T_{GSC}	3.29 b	3.08 b	4.61 a	8.15 a	3.24 a	2.63 a	0.81 a	1.66 ab
T_{GSU}	3.30 b	4.35 ab	6.91 a	4.41 a	3.75 a	2.11 a	1.34 a	1.91 ab
T_{SR}	4.65 ab	4.75 ab	8.73 a	7.87 a	3.61 a	2.63 a	1.30 a	3.04 a
T_{SRC}	3.93 ab	3.54 b	6.63 a	4.15 a	3.75 a	2.28 a	1.14 a	1.06 b
T_{SRU}	5.11 ab	4.31 ab	9.60 a	4.63 a	4.32 a	2.66 a	1.97 a	2.29 ab
Probability	0.048	0.019	0.777	0.803	0.577	0.844	0.172	0.028
SE	0.6	0.59	2.4	1.9	0.4	0.4	0.4	0.3

Treatments with the same letter are not statistically different at p= 0.05; SE: standard error; Treatments key in Fig. 7.1.

Treatments average content of NO_3^--N in the runoff water were significantly different and ranged from 2 to 17 mg L^{-1} in 2001 and from 7 to 23 mg L^{-1} in 2002 (Table 7.4). For the two years, the highest NO_3^--N contents (23 mg L^{-1}) were observed on plots with stone rows barriers (T_{SRC}, T_{SRU}, T_{SR}) while treatments without barriers (T_U, T_C, T_0) showed the least contents (2 mg L^{-1}).

Table 7.4 Effect of treatments on NO_3^--N content and N loss in runoff water for 2001 and 2002 at Saria, Burkina Faso

	NO_3^--N (mg L^{-1})		NO_3^--N (kg ha^{-1})	
	2001	2002	2001	2002
T_0	6.2 bcd	10.3 cd	1.78 a	10.31 a
T_{GS}	6.5 bcd	13.2 c	0.91 ab	6.15 ab
T_{GSC}	4.0 cd	16.9 b	0.43 b	2.69 cd
T_{GSU}	4.6 cd	7.4 d	1.05 ab	3.16 bc
T_C	2.4 d	11.0 cd	0.46 b	1.48 d
T_{SR}	9.5 a	22.8 a	0.80 ab	6.48 ab
T_{SRC}	7.6 bc	20.9 ab	0.58 b	1.23 d
T_{SRU}	8.3 ab	12.0 c	0.84 ab	3.59 bc
T_U	2.5 d	12.4 c	0.39 b	6.28 ab
Probability	0.001	0.002	0.049	0.001
SE	1.57	2.67	0.03	0.04

Treatments with the same letter are not statistically different at p= 0.05; SE: standard error; Treatments explained in Figure 7.1.

7.3.3 Organic C and nutrients losses through runoff and sediment

Organic C and nutrient amounts in eroded sediments were significantly different among treatments (Table 7.5). Results for year 2002 did not take into account the exceptional rainfall event of 27.07.02, which was analyzed separately and results tabulated in Table 7.6. The highest losses of OC, N, P and K were observed in the control treatment followed by treatments T_U and T_{GSU}. Results of the two years showed that annual losses from eroded sediments reached 84 kg ha^{-1} for OC, 6.5 kg ha^{-1} for N, 2 kg ha^{-1} for P and 1.5 kg ha^{-1} for K in the control plots. T_{SRC} lost the least amount of nutrients. The amounts of lost OC and nutrients were significantly correlated to the soil losses (Figure 7.3).

Table 7.5 Effect of treatments on organic C and N, P, K losses in eroded sediment for years 2001 and 2002 at Saria

	OC ($kg\ ha^{-1}$)		N ($kg\ ha^{-1}$)		P ($g\ ha^{-1}$)		K ($g\ ha^{-1}$)	
	2001	2002	2001	2002	2001	2002	2001	2002
T_0	5.7 a	84.4 a	0.40 a	6.46 a	97 a	2026 a	250 a	1421 a
T_C	1.6 c	2.8 d	0.12 b	0.29 c	38 bc	74 d	61 abc	58 c
T_U	2.2 c	36.4 b	0.17 b	2.92 b	42 bc	884 b	111 ab	1055 b
T_{GS}	1.7 c	14.1 cd	0.14 b	1.24 c	41 bc	369 c	64 abc	250 c
T_{GSC}	1.8 c	1.0 d	0.13 b	0.26 c	34 bc	34 d	53 bc	20 c
T_{GSU}	3.1 b	19.2 c	0.24 b	1.37 c	59 b	476 c	122 ab	315 c
T_{SR}	1.3 c	3.1 d	0.12 b	0.29 c	25 bc	78 d	47 bc	60 c
T_{SRC}	1.2 c	0.8 d	0.10 b	0.07 c	20 c	19 d	50 bc	21 c
T_{SRU}	1.3 c	6.2 d	0.11 b	0.53 c	21 c	130 d	42 c	129 c
Probability	0.001	0.001	0.001	0.001	0.001	0.001	001	0.001
SE	0.83	4.61	0.07	0.07	15.28	57.7	28.91	21.79

Treatments with the same letter are not statistically different at p= 0.05; SE: standard error; Treatments explained in Figure 7.1.

The amounts of N lost through runoff water in the form of NO_3^- were significantly different among treatments (Table 7.4). In 2001, treatments $T_{U,}$ T_{SRC}, T_{GSC} and T_C showed the least losses of NO_3^-N followed by stone rows treatments (T_{SR} and T_{SRU}). The least amounts of N lost in 2002 were observed in composted treatments (T_{SRC}, $T_{C,}$ and T_{GSC}), followed by treatments with urea application (T_{SRU} and T_{GSU}). The control treatment showed the highest losses of NO_3^--N during the two rainy seasons, which reached 10.3 kg ha^{-1} in 2002. N losses through runoff were 2 to 5 times greater than N losses through eroded sediments (Table 7.4).

When considering the exceptional heavy rainfall of 27.07.2002, one can observe the huge soil and nutrient losses in only one rainfall event (Table 7.6) despite the low concentrations of OC and nutrients in its sediment (Figure 7.2). This sole event has caused greater soil and nutrient losses than the loss induced by all the others rainfall events in this year. The highest nutrient losses reached 500 kg ha^{-1} for OC, 30 kg ha^{-1} for N, 13 kg ha^{-1} for P and 7 kg ha^{-1} for K in the control treatment. The performance of the treatments maintained the same trends as observed with the small rainfall events.

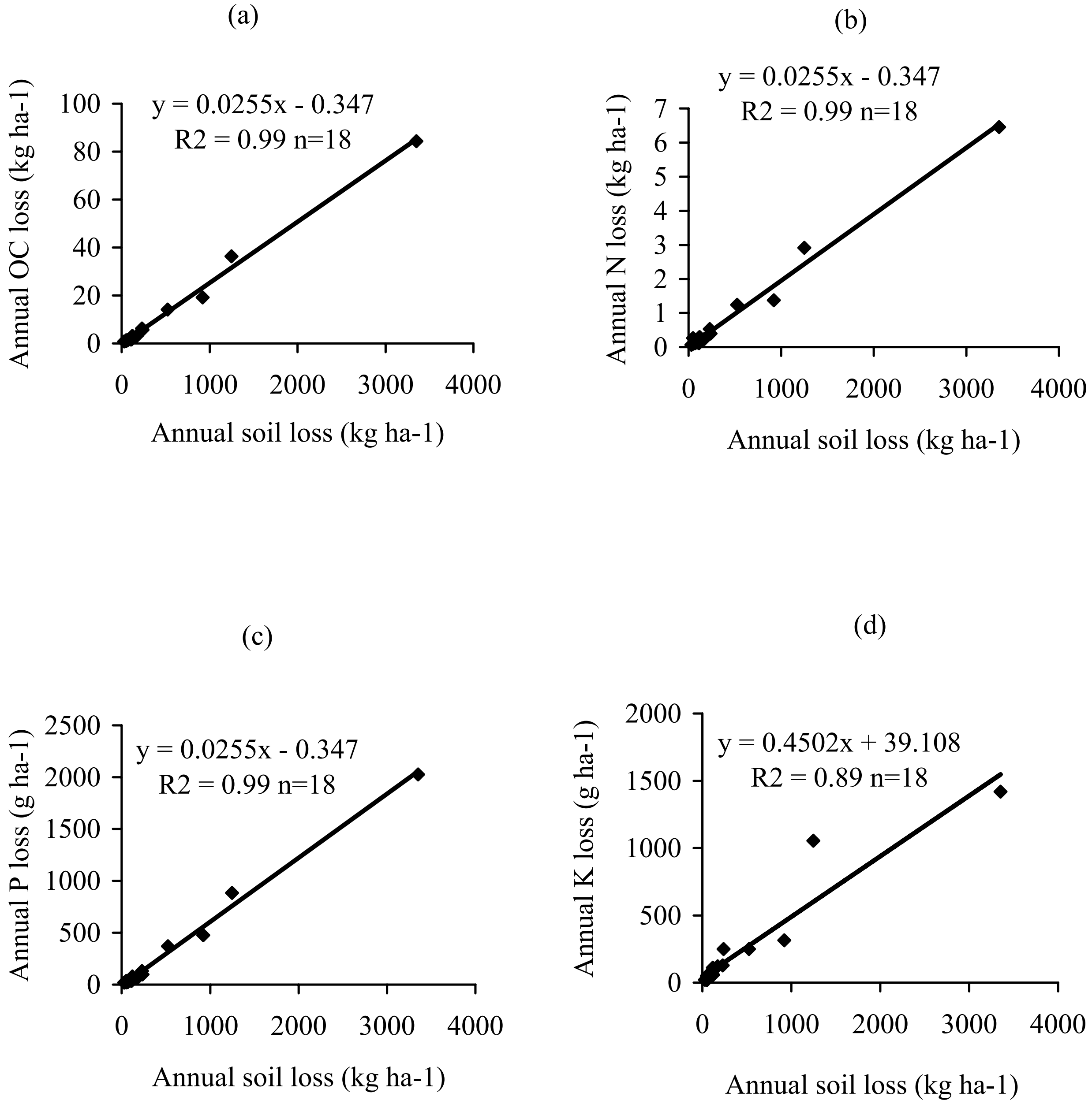

Figure 7.3 Correlations between annual soil losses and annual organic C, N, P, and K losses per treatment; (a) for organic C (b) for N, (c) for P, (d) for K.

Table 7.6 Effect of treatments on organic C and N, P, K losses during the severe erosion rain event of 27.07.02 at Saria, Burkina Faso (kg ha^{-1})

	Soil loss	Soil loss	C	N	P	K
	2002	27.07.02				
T_0	32711	29359	501	29.8	13.5	7.4
T_{GS}	5639	5116	81	7.2	2.8	3.9
T_{GSC}	1933	1884	31	7.7	1.0	1.1
T_{GSU}	9858	8937	139	8.9	4.1	2.6
T_C	802	686	16	1.9	0.6	0.8
T_{SR}	1035	913	14	1.0	0.5	0.6
T_{SRC}	569	539	14	1.2	0.4	0.1
T_{SRU}	3621	3392	88	5.1	1.9	1.0
T_U	8705	7457	159	9.6	4.1	6.2

Treatments explained in Table 7.2.

7.4 Discussion

7.4.1 Effect of treatments on soil loss

Stone rows reduced soil loss more than grass strips (Figure 7.1). This was mainly explained by the better efficiency of stone rows to reduce runoff than grass strips. Indeed, several studies in the region (Casenave and Valentin, 1989; Roose, 1981) have shown that sediment transport is intimately linked to the amount of runoff water. Yet, as established by results of Zougmoré et al. (2003), stone rows reduced runoff more than grass strips did. These authors argued that due to their better architecture, stone rows were better able to slow down runoff and to improve water infiltration compared to vegetation bunds. Furthermore, because the grass strips take at least one month to be effective after the long, harsh, 6-month dry season, they are less effective at the onset of the rainy season and this may explain the better performance of stone rows in reducing runoff and soil loss.

Application of compost-N resulted in better soil loss reduction than application of urea-N. Several studies have established that application of decomposed organic resources like compost increased soil structure stability (Feller and Beare, 1997), soil resistance to rainfall impact (Wischmeier et al., 1971), and soil macroporosity and infiltration (Carter and Steward, 1996). As reported by Tolk et al. (1997), compost application also improves soil water-holding capacity.

Indeed, Ouédraogo et al. (2001) observed in the same region that compost amendment resulted in a better soil structure with well-developed aggregates and many voids that improved rainwater infiltration, thus reducing runoff and soil loss. In contrast, application of fertilizers has less direct impact on soil physical properties.

Combining runoff barriers with compost application increases soil moisture and nutrient availability; not only the release of the macronutrients such as nitrogen and phosphorus, but also micronutrients for plants (Velthof et al., 1998), thus improving soil surface cover by sorghum plants. Application of urea also improves crop performance and therefore leads to an improvement of soil surface cover (Zougmoré et al., 2003). Raindrops cause splash erosion and are more erosive than runoff (Morgan, 1995); therefore, soil surface protection through sorghum plant cover leads to less displacement of solid particles (Zougmoré et al., 2000b). This confirms findings by Lal (1975) and Roose (1981) that permanent protection of the soil with dead or living cover is one of the most effective ways of controlling erosion. Furthermore, compost improves soil stability (Hernanz et al., 2002) and this together with compost-mediated improvement of plant cover explains the least soil losses in plots with compost.

The huge amount of soil loss from the control treatment during heavy rain events was mainly explained by the low plant cover that expose the low-organic content soil to splash erosion and crusting, which increases runoff during such events if there is no soil and water management (Roose, 1981). Indeed, as much as runoff speed increases, considerable amount of fine particles are removed from the topsoil and transported with runoff water. Conversely, in plots with SWC measures, runoff speed is slowed down thus reducing soil particles detachment and transport. This is in accordance with results reported by Greer (1971) and Roose (1981) who explained that during exceptional heavy rainfalls in the sub-Saharan zone, the combined effects of the very high rain intensity, long duration of rainfall and soil saturation, induced enormous runoff and sediment transport.

7.4.2 Organic C and nutrients in eroded sediment and runoff water

The slow down of runoff in treatments with stone rows hampers the transport of coarse material but does not prevent the transport of fine soil particles. Moreover, applications of mineral or organic N have induced early fast growth of sorghum crop that resulted in soil cover improvement; this also contributed to slow down runoff in these treatments. Therefore, more rich sediment was lost in these treatments than in treatments without barriers, where even heavier particles are displaced by runoff (Table 7.2). This explained the high content of OC and nutrients in treatments with stone rows and N inputs (T_{SRC} and T_{SRU}) in 2001 but also in treatments with N inputs only in 2002 ($T_{C,}$ T_U).

The high contents of OC and K during 2001 rainy season in the control treatment were mainly due to the occurrence of several low speed runoffs that did not occur in the others treatments, which have selectively removed greater amounts of fine organic particles than in treatments with soil conservation barriers. Previous studies in semi-arid regions of Burkina (Roose, 1981) and India (Cogle et al., 2002) reported similar high-eroded sediment contents of carbon.

As shown on Figure 7.2, the selectivity of erosion during small rainfall events can highly increase nutrient contents in eroded materials per unit soil loss compared to large rainfall events. Bilgo et al. (2003) reported similar results in the same zone where severe erosion events showed lower OC, N and P contents than slight erosion ones. As pointed out by Lal (1998), sheet erosion selectively exports clay, silt, nutrients and SOM from the topsoil. This selectivity is particularly high on a gentle slope when runoff and erosion rates are low (Roose and Barthès, 2001). Cogle et al. (2002) indicated that suspended particles were a major part of eroded sediments from Lixisols. As soon as runoff increases, it coalesces into rills, which scour the whole mass of the upper rich soil horizons. The high values of OC and nutrient ER confirm that erosion may drastically affect soil productivity particularly on the inherently low fertility soils.

In composted plots, the release of labile soil OC through mineralization process of applied compost is done gradually over time, as in most soils, humic substances, the most recalcitrant component of soil OM represent most 60–80% of soil OM; This may contribute to sustain soil OC in composted plots (Woomer et al., 1994). Moreover, compost incorporation into the soil has certainly improved soil aggregate stability and increased soil OC in composted plots (Feller and Beare, 1997), thus reducing the difference of soil OC content between parent soil and eroded sediment. This explained the least ER for OC in plots that received compost.

Pimentel et al. (1995) reported that soil erosion causes loss of basic plant nutrients such as N, P, K and Ca^{+2} and that water erosion selectively removes the fine organic particles. As stated by Roose (2003), major sandy soils in Sahelian countries with their top layers poor in stable aggregates, are very sensitive to splash, sheet erosion and crusting. Sheet erosion is dominant and transports mostly the fine particles from the topsoil that is richer than lower layers, leading to very high enrichment ratios.

Also, in plots with SWC barriers, runoff speed was more slowed down than in plots without soil conservation barriers. Therefore, the contact between runoff water and soil material is longer, giving more time for the solubilization of chemical components and the diffusion of ions into the runoff. This explained the highest NO_3^--N contents in plots with stone rows barriers and the least contents of NO_3^--N in treatments without barriers.

OC and nutrient losses are directly function of the amounts of annual soil loss and runoff (Roose and Barthès, 2001; Bilgo et al., 2003). This explains the greatest nutrient losses in the control (greatest annual soil loss) and the least nutrient losses in stone rows + compost plots, which had the smallest soil losses. The decrease of K content in eroded sediments in 2002 could be due to soil K mining as crop residues are totally removed after harvest. This ultimately suggests bringing back to the soil the removed straw preferably in the form of well-decomposed organic matter like compost.

The considerable amounts of soil loss during exceptional heavy rainfalls explained their great organic C and nutrient losses. Diallo et al. (2003) reported similar results on a ferruginous soil in Mali where they concluded that the amount of annual organic C and nutrient losses were greatly related to the magnitude of the rains. Our results are also consistent with those of Cogle et al. (2002) who reported large amounts of nitrogen and carbon losses on a Lixisol during an exceptional rain event at early rainy season in semi-arid India.

7.5 Conclusion

The following conclusions can be highlighted from this study:

- Stone rows reduced soil loss more efficiently than grass strips. Soil loss was significantly reduced by application of compost.
- Eroded sediments were significantly richer in organic C, N, P and K than the soil from which they originated. High enrichment ratios were observed particularly for N, indicating severe losses of one of the more deficient element in West African soils.
- Stone rows barriers induced high concentrations of OC, N and K in eroded sediments and runoff water.
- Small rain events were more selective for organic C and plant nutrients (through the displacement of topsoil fine particles) than heavy rains.
- Exceptional heavy rainfalls greatly influenced the annual soil and nutrient losses.
- Combining runoff barriers (stone rows or grass strips) with the application of compost appeared the most effective practice that significantly controlled erosion and reduced organic C and nutrients losses.

We hypothesised that combining the use of organic or mineral sources of N with runoff barriers could improve soil productivity and thus mitigate severe effect of sheet erosion on the unfertile West African soils.

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Chapter 8

Nitrogen flows and balances as affected by water and nutrient management in a sorghum cropping system of semi-arid Burkina Faso

Zougmoré, R., Mando, A., Stroosnijder, L., Guillobez, S., 2003. Nitrogen flows and balances as affected by water and nutrient management in a sorghum cropping system of semi-arid Burkina Faso. *Field Crops Research, submitted.*

Abstract

Efficient use of external inputs and water conservation are perquisite of sustainable agricultural productivity in semi-arid West Africa. A field experiment was carried out during three years (2000‒2002) in semi-arid Burkina (Saria, 800 mm of annual rainfall, PET of 2000 mm y^{-1}) to assess the effects of stone rows or grass strips of *Andropogon gayanus* Kunth cv. *Bisquamulatus* (Hochst.) Hack.) as soil and water conservation (SWC) measures, the sole application of an organic (compost-N) or mineral (urea-N) source of nitrogen and the combined use of SWC and compost-N or urea-N on nitrogen flows and balances. The trial was on a Ferric Lixisol, 1.5% slope and consisted in two replications of 9 treatments in which the runoff barriers were put along contours lines. During the three consecutive years, all treatments induced negative annual N balances (-75 to -24 kg N ha^{-1}). The main factors explaining these negative balances were respectively N exportation by sorghum biomass and soil erosion induced nitrogen loss. Great amounts of N (7 kg N ha^{-1} y^{-1} in 2000 and 44 kg N ha^{-1} y^{-1} in 2002) were lost in the control treatment through runoff and eroded sediments, which corresponds respectively to about 10% and 43% of the total outflow of N. The sole stone rows reduced erosion N losses to 8% while this was 12% by the sole grass strips. The combined application of SWC measures and nutrients inputs reduced this erosion N loss to only 2‒7% of the annual N loss. The application of urea-N or compost-N induced the least soil N-mining over the three years, while the highest N-mining was observed in plots without N input. We conclude that N-mining in poor fertile soils of West Africa can be mitigated through integrated water and nutrient management.

Keywords: Nutrient balance; Stone rows; Grass strips; Compost; Urea; Soil erosion

8.1 Introduction

Soil degradation is a major issue for arid and semi-arid tropics (Ryan and Spencer, 2001) and erosion induced-soil degradation is recognized as one of the serious threats to sustainable agricultural productivity in the semi-arid zone of West Africa (Laflen and Roose, 1998; Lal, 1998). Indeed, soil erosion can accelerate soil fertility depletion, which is the fundamental biophysical cause for declining per capita food production in smallholder farms in sub-Saharan Africa (Sanchez and Jama 2002). Erosion influences several soil properties, e.g., topsoil depth, soil organic carbon content, nutrient status, soil texture and structure, available water holding capacity and water transmission characteristics. All these together regulate soil quality and determine crop yield (Kaihura et al., 1999). A study by Cogle et al. (2002) found that up to 39% of potential crop N-uptake was lost on a Lixisol because of soil erosion in semi-arid zone of India.

In addition to erosion, leaching, volatilization and exportation of nutrients by edible crop products are main causes of nitrogen losses. Brouwers and Powell (1998) reported, from studies in Niger on sandy soils receiving important amount of organic matter (manure, compost), that there were considerable losses of locally available nutrients mainly N (91 kg ha^{-1}) and P (19 kg ha^{-1}) through leaching process. More recently, Bonzi (2002) reported in Burkina (Saria) that losses of N through denitrification and volatilization in an intensified system could reach 60–70 kg ha^{-1} y^{-1} while N exported through sorghum crop averaged 49 kg ha^{-1} y^{-1}.

Nitrogen is of all nutrients, the one required in a large quantity for crop growth and productivity (Sinclair and Vadez, 2002), which means that adequate management of the nitrogen, highly subjected to all kinds of losses, is a key element for intensive crop production (Giller et al., 1997). Therefore, as stated by Brouwers and Powell (1998), it is imperative that agricultural research looks not only at raising production using external inputs, but also at reducing unproductive nutrient losses while increasing beneficial export of nutrients. Implementing SWC measures such as stone rows or grass strips in combination with the application of organic (compost, manure) or mineral nitrogen could limit N losses and improve crop nutrient uptake.

Nowadays, the nutrient balance approach has become an important tool that helps to understand the status and dynamics of soil fertility in different cropping systems (Smaling and Fresco, 1993; Bationo et al., 1998). The present study analyzed the N balance of combined soil water (stone rows, grass strips) and nutrient management practices (supply of compost-N or urea-N) in the north-sudanian climate zone of Burkina.

8.2 Material and methods

8.2.1 Site description and experimental design

The experimental field was 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). Over the last 30 years, the average annual rainfall was 800 mm. Rainfall is mono-modal, lasts 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 may reach 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. The soil type was Ferric Lixisol (FAO-UNESCO, 1994) with an average slope of 1.5% and a hardpan at a depth of 70 cm. 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 the 0-5-cm layer to 30% at 10-cm depth.

The trial combined linear SWC measures with organic or fertilizer sources of nitrogen. The experimental design was a randomized Fisher bloc with two replications and nine treatments: 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 and T_0: no SWC measures, no N input.

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) as explained in Chapter 5. Each plot (100 m by 25 m) was isolated from the surrounding area by an earth bund 0.6 m high. The stone rows and the grass strips were installed during 1999 rainy season with a spacing of 33 m (i.e., 3 barriers per plot) along contours as recommended by previous studies (Zougmoré et al., 2000a, Zougmoré et al., 2000b). Each stone row consisted in 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. Each grass strip was made of three rows of grass, resulting in a thick barrier of 0.3 m width.

A 110-day sorghum (*Sorghum bicolor* (L.) Moench) variety Sariasso 14 was sown by hand in rows across the slope at 31250 seedlings per hectare in all plots. The plots were weeded with hand hoes twice a year. Prior to sowing, plots were ploughed to 15-cm 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 ranged between 5 to 7 t ha^{-1}, and therefore were about the minimal rates recommended in Burkina (Sédogo, 1993; Berger, 1996). Urea was applied in two times (first application at 21 days after planting and second application at 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 in all treatments.

8.2.2 Data collection

8.2.2.2 Erosion induced loss in soil nitrogen

Rainfall intensity was recorded using an automatic rain gauge (tipping bucket). The first replication was instrumented with runoff collection devices and equipment to record runoff. Runoff and sediments 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) that recorded the overland flow hydrograph.

When rainfall was high enough to generate overland flow, runoff was quantified by pumping out and measuring the water collected in each runoff-pit but also by recording the runoff volume with the TD-divers placed in the pits. Before pumping out the water, runoff water was thoroughly stirred and sampled in plastic barrels (60 L) 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 collected coarse sediment. For each treatment, a fraction (1/SF) of the coarse sediment was added to the dried fine sediment per rain event, thoroughly mixed and sampled for N, P and K analysis. Runoff water was analyzed for dissolved NO_3^--N and NH_4^+-N contents. Soil core samples were taken each year at depths 0─15 cm and 15─30 cm in triplicate at the onset of the rainy season from each treatment to determine content of OC (Walkley and Black method), N, P (automatic colorimetric method), and K (flame photometric method).

Rainfall events that produced runoff and sediment loss were 10 in 2000 cropping season, 9 in 2001, and 16 in 2002.

8.2.2.2 Nitrogen exported by sorghum crop

At sorghum maturing period, 2 entire plants (straw and entire panicle) were sampled in each plot at 1 m downslope and 0.1 m, 4 m, and 12 m upslope the middle barriers. Each of the 8 plant samples per plot were dried and ground to 0.2 mm for total N analysis. The amount of N exported through sorghum was determined using these N contents and the total dry biomass of sorghum (TDM).

8.2.2.3 Nitrogen loss through leaching

Four porous ceramics tubes (Tensionics[3]) were installed in each plot at 50 cm depth to extract soil solution for the quantification of leaching-N below 50 cm (Moutonnet et al., 1993). Soil solution

[3] SDEC, Reignac sur Indre, France

was extracted each 14 days during the whole rainy season and conserved in sterilized tubes for the determination of N-NO_3^- and N-NH_4^+ contents. The calculation of the amount of leached N requires the volume of water drained below sorghum rooting depth. 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, to estimate soil drainage (Zougmoré et al., 2003b). In 2001 and 2002, soil moisture was measured weekly with the time domain reflectometry method (TDR-TRIME-FM) at depths of 0–20 cm, 20–40 cm, 40–60 cm and 60–80 cm. Soil drainage was determined using the most commonly method in water balance studies in the Sahel as described by several authors (Stroosnijder and Koné, 1982; Mando, 1997). In brief, the determination of drainage volume is based on the magnitude of infiltration water and the variation of soil water storage over the considered soil depth. The amount of leaching N for a given week was therefore the drainage volume times the corresponded period N concentration.

8.2.2.4 Other N losses

All N flows were determined as described by Van den Bosch et al. (1998) for a full balance. N exportation through sorghum products, erosion losses and leaching N were measured through the experiment. Only gaseous N losses (denitrification and volatilization) were estimated using the below regression model given by IFA and FAO (Lesschen et al., 2003).

$$OUT4 = (0.025 + 0.000855 * P + 0.01725 * F + 0.117 * C) + 0.113 * F$$

Where, OUT4 = annual gaseous losses (kg ha^{-1}), P = annual precipitation (mm), F = Mineral and organic N-input (kg ha^{-1}), C = soil organic carbon content (%).

8.2.2.5 N inputs

According to treatments defined above, organic and fertilizer N inputs were applied at a dose equivalent to 50 N ha^{-1} y^{-1}. For the study region, atmospheric depositions (rain and dust) were estimated to an average of 5 kg ha^{-1} from literature (Pieri, 1985; Pol and Traoré, 1993). Non-symbiotic fixation of nitrogen was ignored in this study.

8.2.3 Data analysis

Data were statistically analyzed using STATITCF package (Gouet and Philippeau, 1986), including ANOVA and Newman-Keuls test for significant differences between treatments at $p < 0.05$.

8.3 Results

8.3.1 Effect of water and nutrient management on sorghum N

Treatments showed significant differences for annual N exportation through sorghum during the three successive years. These amounts followed the trend of sorghum TDM (Table 8.1). The highest N exportation were observed on treatments that combined stone rows or grass strips with compost-N or urea-N application (T_{SRC}, T_{SRU}, T_{GSC}) while the least were recorded in treatments without N-input (T_{SR}, T_{GS}, T_0). For the three years, the exportation of N by sorghum crop accounted for 82─87% of total N loss from plots in treatments T_{SRC}, T_{SRU}, T_{GSC}, T_C, and for 75─83% in treatments T_{SR}, T_{GSU}, T_U, T_{GS} and T_0. One can observe that on average during the three years, the annual amount of N exported through sorghum for treatments receiving compost-N or urea-N (80 kg N ha^{-1}) were higher than the annual total N input (Table 8.1). The three treatments without N-input (T_{SR}, T_{GS}, T_0) exported 60% of the amounts of sorghum N in compost-N or urea-N treatments (47 kg N ha^{-1}).

8.3.2 N losses through erosion and leaching

A previous study in the same experiment has dealt with soil losses through runoff and sediment transport (Zougmoré et al., 2003a). Table 8.1 presents the N-loss through erosion and runoff per treatment. For the three years, the control treatment showed significant higher N losses than the water and nutrient management treatments (T_{SRU}, $T_{SRC,}$ $T_{SR,}$ $T_{GSU,}$ $T_{GSC,}$ T_{GS}, $T_{U,}$ T_C). The lowest erosion and runoff mediated N losses were recorded in composted plots (T_{SRC}, T_C). In 2000 and 2001 with less erosive rain events, the N losses through runoff and erosion did not exceed 7 kg ha^{-1}. However, in 2002, when an intensive rain event occurred, N losses in decreasing order amounted to 44 kg ha^{-1} for the control treatment, 18 kg ha^{-1} for T_U, 14 kg ha^{-1} for T_{GS} and T_{GSU}, 10 kg ha^{-1} for T_{GSC}, T_{SR}, and T_{SRU}, and only 3 kg ha^{-1} for T_C and T_{SRC}.

Quantities of N loss through leaching were not significantly different among treatments over the three years (Table 8.1). However, urea-N treatments showed higher leaching-N than compost-N treatments when compared in pairs (T_{SRU}/$T_{SRC,}$ T_{GSU}/$T_{GSC,}$ T_U/T_C). In 2001, the least N losses through leaching were recorded in treatments without SWC measures ($T_{U,}$ T_0 and T_C) while the greatest losses were observed in treatments with SWC measures ($T_{GSU,}$ $T_{GSC,}$ $T_{SR,}$ T_{SRU}, T_{GS}, T_{SRC}). In 2002, treatments $T_{GSU,}$ T_{GSC} showed the highest leached-N, followed by treatments T_U, T_{SRU} and T_{SRC}. The least losses through leaching were observed in T_{GS} (Grass strip alone). In the 2000 rainy season with greater drainage than in 2001 and 2002 (Zougmoré et al., 2003b), N losses through leaching averaged 3─9 kg ha^{-1} y^{-1} while this was only 1─6 kg ha^{-1} y^{-1} in 2001 and 2002. Compared to the annual outflow of N, this corresponds to about 3─14% of total N losses in 2000, 3─10% in 2001 and 2─5% in 2002.

8.3.3 Effect of water and nutrient management on N flows and balance

In 2000, the N balance for all treatments were negatives and ranged from -26 kg ha^{-1} y^{-1} to -60 kg ha^{-1} y^{-1} (Table 8.2), which means that N exported from the soil was greater than the N inputs in the soil. A first group of treatments with high negative N balances (<-40 kg ha^{-1} y^{-1}) comprises T_0 (control), T_{SR} (stone rows alone), and T_{GS} (grass strips alone). These treatments did not receive organic or mineral N input. A high negative N balance of -60 kg ha^{-1} y^{-1} was also observed in treatment T_{GSC}, which N exportation through sorghum and leaching was the highest in this year. Treatments that combined SWC measures and organic-N or mineral-N in the decreasing order T_{SRU}-T_{SRC}-T_{SRM}- T_{GSU}-T_{GSM} formed the second group with N balances greater than -40 kg ha^{-1} y^{-1}. In this year, N loss through erosion did not exceed 7 kg ha^{-1} y^{-1} but loss of N through leaching reached 9 kg ha^{-1} y^{-1}. N loss through erosion and leaching totalized both 8─21% of the outflow of N.

The same trend was observed in 2001 with lower negative balances ranging from -18 to -57 kg ha^{-1} y^{-1} (Table 8.3). N inputs (organic or mineral) and N exported through crop products were the main factors determining these balances as leaching N and erosion N were low in this year (3─12% of total N output).

In 2002, like in the previous years, the control treatment showed the highest negative N balance with -99 kg N ha^{-1} y^{-1} followed by T_{SRC}, T_{GSC}, and T_{SRU} which N exportation through sorghum were high (90─118 kg N ha^{-1} y^{-1}) (Table 8.4). Treatments T_{SR}, T_{GS} and T_C showed negative N budgets of -50 kg ha^{-1} y^{-1} while the least negative N balances were observed in treatments T_U, and T_{GSU} (-43 and -32 kg ha^{-1} y^{-1} respectively). N balances in 2002 were 1.5─4 times higher than in the previous years. Quantities of N exported through sorghum were similar to those obtained in 2000; however, a great influence of erosion was observed. Indeed, the amounts of N loss through erosion were 3─20 times higher than erosion N in 2001, and corresponded to 2–43% of the total outflow of N.

Table 8.1 Effect of water and nutrient management on N-losses through sorghum, soil erosion and leaching at Saria, Burkina Faso

	Sorghum total biomass ($Kg\ ha^{-1}$)			N exportation through sorghum total biomass ($Kg\ ha^{-1}$)			N loss through soil erosion ($Kg\ ha^{-1}$)			N loss through leaching ($Kg\ ha^{-1}$)		
	2000	2001	2002	2000	2001	2002	2000	2001	2002	2000	2001	2002
T_0	4067 bc	4285 ab	3614 ab	49 c	57 bc	57 c	7.0 a	2.2 a	44 a	9.2	2.4	2.4
T_{SRM}/T_U	6136 ab	6178 ab	4397 ab	68 b	63 bc	69 c	3.3 cd	0.6 b	18 b	6.4	2.7	4.3
T_{GSM}/T_C	5428 abc	7320 a	6965 ab	68 b	75 ab	92 ab	4.2 b	0.6 b	4 e	4.9	1.8	2.5
T_{GS}	3329 c	3233 b	3109 b	38 d	43 c	40 d	3.4 cd	1.1 ab	14 bc	7.0	3.6	0.9
T_{GSU}	4314 bc	5446 ab	3831 ab	64 b	69 ab	62 c	3.4 bc	1.3 ab	13 bc	9.3	5.5	4.3
T_{GSC}	7606 a	7595 a	7580 a	95 a	72 ab	90 ab	3.5 bc	0.6 b	10 cd	6.6	5.1	6.2
T_{SR}	3717 bc	4595 ab	3992 ab	47 c	48 bc	48 d	5.1 ab	1.5 ab	8 d	2.5	3.9	2.7
T_{SRU}	6210 ab	6254 ab	4887 ab	86 a	94 a	93 ab	3.1 cd	0.9 b	9 cd	6.7	3.7	3.9
T_{SRC}	6939 a	8252 a	7781 a	77 ab	87 ab	118 a	2.4 d	0.7 b	3 e	6.7	3.2	3.2
Probability	<0.01	0.019	0.04	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.248	0.185	0.65

Treatments with the same letter are not statistically different at P= 0.05. T_0: no SWC measures, no N input; T_U: Urea-N, no SWC measures; T_C: compost-N, no SWC measures; T_{GS}: grass strips, no N input; T_{GSU}: grass strips + urea-N; T_{GSC}: grass strips + compost-N; T_{SR}: stone rows, no N input; T_{SRU}: stone rows + urea-N; T_{SRC}: stone rows + compost-N.

Table 8.2 Effect of water and nutrient management on N flows and balances for year 2000 at Saria (Kg ha^{-1})

	T_0	T_{SRM}	T_{GSM}	T_{GS}	T_{GSU}	T_{GSC}	T_{SR}	T_{SRU}	T_{SRC}
IN1, chemical fertilizer	0	50	0	0	50	0	0	50	0
IN2, organic fertilizer	0	0	50	0	0	50	0	0	50
IN3, atmospheric deposition	5	5	5	5	5	5	5	5	5
TOTAL INPUT	5	55	55	5	55	55	5	55	55
OUT1+OUT2, crop exportation	49	68	68	38	64	95	47	86	77
OUT3, leaching	4.9	6.4	2.5	6.7	9.3	9.2	6.6	6.7	7.0
OUT4, gaseous losses	0.7	7.3	7.3	0.8	7.3	7.3	0.8	7.3	7.3
OUT5, erosion	6.9	3.3	4.2	3.4	3.4	3.5	5.1	3.1	2.4
TOTAL OUTPUT	62	85	81	49	84	115	59	103	93
BALANCE 2000 (Input – Output)	-57	-30	-26	-44	-29	-60	-54	-48	-38

Treatments explained in Table 8.1.

Table 8.3 Effect of water and nutrient management on N flows and balances for year 2001 at Saria (Kg ha^{-1})

	T_0	T_U	T_C	T_{GS}	T_{GSU}	T_{GSC}	T_{SR}	T_{SRU}	T_{SRC}
IN1, chemical fertilizer	0	50	0	0	50	0	0	50	0
IN2, organic fertilizer	0	0	50	0	0	50	0	0	50
IN3, atmospheric deposition	5	5	5	5	5	5	5	5	5
TOTAL INPUT	5	55	55	5	55	55	5	55	55
OUT1+OUT2, crop exportation	57	63	75	43	69	72	48	94	87
OUT3, leaching	2.4	2.7	1.8	3.6	5.5	5.1	3.9	3.7	3.2
OUT4, gaseous losses	0.7	7.2	7.2	0.7	7.2	7.2	0.7	7.2	7.2
OUT5, erosion	2.2	0.6	0.6	1.0	1.3	0.6	1.5	1.0	0.7
TOTAL OUTPUT	62	73	84	48	83	85	54	105	98
BALANCE 2001 (Input – Output)	-57	-18	-29	-43	-28	-30	-49	-50	-43

Treatments explained in Table 8.1.

Table 8.4 Effect of water and nutrient management on N flows and balances for year 2002 at Saria (Kg ha^{-1})

	T_0	T_U	T_C	T_{GS}	T_{GSU}	T_{GSC}	T_{SR}	T_{SRU}	T_{SRC}
IN1, chemical fertilizer	0	50	0	0	50	0	0	50	0
IN2, organic fertilizer	0	0	50	0	0	50	0	0	50
IN3, atmospheric deposition	5	5	5	5	5	5	5	5	5
TOTAL INPUT	5	55	55	5	55	55	5	55	55
OUT1+OUT2, crop exportation	57	69	92	40	62	90	48	93	118
OUT3, leaching	2.4	4.2	2.5	0.9	4.3	6.2	2.7	4.0	3.2
OUT4, gaseous losses	0.7	7.2	7.2	0.7	7.2	7.2	0.7	7.2	7.2
OUT5, erosion	44.2	18.4	3.5	14.4	13.3	10.4	7.7	9.2	2.5
TOTAL OUTPUT	104	98	105	56	87	114	60	113	131
Full balance 2002 (Input – Output)	-99	-43	-50	-51	-32	-59	-55	-58	-76

Treatments explained in Table 8.1.

Figure 8.1 shows the average annual N balances per treatment during the three cropping seasons. The highest negative N balance was observed in the control treatment (-71 kg ha^{-1} y^{-1}) while the least values were observed in treatments T_{GSU}, T_U and T_C (-32 kg ha^{-1} y^{-1}).

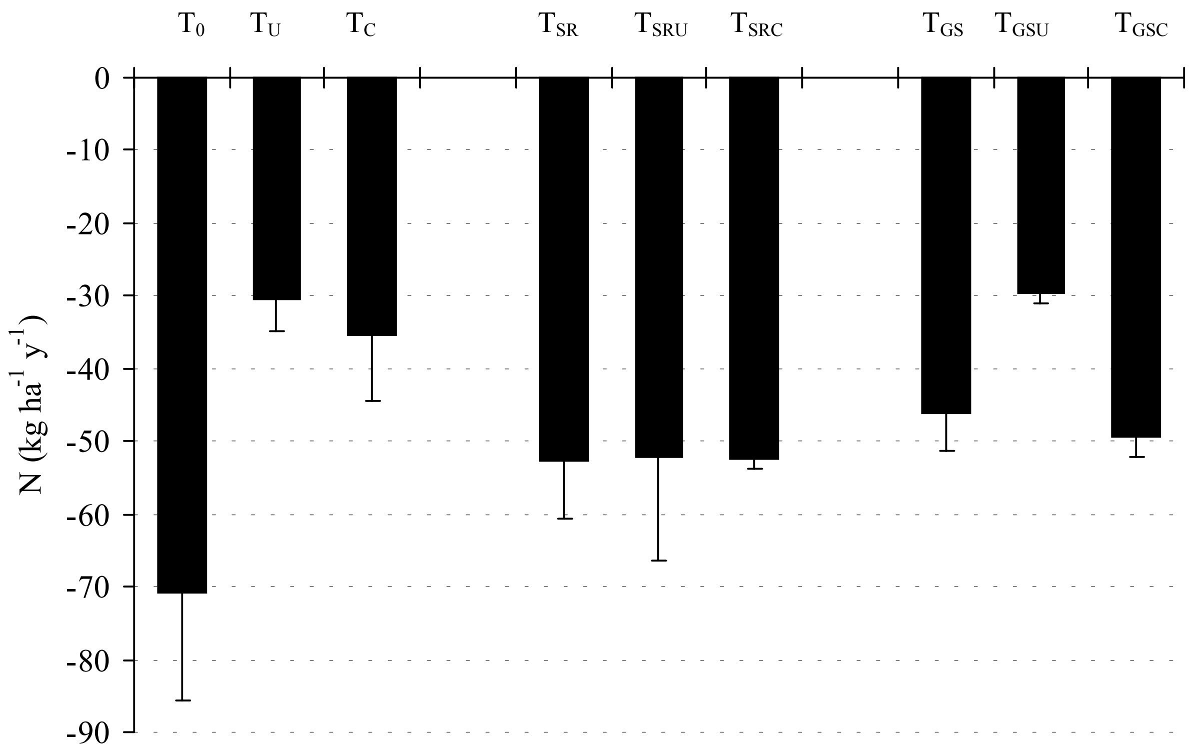

Figure 8.1 Mean annual N balance per treatment over the three cropping seasons (2000-2002) at Saria. Treatments explained in Table 8.1.

8.4 Discussion

8.4.1 Effect of water and nutrient management on N exportation by sorghum

The greatest availability of water and nutrients in treatments that combined SWC measures and compost-N explained the greater TDM and N exportation in these treatments than in no N-input treatments. Indeed, SWC measures by reducing runoff and increasing soil water storage in the crop-rooting zone (Zougmoré et al., 2003b) increased the use of soil major nutrients (N, P, K). The input of potassium and micronutrient through compost may have increased N uptake in composted plots. Moreover, organic inputs are a source of energy and nutrients for soil microbial communities, which promote nutrient availability (Bielders et al., 2002).

The application of urea-N in plots with SWC measures, which have created sound soil moisture conditions, improves N uptake by sorghum plants, as confirmed by quantities of N in sorghum (Table 8.1).

Several studies (Vanlauwe et al., 2000; Bationo and Buerkert, 2001) also reported that urea-N application improves uptake of available phosphorus and potassium by sorghum crop, which by feedback, can improve N uptake. This explains the greater N exportation in combined SWC measures and urea-N treatments than in no N-input treatments.

Also, outflows of N through sorghum products were greatly related to the amounts of TDM produced per treatment, which explained the greater quantities of N exported through sorghum in compost-N and urea-N treatments than in no N input treatments. This is consistent with several results in sub-Saharan West Africa (Bationo et al., 1998; Ramisch, 1999) who reported that adequate addition of nutrients stimulates an improved biomass production but in turn also extracts considerable quantities of nutrients from the soil. The application of 50 kg ha^{-1} y^{-1} through urea-N or compost-N was below the N exportation through sorghum products, which means that the soil N-stock undoubtedly contributed for crop biomass production in both the receiving-N treatments and in the non receiving-N plots.

8.4.2 Effect of water and nutrient management on erosion and leaching N

Annual losses of N through soil erosion were greatly dependant on the magnitude of annual runoff and sediment loss (Zougmoré et al., 2003b). If sediment loss could be considered in some cases as negligible, this does not apply to nutrient losses particularly for N, as small runoffs transport fine soil particles, the most rich in N, and N dissolved in water. Cogle et al., (2002) pointed out that since the fine soil fraction containing nutrients is preferentially eroded, a disproportionate loss of soils nutrients can occur and leads to great soil degradation. Several studies (Quansah and Ampontuah, 1999; Zougmoré et al., 2003a) have demonstrated that nutrient losses through soil erosion were higher during small intensive rain events than during heavy and high erosive rain events. Our results also indicated that water and nutrient management induced significant reduction of nutrient losses. On average, these reductions reached 40-70% compared to the control, thus showing a great effect of soil management. These findings indicates that on gentle slopes (> 3%), erosion induced nutrient losses can keep into harmless proportion (N loss lower than N input through atmospheric deposition) with proper management while poor management leads to severe losses. Therefore, nutrient balance studies should take into account a management factor when estimating erosion-induced loss in soil nutrients in semi-arid West Africa. Indeed, N losses through erosion represent 43% of the total output in the worst case (T_0) of this study (during rainy seasons with exceptional rain events) while the application of water and nutrient management practices (T_{SRC}, T_C,), significantly reduced N losses to only 2% of total outflow of N.

During 2001, a year with several small and well-distributed rainfalls, the slow down of runoff by stone rows and grass strips may have induced more N concentration of drainage water in plots with SWC measures than in plots without SWC measures. This explains the larger amount of N loss through leaching in plots with SWC measures than in plots without barriers in 2001. This effect of SWC measures on the nutrient concentration in drainage water was also observed during rainy season of 2002. In addition, plots with application of organic-N or mineral-N showed greater drainage than plots without N input (Zougmoré et al., 2003b). The greater amounts of drainage water in addition to their higher N concentration explain the larger amount of N loss through leaching in treatments that received compost-N or urea-N than treatment without N-input in 2002. These results are closed to those of Bonzi (2002) who reported similar values of leaching N at Saria in the same type of soil. He also concluded that treatments with different types of fertility management did not show significant differences of leaching N, although treatment with application of mineral fertilizers only induced slight increases of leaching N. This may be due to the more rapidly drop of $N0_3^-$ anions below the rooting zone in urea-N treatments than in compost-N treatments, the latter's taking more time to mineralize and release N in the soil solution.

Our results indicate that the amount of N loss through leaching is greatly related to the magnitude of drainage water but also to the type of soil, water and nutrient management. Brouwers and Powell (1998) came to similar conclusions in Niger.

8.4.3 Effect of water and nutrient management on soil N balance

From the three years results, it appears that the outflow of N through sorghum biomass was the first factor that explained negative balances in both input-N treatments and no input-N ones. The application of organic-N or urea-N has induced an important increase of sorghum biomass production and consequently, higher amounts of N were exported from the plots with N-input compared to plots without N input (Table 8.1). Smaling et al. (1997) came to similar conclusions in nutrient budgeting in Kenya and Mali where they indicated that most nutrients leave the system through the harvested crop. The magnitude of this exportation was as such that the total N input was not enough to compensate the surplus of N exportation. Through an estimation of the amounts of N exported through crop residues per treatment using the average straw-N/grain-N ratio (1.43) as determined at Saria by Bonzi (2002) for the same variety of sorghum, it was observed that on average, N exportation through sorghum residues were 33─36 kg ha^{-1} for treatments T_{SRC}, T_{SRU} and T_{GSC}, 31 kg ha^{-1} for T_C, 25 kg ha^{-1} for T_{GSU}, 23 kg ha^{-1} for T_U, 21 kg ha^{-1} for T_0, 19 kg ha^{-1} for T_{SR} and 15 kg ha^{-1} for T_{GS}. This suggests that proper crop residue management could bring back to the soil about 83% of the annual N deficit for treatment T_{SRU}, 90% for T_{SRC}, 95% for T_{GSC}, 37% for T_{SR} and T_{GS}, 31% for T_0, and up to 113% and 145% of annual N balance for respectively T_C and T_{GSU}. Despite the large exportation of N through sorghum in combined SWC measures and N-input plots, these treatments could better insure soil N replenishment through a return of crop residues than treatments without N-input.

In addition to the outflow of N through sorghum products, the very low N input aggravated the negative balance in treatments without N application. In 2001, despite that N exportation through sorghum remained at the same level as in 2000, average N balances were less negative than in 2000 certainly because of the very low losses of N through erosion and leaching.

In 2000, erosion and leaching accounted on average for 14% of the total outflow while 7% in 2001. In 2002, in addition to high amounts of N exported through sorghum, loss of N through runoff and erosion greatly contributed for the high negative N balances due to a single great rainstorm (Table 8.2).

8.5 Conclusion

Our results support the followings conclusions:

- Stone rows or *Andropogon gayanus* grass strips combined with mineral-N or organic-N induce greater sorghum biomass production that lead to significant exports of nutrients from the soil than no N input management system.
- On gentle slopes, soil erosion induces significant loss of N through both fine sediments transport and runoff water. Nutrient loss through soil erosion is an important contributor to the generally negative N balances, as it can represent up to half of the total outflow of N in the case of no input and no soil water conservation management options. Integrated water and nutrient management tremendously reduce unproductive losses of N.
- During the three successive study years, the application of SWC measures alone or combined with urea-N or compost-N induced negative N-balances. N losses through sorghum exportation and through soil erosion were the two main factors explaining these negative balances.
- The restitution of crop residues produced under integrated water and nutrient management options can reduce actual soil negative N balance by 90%.

- We conclude that continuous N mining in poor fertile soils of semi-arid West Africa can be mitigated through the application of integrated water and nutrient management.

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Chapter 9

Economic benefits of combining soil and water conservation measures with nutrient management in semi-arid Burkina Faso

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Abstract

Nutrient limitation is the main cause of per capita decline in crop production in the Sahel where water shortage limits an efficient use of available nutrients. Combining soil and water conservation measures with locally available nutrient inputs may optimize crop production and economic benefit in cereal-based farming systems. A study conducted in 2001 and 2002 at Saria, Burkina Faso (annual rainfall 800 mm, PET of 2000 mm y^{-1}) assessed the combined effects of two types of semi-permeable barriers (stone rows and grass strips of *Andropogon gayanus* Kunth *cv. Bisquamulatus* (Hochst.) Hack.) and the application of compost or urea on sorghum performance and economic benefits. The field experiment was carried on a Ferric Lixisol, 1.5% slope and comprised 9 treatments in which the barriers were put along contours and combined with compost-N or urea-N. Installation of stone rows or grass strips without addition of nutrient inputs was not cost effective although it induced sorghum yield increase (12─58%) particularly under poor rainfall conditions. Combining compost with stone rows or grass strips significantly increased sorghum yield that induced positive interaction effects (Mean added effects of 185 kg ha^{-1} for stone rows combined with compost-N and 300 kg ha^{-1} for grass strips combined with compost-N). Economic benefits were substantial (145000 to 180000 FCFA ha^{-1}) when adding compost-N to both stone rows and grass strips whereas limited economic benefits were observed with the application of urea-N (1120 to 62500 FCFA ha^{-1}). This may provide to farmers capital to invest in soil management and may also contribute for poverty alleviation in sub-Saharan Africa.

Key words: Stone row, Grass strip, Nitrogen input, Added benefit, Sorghum, Sahel

9.1 Introduction

Soil degradation and nutrient depletion have gradually increased and have become serious threats to agricultural productivity in sub-Saharan Africa (Vanlauwe et al., 2002). Nutrient budgets of arable lands are on average negative (Smaling 1998; Henao and Baanante 1999) and fertilizer consumption is in most cases less than 10 kg ha^{-1}. According to Breman et al. (2001), only two countries in sub-Saharan Africa do not have negative nutrient balances; twelve countries in this region show an average depletion of 0─50 kg ha^{-1} of $N+P_2O_5+K_2O$, while depletions of 50─100 kg ha^{-1} were observed in 27 countries.

In semi-arid west African zone, 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).

In order to be effective, application of nutrient inputs in semi-arid areas need to be combined with water harvesting and water conservation or by small-scale irrigation (Dudal, 2002). In the Sahel, several local soil and water conservation (SWC) measures offer potential for reducing runoff, soil loss, and improving soil moisture. This includes improved soil erosion control using stone rows, hedgerows or micro-catchments (Zougmoré et al., 2000a; Stroosnijder and van Rheenen, 2001). Also, some studies have reported that the beneficial effect of SWC measures such as stone rows on soil productivity was limited under continuous non-fertilized cereal cropping (Walle and Sims, 1999; Zougmoré et al., 2002). This implies that there is no effective water use efficiency without improved nutrient management.

Several studies have shown the great importance of organic sources of nutrients in improving soil fertility. Indeed, the maintenance of soil organic matter in low-input agro-systems includes retention and storage of nutrients, increasing buffering capacity in low activity clay soils, and increasing water holding capacity (Bationo et al., 1998). However, due to the low availability of organic resources, intensive farming can only be maintained through integrated organic and fertilizer inputs (Vlek, 1990).

The lack of economic motivation has been one of the major constraints to improved plant nutrition in sub-Saharan Africa (Dudal, 2002). Moreover, economic evaluation of stone rows in Burkina (Zougmoré et al., 2000b; Posthumus et al., 2001) concluded that when the construction is done in teams with the aid of a project for stone transport and contour tracing, the net present value of stone rows is negative because of the high labor cost and truck rental. The performance of the agricultural sector is poor and greatly influenced by low land and low labor productivity (Breman et al., 2001).

Therefore, interactions of SWC measures with organic or mineral source of nutrients need to be examined. This work aims to analyze the added effects of combining SWC measures with organic or fertilizer inputs during two successive cropping seasons in semi-arid Burkina Faso. It is hypothesised that application of SWC measures can increase the added benefits of organic or mineral inputs in smallholder farming systems of semi-arid Burkina Faso.

9.2 Materials and methods

9.2.1 Site description

The experimental field was 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). 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 with an average slope of 1.5% and with a hardpan at 70 cm depth. 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 depth. The rooting depth for sorghum in these soils is 80 cm. 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 fell from 70% in the topsoil to 30–50% at 80 cm depth, in line with the pH (H_2O), which decreased from 5.3 to 4.9.

9.2.2 Experimental design

The study was conducted during two successive cropping seasons (2001–2002). The trial consisted of a randomized Fisher bloc design with nine treatments in two replications: Treatments were as follows: 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_{SRU}: stone rows + urea-N, T_{GSU}: grass strips + urea-N, T_U: Urea-N, no SWC measures, T_C: compost-N, no SWC measures, T_0: no SWC measures, no N input.

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 had been installed during the 1999 rainy season, spaced 33 m apart (i.e., 3 barriers per plot) along the contours. Indeed, previous studies showed that for the more common case of farmers working with an NGO to trace contours and transport rocks, the optimal economic spacing in a sorghum-based system was between 30 m and 43 m (Zougmoré et al., 2000a, Zougmoré et al., 2000b). 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. Each grass strip comprised three rows of grass, resulting in a thick barrier 0.3 m wide.

In relevant plots compost was applied each year at once before sowing at a equivalent dose of 50 kg N ha^{-1} (4800 kg ha^{-1} in 2001 and 5600 kg ha^{-1} in 2002). Urea was also applied at the dose of 50 kg N ha^{-1} in two times (25 kg N ha^{-1} was applied 21 days after planting and 25 kg N ha^{-1} 56 days after planting). In all plots, a 110-day improved sorghum (*Sorghum bicolor* (L.) Moench*)* variety (Sariasso 14) was sown in rows across the slope by hand at the rate of 31250 seedlings per hectare. Prior to sowing, the plots were ploughed at 15-cm depth using oxen power in June 2001 and in July 2002 resulting in the incorporation of the applied urea or compost. The plots were weeded with hand hoes twice a year. All plots received a base dressing of 20 kg ha^{-1} P in the form of triple super phosphate to eliminate phosphorus deficiency as a factor in the experiment.

9.2.3 Data collection and analysis

From definitions of 'added effect' and 'interaction effect' given by Vanlauwe et al. (2001), Giller (2002) and Iwafor et al. (2002), we consider that 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. If x_1= Stone rows or grass strips, x_2= Application of compost-N or urea-N, (x_1+x_2) = Combined SWC measure (x_1) and compost-N or urea-N (x_2), x_0= Control (no SWC measures, no N input), Y= yield;

$$\Delta Yx_1 = Y(x_1) - Y(x_0) \qquad (1)$$

$$\Delta Yx_2 = Y(x_2) - Y(x_0) \qquad (2)$$

$$\Delta Y(x_1+x_2) = Y(x_1+x_2) - Y(x_0) \qquad (3)$$

$$IE = \Delta Y(x_1+x_2) - (\Delta Yx_1+\Delta Yx_2) \qquad (4)$$

There is positive interaction between x_1 and x_2 when AI > 0, and negative interaction between x_1 and x_2 when AI < 0.

In order to be able to determine the economic benefit of single or combined N-input and SWC measures, a minimum yield value was calculated per treatment. It corresponds to the minimum excess yield that supports the annual cost of the applied technology. 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}.

$$\Delta Y/\Delta N\ (x_2) = \Delta Y(x_2)\ /\ 50 \qquad (5)$$

In 2001 and 2002, the price of 1 kg urea-N was about 544 FCFA (CFA is the most West African currency). The price of 1 kg of sorghum in the region of Saria fluctuated between 100 FCFA and 180 FCFA. Therefore, to be economic, sorghum yield increase ($\Delta Y/\Delta N$) should exceed 3 to 5.4 kg per unit urea-N applied. 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 75520 CFA ha^{-1} and 33200 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 (Table 9.1). We assumed 300 m of bund per hectare and an amortization in 10 years for stone rows and 5 years for grass strips (Zougmoré et al., 2000b). The annual opportunity cost of capital rate, which measures the income foregone by investing in stone rows instead of livestock, small scale commerce or other activities, was fixed to 50% for Burkinabé farmers, and a repair and maintenance cost of 10 FCFA m^{-1} of bund (Lowenberg DeBoer et al., 1994). The latter authors explained that the high discount rate (50%) is linked to the poorly developed financial institutions and a chronic shortage of capital. The discounted average cost for stone rows using truck transport was 48312 FCFA ha^{-1} y^{-1} while grass strips installation cost using root transplanting was 26240 FCFA ha^{-1} y^{-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 (Table 9.3).

Table 9.1 Annual costs of SWC measures and compost production in pits in Burkina Faso (FCFA ha^{-1})

	Stone rows	Grass strips	Compost pit
Installation cost	75520	33200	10000
Useful life (year)	10	5	5
Amortization cost	7552	6640	2000
Composting cost	-	-	19000
Opportunity cost of capital	37760	16600	14500
Maintenance and repair costs	3000	3000	2400
Discounted annual cost	48312	26240	37900

Repair and maintenance cost for stone rows and grass strips = 10 FCFA m^{-1}; Rate of opportunity cost of the capital = 50%.

The production cost of 5 ton of compost in pit was determined from results of Bazié (1995) and Graaff (1996). The discounted cost for the pit establishment was about 10000 FCFA while the operational cost (pit filling, watering and emptying/pilling) was 19000 FCFA. The discounted annual cost was therefore 37900 FCFA ha^{-1} (Table 9.1) and the price of 1 kg compost-N was 758 FCFA. Compost cost did not include straw cost comparable to the zero cost of the rocks that were used to construct the stone rows. Also, compost transport cost was not included, assuming that the pit was situated in the field or nearby as recommended by extension services. 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.

Sorghum grain and straw yields were measured after sun drying at harvest from the 36 subplots in each plot. STATITCF package (Gouet and Philippeau, 1986) was used for statistical analyses, including ANOVA and Newman-Keuls test for significant differences between treatments at $p < 0.05$.

9.3 Results and discussion

9.3.1 Effects of SWC measures and nutrient management on sorghum performance

Sorghum yields were significantly different among treatments in 2001 and 2002 (Figure 8.1). 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 two years. In 2001, 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. Zougmoré et al. (2003a) explained that due to their architecture, stone rows were better able to slow down runoff and to improve water infiltration compared to vegetation bunds and this may explain the better performance of sorghum with stone rows. 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 (Hamer, 1996; Zougmoré et al., 2003a).

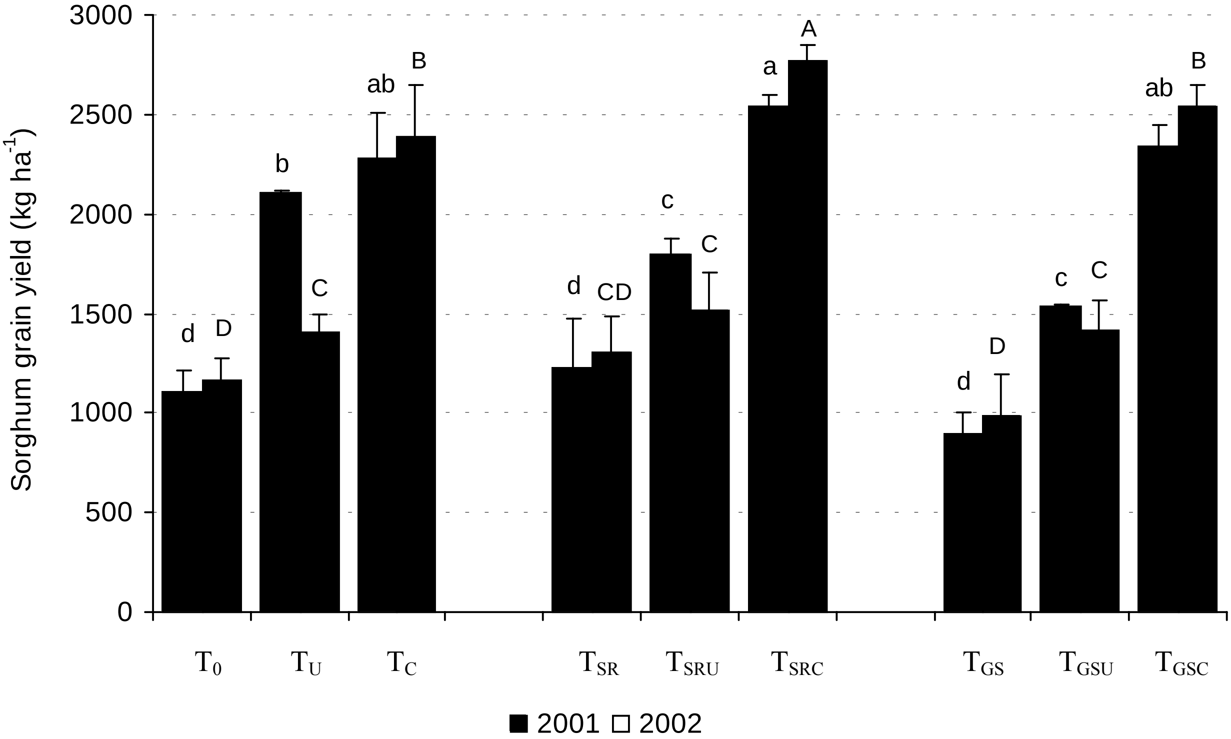

Figure 9.1 Effect of single or combined SWC measures and compost-N or urea-N on sorghum grain yields in 2001 and 2002 at Saria, Burkina Faso.

Treatments with the same letter are not statistically different at p= 0.05; Lower case for year 2001, upper case for year 2002. T_0: no SWC measures, no N input; T_U: Urea-N, no SWC measures; T_C: compost-N, no SWC measures; T_{GS}: grass strips, no N input; T_{GSU}: grass strips + urea-N; T_{GSC}: grass strips + compost-N; T_{SR}: stone rows, no N input; T_{SRU}: stone rows + urea-N; T_{SRC}: stone rows + compost-N.

In 2001, application of compost (T_C) or urea (T_U) alone greatly 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}). In 2002, as in 2001, single application N-input (T_C, T_U) induced 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) increased yield by respectively 82% and 143% compared to stone row (T_{SR}) and grass strip plots (T_{GS}). According to Sanchez and Jama (2002), soil fertility depletion is increasingly recognized as the fundamental biophysical root cause for declining crop productivity in smallholder farms of sub-Saharan Africa. As stated by Bationo et al. (1998), the productivity of most soils in their native state in the study zone is very low because of low inherent levels of plant nutrients, leading to soil mining. Thus, applying plants nutrients (50 kg N ha^{-1}) in these poor soils induced great positive reaction in biomass production (Figure 8.1), particularly when the constraint of limited-soil moisture is small during good rainfall years (Figure 6.2). 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 yield increase of 106% when compared to plots with stone rows alone (T_{SR}). Similarly, combining grass strips and compost (T_{GSC}) induced a 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}) increased grain yield by 46% and 71% respectively compared to plots with barriers only (T_{SR}, T_{GS}). These results were confirmed in 2002: treatments combining barriers with compost (T_{SRC}, T_{GSC}) induced yield increase by respectively 138% and 118% compared to the control. Adding urea to plots with barriers (T_{SRU}, T_{GSU}) increased grain yield by 30% and 21% respectively when compared to control plots.

In general, only slight differences of grain yields 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). This was also the case for sorghum harvest index and N utilization efficiency (NUE) as shown in Table 9.2. Janssen (1998) defined NUE as the ratio of grain yield and crop N exportation. In 2001, the highest values of NUE were observed with treatments T_U, and $T_{GSC,}$ which did not differ significantly with treatments T_C and T_{SRC}. Similar results were observed in 2002: Although treatment T_{GSC} showed the highest NUE, there was no significant difference among treatments receiving compost-N (T_{SRC}, T_{GSC}, T_C) and as well as among treatments receiving urea-N (T_{GSU}, T_{SRU}, T_U). This confirm the conclusion that in the North-Sudanian climate zone of Burkina, during rainy seasons with good rainfall distribution, implementing SWC measures without adding nutrients does not significantly improve crop production and that agriculture intensification should necessarily pass through the use of external nutrient inputs in combination with water management options.

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 intensive SWC technologies and improved practices of soil fertility replenishment (Schreurs et al., 2002; Dudal, 2002).

Table 9.2 Nitrogen utilisation efficiency and sorghum harvest index as affected by water and nutrient managements in 2001 and 2002 at Saria, Burkina Faso

	Harvest index	N utilization efficiency	Harvest index	N utilization efficiency
	2001	2001	2002	2002
T_0	0.38 b	20.9 c	0.58 ab	23.4 abc
T_{GS}	0.44 ab	22.7 bc	0.58 ab	28.5 ab
T_{SR}	0.39 b	26.9 abc	0.53 b	28.6 ab
T_U	0.56 a	35.3 a	0.59 ab	23.7 abc
T_{GSU}	0.44 ab	24.1 bc	0.59 ab	22.6 bc
T_{SRU}	0.45 ab	20.6 c	0 .50 b	17.7 c
T_C	0.49 a	32.3 ab	0.61 a	28.5 ab
T_{GSC}	0.50 a	34.9 a	0.56 ab	30.3 a
T_{SRC}	0.50 a	31.5 ab	0.60 a	24.5 ab
SD	0.04	2.84	0.04	1.9
Probability	0.008	0.0035	0.0248	0.0034
CV (%)	9.2	10.2	7.2	7.5

Nitrogen utilization efficiency (NUE) = Grain yield/crop exportation of N. Treatments explained in Figure 9.1.

9.3.2 Interaction effects of combining organic-N or fertilizer-N with SWC measures

Positive interactions ($\Delta Y(x1 + x2)$) of combined SWC measures and N-inputs were observed (Figure 9.2) apart for T_{GSU} in 2001 (-367 kg ha^{-1}) and T_{SRU} in 2001 (-437 kg ha^{-1}) and 2002 (-36 kg ha^{-1}). The negative interactions in the latter treatments were mainly explained by the higher response of sorghum yield to single N-inputs (T_C, T_U) than to single SWC measures (T_{SR}, T_{GS}), particularly during these two well-distributed rainfall years with little water stress (Figure 6.2). This is accordance with results of Fatondji et al. (2001) and Zougmoré et al. (2003b) who found in the same region that the supply of organic source of nutrients (manure, compost) in *zaï* and half-moons pits dug in a very degraded bare soil (locally called *zipellé*) leads to significant modifications of soil mineral status and increased crop yields. The high response of sorghum yield to single N-inputs (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.

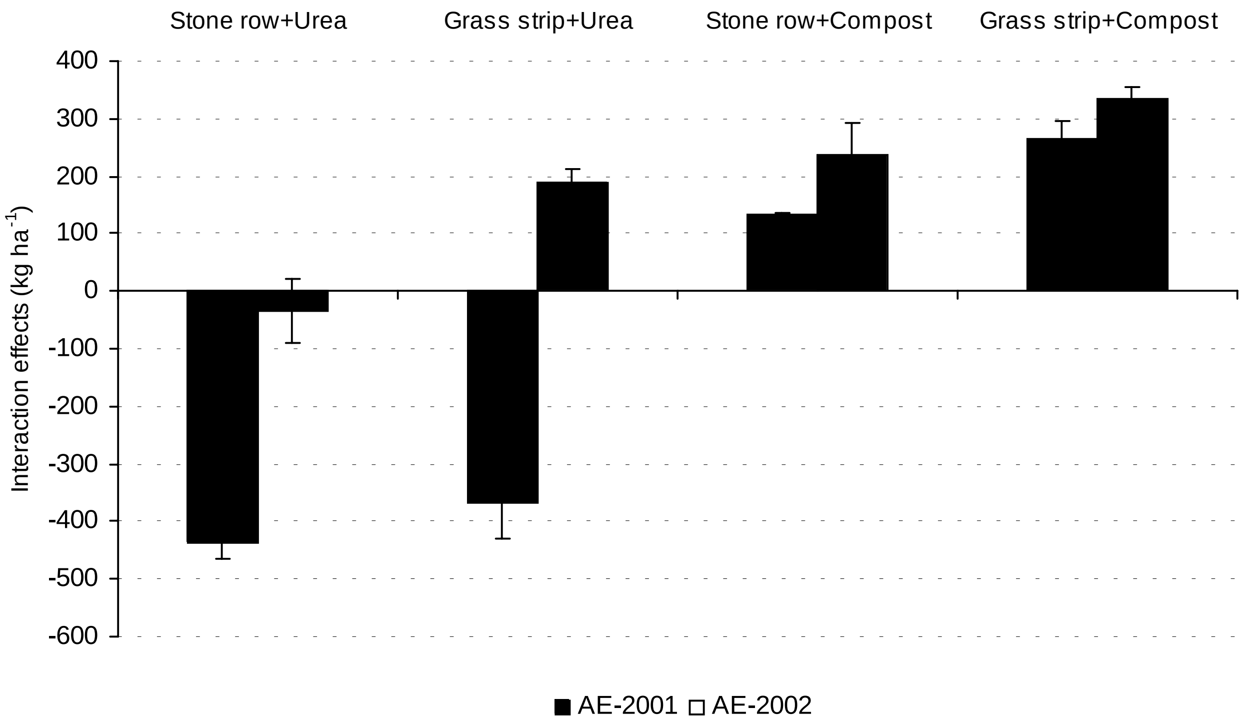

Figure 9.2 Interaction effects of combined SWC measures and compost or urea-N in 2001 and 2002 at Saria, Burkina Faso.

The positive interaction of combined SWC measures with compost-N was 1.3—1.7 times greater than when combined with urea-N. In 2001, treatments T_{SRC} and T_{GSC} showed positive interaction (132 kg ha^{-1} and 265 kg ha^{-1} respectively) whereas in 2002, treatments T_{SRC}, T_{GSC} and T_{GSU} showed higher positive interactions than in 2001 (Figure 9.2). This was mainly due to the cumulative and positive effect of successive application during two years of nutrient inputs particularly for compost-N. Moreover, rainfall distribution at maturing period in 2002 was better than in 2001 (Figure 6.2), which may have great impact on sorghum grain production. The higher response of yield to compost than to urea suggests that soil fertilizer recovery is low and a way to improve soil productivity would consist in increasing fertilizer recovery through urea and organic resource combination and the use of fertilizers that release slowly nitrogen (e.g.: urea super granules).

One should take care on whether the positive or negative interaction results into an economic benefit since this depends mainly on the yield level of treatments. Moreover, adoption by farmers of these technologies is only effective if they perceive a clear return on their direct investment costs (Dudal, 2002).

9.3.3 Economic benefit of water and nutrient management

Results in Table 9.3 imply that yield increases in 2001 and 2002 did not cover annual costs of stone rows or grass strips alone. Indeed, excess yields were negative for treatments T_{SR} (-210 kg ha^{-1}) and T_{GS} (-380 kg ha^{-1}). This confirms results of Zougmoré et al. (2000b) who found that when using truck transport under the project scenario (Local people work together to gather stones and build the stone rows on a given watershed or village during community workdays), stone rows construction (not combined with application of nutrient inputs) had no economic benefit for the individual farmer, as the grain yield increase does not cover the high cost of construction. Studies by de Graaff and Spaan (2000) in the same region concluded that the cost of constructing stone rows is too high for the individual farmer, certainly for marginal semi-arid Sahelian farmers. This suggests that stone row construction is only profitable if the investment costs are lowered by providing the transport of stones free of charge. Sorghum production was less in grass strips plots (particularly near the strips) than further away probably because of the shading from the grass and competition with sorghum plants for nutrients and water. The results above indicate that under Sahelian conditions, application of SWC measures cannot be justified on economic grounds. However, environmental and other benefits not considered in this study may still justify their application.

Table 9.3 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})	48312	48312	26240	26240
Sorghum average price (FCFA kg^{-1})	140	140	140	140
Minimum yield (kg ha^{-1})	345	345	187	187
ΔY (kg ha^{-1})	127	144	-203	-181
Excess yield (kg ha^{-1})	-218	-201	-390	-368
Economic benefit (FCFA ha^{-1})	-30520	-28140	-54600	-51520

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

Conversely, economic benefits of treatments in Table 9.4 showed that single application of compost-N or urea-N were cost-effective but supply of urea-N was less beneficial (6160 FCFA) in 2002 than compost-N (133040 FCFA).

Table 9.4 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
ΔY / ΔN (kg kg^{-1})	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})	113820	6160	127020	133040

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

Table 9.5 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 measures (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})	22120	7560	114940	109480	-27020	-18900	138180	128100

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

The combinaition of SWC measures with urea-N (T_{SRU}, T_{GSU}) or compost-N (T_{SRC}, T_{GSC}) induced positive economic benefits in 2001 (Table 9.5), 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. However, in 2002, compared to results of 2001, economic benefits for treatments with SWC measures and compost-N increased on average by 16% while economic benefits for combined SWC measures and urea-N treatments decreased by 200% and even showed negative values.

Economic benefits become more interesting when adding N-inputs to SWC measures that were installed some years ago and already repaid (Table 9.6). This is the case of cultivated areas in Burkina Faso that are nowadays largely implemented with SWC measures thanks to several agricultural projects.

Table 9.6 Economic benefit of adding N-inputs (urea-N or compost-N) to already paid SWC measures in 2001 and 2002, 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 kg^{-1})	3.9	3.9	5.4	5.4	3.9	3.9	5.4	5.4
Yield increase ($\Delta Y/\Delta N$) (kg kg^{-1})	11.4	12.8	26.2	28.8	4.06	8.56	29.16	31.06
Excess yield of N inputs (kg kg^{-1})	7.5	8.9	20.8	23.4	0.2	4.7	23.7	25.6
Excess yield of N input (kg ha^{-1})	376	446	1038	1171	8	233	1187	1282
Economic benefit of N inputs (FCFA ha^{-1})	52640	62440	145360	163980	1120	32620	166220	179520

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

Economic benefits obtained in 2001 when adding compost-N to both stone rows and grass strips were substantial (145000 to 164000 FCFA ha^{-1}) whereas acceptable amounts were observed with added urea-N (52500 to 62500 FCFA ha^{-1}). These values increased in 2002 for compost-N (166000 to 180000 FCFA ha^{-1}) compared to 2001 but decreased for urea-N (1000 to 33000 FCFA ha^{-1}).

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 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 a soil physical, chemical and biological balance that would accelerate crop root formation in the soil profile (Piéri, 1989). The greatest sorghum production resulting from this positive interaction effect of SWC measures and N-inputs explains their best economic benefits. Loss of available Urea-N through runoff or leaching could explain the least interactive effect of urea-N that has resulted in lower economic benefits than organic-N (Ouédraogo et al., 2003, in press).

9.4 Conclusions

Results of this study suggest that:

- 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 two years.
- Economic benefits when combining compost-N to both stone rows and grass strips were substantial (109000 to 138000 FCFA ha^{-1}) while the greatest amounts observed with added urea-N were small (7560 to 22120 FCFA ha^{-1}). The economic benefits were more substantial when adding compost-N to existing stone rows or grass strips that are already paid for (145000 to 180000 FCFA ha^{-1}) while acceptable benefits were observed with added urea-N (1120 to 62500 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 poor fertile soils.

Acknowledgement

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Compost production in pits, Saria, Burkina Faso

Compost production in heaps, Saria, Burkina Faso

Water retention uplospe a stone row in a farmer's field after a heavy rainfall, Sakoinsé, Burkina Faso

Experimental plots with sorghum crop at flowering stage, Saria, Burkina Faso

Experimental plots with sorghum crop at maturing stage, Saria, Burkina Faso

A woman harvesting sorghum, Saria, Burkina Faso

Chapter 10

Synthesis and conclusions

Integrated water and nutrient management in the Sahel

10.1 Introduction

Unreliable rainfall, inherent low soil fertility and crust-prone soils affect crop growth in the semi-arid zone of Burkina, resulting in low land productivity and therefore low crop yields and recurrent food shortage in most poor households. Given the current high population pressure on arable lands, recognition is growing that any increase in food production will largely have to originate from improved productivity per unit soil, water and nutrient. Therefore, the primary essential issue to address in order to increase crop yields will be the more efficient use of rainwater and soil nutrients. This implies reducing runoff, increasing water infiltration and retention in the crop-rooting zone, and using external inputs judiciously. This will create favorable conditions that may sustain crop production and allow soil potential yields. In the foregoing chapters of this thesis, the results of applying semi-permeable soil and water conservation measures and organic or fertilizer sources of nutrients, individually and in combination were presented. They were evaluated in terms of the soil water and nutrient use efficiency, and on the soil water and nutrient balances under continuous sorghum cropping in semi-arid Burkina Faso. It was hypothesized that synergy (positive interaction) could be achieved through integrated water and nutrient management. In the sections below, the main conclusions of the research are summarized, considering each soil and water conservation measure and nutrient management.

10.2 Stone rows

Chapter 2 shows that on the sandy-loamy and crust prone soils of the semi-arid Sahelian zone of Burkina, stone rows are SWC measures that greatly reduce runoff and improve soil moisture. The efficiency of stone rows, however, was found to be dependent on the spacing between the rows: the wider the spacing, the less effect on runoff and soil water storage. Under water-limiting conditions, stone rows improve sorghum yields by 2–3 times compared to plots without stone rows. This indicates that stone rows can help mitigate the effect of drought and, therefore, reduce the risk of crop failure during erratic rainy seasons. The results also showed that during good rainfall years (with regular rainfall distribution), the beneficial effects of stone rows were lessened and the resulting major accumulation of water in fields could even lead to water logging and, therefore, could harm crop production.

In Chapter 3, to determine the optimal economic spacing of stone rows a method called maximizing net present value was developed, and applied over three successive and contrasting rainy seasons. This analysis suggests that the optimum spacing of stone rows depends on the type of construction, the transport cost and how labor is organized. The results indicate that under the conditions of the semi-arid Sahelian zone of Burkina, the optimal spacing for a farmer who can construct stone rows with farm tools using stones available close to the field is between 23 m and 45 m. For the more common case of a farmer who works with an NGO to trace contours and transport stones, the net present value maximizing spacing is 30 to 43 m. Because labor inputs are high, yield increases do not cover the costs of constructing stone rows in the community project scenario; however, environmental and other benefits not considered here may still justify this type of project.

From the results of soil chemical analysis (Chapter 4) it was concluded that under unfertilized continuous sorghum cropping systems in Sahelian zones, stone rows induced negative effects on soil fertility. The finding supporting this conclusion was that five years after laying stone rows, a drop in soil pH and organic C, N, and P concentrations was observed. This implies that when stone rows are used, external nutrient inputs must also be applied, to ensure crops grow well.

10.3 Grass strips

Because of the large-scale implementation of stone rows through government agricultural projects and NGO's, stones are becoming scarce and this could limit the further adoption of this soil and water conservation practice. Grass strips have therefore been promoted as an alternative semi-permeable barrier. In Chapter 5, it became clear that stone rows reduce runoff and soil loss more efficiently than strips of the grass *Andropogon gayanus*. However, the differences were small when the two SWC barriers were combined with organic amendments. Indeed, on average, stone rows reduced runoff by 10 % more than grass strips when combined with compost, by 28 % when combined with urea and by 19 % when applied alone. After three years, soil loss was reduced by only 4 % more with stone rows than with grass strips when combined with compost, 19 % when combined with urea and 13 % when stone rows and grass strips are applied alone. Overall, both stone rows and grass strips were more efficient in reducing runoff and soil loss than the control (no SWC measure), indicating that like stone rows, grass strips play a major role in rainwater harvesting, improve soil water storage (Chapter 6) and limit sediment and nutrient losses through runoff (Chapter 7). However, the competition of the grass for light, water and nutrients affects crop productivity (Chapter 5). An important benefit of grass strips is that their by-products can be exploited for the home (baskets, hats, doors and roofs for houses, etc.) and for feeding livestock, without decreasing their water-harvesting effect.

It is concluded that as an anti-erosive measure, grass strips could be an interesting alternative to stone rows in semi-arid West Africa.

10.4 Nutrient management

Chapter 5 indicates that the sole application of compost induced greater reduction of runoff and sediment transport than the sole application of urea. After two successive years' application, solely applying compost reduced runoff and soil loss as much as the stone rows did. The effect of organic or mineral sources of nutrients on the soil–plant water balance was discussed in Chapter 6. During rainy seasons with well-distributed rainfall, the sole application of compost improved soil water storage more than the sole application of urea. However, soil water storage was lower in compost plots than in urea plots during rainy seasons with erratic rainfall, because water consumption (plant transpiration) was higher due to the greater biomass in composted plots. The sole application of compost or urea improved the water use efficiency and sorghum yield more than using stone rows or grass strips (Chapter 5). Chapter 7 indicates that compost application reduced sediment transport, organic C and nutrient losses more than urea application, although both induce high nutrient concentrations in eroded materials. The application of urea induced greater loss of N through leaching than application of compost (Chapter 8).

10.5 Synergy of water and nutrient management

The synergistic effect of SWC measures and nutrient inputs emerged in several Chapters as the best way to reduce runoff, soil loss and improve nutrient use efficiency. Indeed, during the three years, stone rows and grass strips combined with compost induced the least runoff. The same trends were reported for soil erosion and nutrient losses, with compost application consistently performing better than urea application. All these improved soil, water and nutrient conditions increased nutrient uptake; as evidenced by the crop product N being higher in plots receiving N than in plots not given N. Furthermore, during the study period, the water and nutrient use were most efficient in treatments that combined SWC measures and compost or urea (Chapters 5, 6 and 9). The slight differences in water and nutrient use efficiency between treatments in which a SWC measure was combined with nutrient input, and treatments with sole application of nutrient suggest that in years with well distributed rainfall, the improvement in crop production was determined more by nutrient supply than by water retention by the SWC barriers. Therefore, crop growth was boosted, which led to significantly increased sorghum grain and straw yields (Chapters 5 and 9). On average, compared to the control, sorghum yield increase as a combined effect of SWC measure and nutrient input was 148 % for stone rows + compost, 136 % for grass strips + compost, 55 % for stone rows + urea and 24% for grass strips + urea (Chapter 9). Both semi-permeable barriers combined with nutrient inputs induced positive interactions and economic benefits. The economic benefits of the combinations were even greater with grass strips than with stone rows, which are more costly to install. These benefits can empower farmers to invest in soil management for better crop production.

10.6 Conclusion

Improving arable land productivity for increased food production and reduced risks in West African smallholder farming is an enormous challenge. This study contributed to the theoretical background of the sole and interaction effect of semi-permeable barriers and nutrient inputs on runoff, soil loss and on soil water and nutrient balance in a sorghum-based system in semi-arid Burkina Faso. The empirical results reported in this thesis indicate that runoff and erosion control through application of locally accepted soil and water conservation measures increased soil water storage and improved water availability. Through application of external sources of nutrients (organic or mineral), soil nutrient availability was improved. The integration of water and nutrient management through the combination of SWC measures and the application of organic or mineral N inputs improved water use efficiency and nutrient uptake, boosting crop production. The main advantage of this synergy is the substantial economic benefit of 145 000 to 180 000 FCFA ha^{-1} y^{-1} when adding compost-N to both stone rows and grass strips. This may help reduce poverty and may allow farmers to purchase agricultural inputs such as transport equipment (wheelbarrow, cart), fertilizers, improved varieties, etc., that will undoubtedly boost the intensification of agriculture.

10.7 Recommendation

Further adoption and success of these efficient biophysical practices depends on farmers using their local knowledge, innovations and social realities when implementing them in their individual fields. To that end, innovative farmers may play a major role in the adaptation of these practices to local situations and may allow widespread adoption through the ripple effect. In view of the substantial economic benefits, there is a need to develop a market policy for agricultural food crops that makes the production of such crops more competitive and cost-effective. This could improve farmers' income and may stimulate them to invest in their soils. The above issues are prerequisite to establish favorable socio-economic conditions for sustainable agricultural production in the Sahel.

Samenvatting

Onbetrouwbare neerslag, lage bodemvruchtbaarheid en korstgevoelige gronden hebben een negatieve invloed op de gewasgroei in de semi-aride zone van Burkina Faso. Een lage productiviteit en daardoor lage gewasopbrengst zijn het gevolg. Dit resulteert in regelmatig optredende voedseltekorten in de meeste arme huishoudens. Er bestaat een stijgend bewustzijn dat een toename in de voedselproductie, bij de huidige bevolkingsdruk, alleen bereikt kan worden door een verhoogde productiviteit per eenheid bodem, water en nutriënt. Om dit te bereiken is het essentieel om regenwater en bodemnutriënten efficiënter te gebruiken. Dit betekent de reductie van afstroming, het verhogen van de infiltratie en de retentie van het geïnfiltreerde water in de wortelzone van de bodem, maar ook het voorzichtig gebruik van externe nutriënten. De condities voor duurzame gewasproductie kunnen hierdoor worden geoptimaliseerd waardoor, bij de bodem behorende, potentiële opbrengsten mogelijk worden. Deze thesis behandelt de resultaten van het enkelvoudige en gecombineerde effect van half-doorlatende bodem- en waterconservering (BWC) maatregelen én de toediening van organische- en kunstmest. Gekeken is naar bodemwater- en nutriëntenefficiëntie en bodemwater- en nutriëntbalansen onder continue teelt van sorghum in de semi-aride zone van Burkina Faso. De hypothese luidt dat synergie (positieve interactie) kan worden bereikt door middel van geïntegreerd water- en nutriëntenbeheer. In de volgende secties zullen de resultaten van het onderzoek worden samengevat per BWC-maatregel en per wijze van nutriëntentoediening.

Stenenrijen

In Hoofdstuk 2 wordt besproken dat, op de lemig-zandige en korstgevoelige gronden van de semi-aride Sahel van Burkina Faso, stenenrijen een BWC-maatregel is die afstroming reduceert en een positieve invloed heeft op het bodemvocht. Echter, de efficiëntie van stenenrijen is afhankelijk van de afstand tussen de rijen; hoe groter de afstand, des te minder het effect op de afstroming en het bodemvocht. In situaties waar water een limiterende factor voor de gewasgroei is, resulteerden stenenrijen in een sorghum oogst welke 2 tot 3 keer hoger was dan op velden zonder stenenrijen. Dit toont aan dat stenenrijen kunnen bijdragen aan een reductie van de gevolgen van droogte op gewasopbrengsten en daardoor het risico van het mislukken van oogsten tijdens perioden van onregelmatige neerslag kunnen verkleinen. De resultaten van het onderzoek lieten echter ook zien dat tijdens goede regenvaljaren (met regelmatige neerslagverdeling), de positieve effecten van de

stenenrijen verminderden. Het tegengehouden water boven de stenenrijen resulteerde dan zelfs in stagnerend water en zou daardoor zelfs schadelijk voor de gewasproductie kunnen zijn.

In Hoofdstuk 3 wordt een methode ontwikkeld om de optimale economische afstand tussen stenenrijen te bepalen. Deze methode is gebaseerd op het maximaliseren van de netto contante waarde en is toegepast op drie opeenvolgende (en van elkaar verschillende) regenseizoenen. Uit de analyse blijkt dat de optimale afstand tussen de stenenrijen afhangt van het type constructie, de transportkosten en arbeidsorganisatie. Onder de semi-aride condities in de Sahel zone in Burkina Faso blijkt de optimale afstand tussen twee stenenrijen 23–45 m te zijn. Deze afstand geldt voor een boer die de rijen zelf kan aanleggen met behulp van zijn eigen gereedschappen en met stenen uit de omgeving van het veld. Meer algemeen echter is het geval van een boer die samenwerkt met een NGO welke helpt bij het uitzetten van de hoogtelijnen en bij het vervoer van de stenen. In dit soort 'community' projecten ligt de optimale afstand op 30–43 m. Als gevolg van de hoge arbeidsinput dekken de hogere gewasopbrengsten niet de kosten van de aanleg van de stenenrijen bij deze projecten. Ecologische- en andere, hier niet besproken, belangen kunnen echter toch voldoende rechtvaardiging voor dergelijke NGO projecten zijn.

De resultaten van bodemchemische analyses tonen dat onder onbemeste en continue sorghumteelt in de Sahel zone, stenenrijen een negatief effect hebben op de bodemvruchtbaarheid (Hoofdstuk 4). Er werden een verlaging in de pH en in de organische C, N en P concentraties gemeten na vijf jaar gewasteelt in een stenenrijensysteem. Dit impliceert dat de implementatie van stenenrijen gepaard zou moeten gaan met de applicatie van externe nutriënten.

Grasstroken

Als gevolg van het op grote schaal toepassen van stenenrijen door regerings- en NGO projecten, zijn stenen schaars geworden en vormen zij een beperkende factor voor de verdere toepassing van deze BWC-maatregel. Grasstroken worden daarom aanbevolen als een alternatieve semi-permeabele barrière. In Hoofdstuk 5 wordt besproken dat stenenrijen effectiever zijn in de reductie van afstroming dan *Andropogon Gayanus* (een lokaal voorkomend meerjarig gras). Ook in de reductie van bodemverliezen bleek de stenenrijen efficiënter. De verschillen bleken echter gering nadat deze twee BWC-maatregelen werden gecombineerd met het toedienen van organische mest. Gecombineerd met compost was de reductie van afstroming bij stenenrijen 10 % meer dan de reductie bij grasstroken, 28 % meer dan in combinatie met ureum en 19 % meer dan zonder additionele toevoeging. Na drie jaar was de reductie van het bodemverlies op de velden met stenenrijen met compost slechts 4 % meer dan op de velden met de grasstroken met compost. Op de ureum velden was dit 19 % en op de velden zonder toevoegingen 13 %. Zowel de stenenrijen als de grasstroken waren efficiënter in de reductie van afstroming dan de 'control' (zonder maatregelen). Dit impliceert dat, evenals de stenenrijen, grasstroken een belangrijke rol spelen bij 'rainwater harvesting', de opslag van bodemvocht verbeteren (Hoofdstuk 6) en het verlies van sedimenten en nutriënten beperken (Hoofdstuk 7). Echter, de competitie van het gras voor licht, water en nutriënten heeft invloed op de gewasproductie (Hoofdstuk 5). Maar een belangrijk voordeel van de grasstroken is de mogelijkheid om de bijproducten voor huishoudelijke doeleinden (manden, hoeden, deuren, daken etc.) en als veevoer te gebruiken, zonder dat het effect van de grasstroken op de afstromingreductie vermindert. Wij concluderen dat, in semi-aride West Afrika, grasstroken een interessant alternatief kunnen zijn voor stenenrijen.

Nutriëntenbeheer

In Hoofdstuk 5 wordt besproken dat de toediening van uitsluitend compost een groter effect heeft op de afstroming en het sedimenttransport dan de toediening van uitsluitend ureum. Na twee opeenvolgende jaren van toedienen van compost was het effect van deze toediening op de afstroming en bodemverlies net zo groot als het effect van stenenrijen. Het effect van organische en minerale nutriënten op de bodem-plant waterbalans wordt besproken in Hoofdstuk 6. Tijdens regenseizoenen met regelmatig verdeelde neerslag, verbetert het toedienen van uitsluitend compost de hoeveelheid vastgehouden bodemvocht meer dan het toedienen van uitsluitend ureum. De hoeveelheid vastgehouden bodemvocht was echter lager in de compostvelden dan in de ureumvelden tijdens regenseizoenen met onregelmatig verdeelde neerslag. Dit als gevolg van het hogere watergebruik (transpiratie) van de gecomposteerde velden vanwege een hogere biomassa. De toediening van uitsluitend compost of ureum verbeterde de 'water use efficiency' en de sorghumopbrengst meer dan stenenrijen of grasstroken (Hoofdstuk 5). Hoofdstuk 7 beschrijft dat de toediening van compost het sedimenttransport en het organisch C- en nutriëntenverlies meer vermindert dan de toediening van ureum, alhoewel beide toedieningen hoge nutriëntconcentraties in het geërodeerde materiaal veroorzaken. De toediening van ureum veroorzaakte een groter verlies van N door uitspoeling dan de toediening van compost (Hoofdstuk 8).

Synergie van water- en nutriëntbeheer

Het synergetisch effect van BWC-maatregelen en toegediende nutriënten komt in verschillende hoofdstukken naar voren als de beste manier om afstroming en bodemverliezen te beperken en om de efficiëntie van nutriëntengebruik te verbeteren. Inderdaad bleek gedurende de drie jaar van het onderzoek dat op de velden waarop stenenrijen of grasstroken gecombineerd werden met compost de minste afstroming gegenereerd werd. Dezelfde trends werden geconstateerd voor bodemerosie en nutriëntverliezen, met telkens betere resultaten voor compost dan voor ureum. Alle situaties met verbeterde bodem-, water- en nutriënten-condities resulteerden in een hogere nutriëntopname door het gewas; voor een deel is dit bevestigd door de hogere N-waarden in het gewas op de velden welke wel N toegediend kregen ten opzichte van de velden die geen N toegediend kregen. Ook werden tijdens de onderzoeksperiode de hoogste water- en nutriëntenefficiënties waargenomen op de velden waar BWC-maatregelen met compost of ureum werden gecombineerd (Hoofdstukken 5, 6 en 9).

Het kleine verschil in water- en nutriëntenefficiëntie tussen die behandelingen die BWC-maatregelen met nutriënteninput combineerden en die behandelingen waar de nutriënttoediening zonder BWC-maatregelen werden toegepast, doet vermoeden dat, tijdens jaren met een goede regenval verdeling, nutriënttoediening meer dan waterconservering door een BWC-maatregel, de bepalende factor was voor de verbetering van de gewasproductie. Hierdoor werd de gewasgroei gestimuleerd, wat tot een significante verhoging van de sorghum graan- en stro-oogsten leidde (Hoofdstukken 5 en 9). Gemiddeld, vergeleken met het controle veld, was de toename van de sorghumoogst bij een BWC-maatregel gecombineerd met nutriëntinput 148 % voor stenenrijen + compost, 136 % voor grasstroken + compost, 55 % voor stenenrijen met ureum en 24 % voor grasstroken met ureum (Hoofdstuk 9). Beide semi-permeable barrières gecombineerd met nutriënten veroorzaakten positieve interacties en economische voordelen. De economische voordelen van de combinaties waren groter voor de grasstroken dan voor de stenenrijen, aangezien deze laatste hogere aanlegkosten hebben. De voordelen kunnen boeren aanzetten om te investeren in bodembeheer voor betere gewas productie.

Conclusie

Het is een enorme uitdaging om de productiviteit van akkerland te verbeteren om zodoende de voedselproductie te verhogen en het bedrijfsrisico van kleinschalige boeren in West Afrika te verkleinen. Deze studie heeft een bijdrage geleverd aan het theoretisch kader van de toediening van halfdoorlatende BWC-maatregelen en nutriënten op afstroming, bodemverlies en de water- en nutriëntenbalans in een sorghum teeltsysteem in het semi-aride deel van Burkina Faso. De empirische resultaten van het onderzoek waarover deze thesis rapporteert laten zien dat de beheersing van afstroming en erosie door de toepassing van lokaal geaccepteerde BWC-maatregelen de hoeveelheid bodemvocht kunnen verhogen en de beschikbaarheid van water voor het gewas doen toenemen. Door de toediening van externe nutriënten (organisch en mineraal) is de beschikbaarheid van bodemnutriënten verbeterd. Het integreren van water- en nutriëntenbeheer door een combinatie van BWC-maatregelen en de toepassing van organische- of minerale-N verbeterde de 'water use efficiency' en de nutriëntenopname, waardoor gewasproductie geïntensifieerd wordt. Het belangrijkste voordeel van het synergetisch effect is een substantieel economisch voordeel: 145.000 tot 180.000 FCFA ha^{-1} j^{-1} wanneer er compost wordt toegediend op velden waar stenenrijen of grasstroken al eerder werden aangelegd. Dit zou kunnen bijdragen tot de reductie van armoede en kan het boeren mogelijk maken om agrarische inputs zoals transportmaterialen (kruiwagen, kar), kunstmest, verbeterde variëteiten, etc., aan te schaffen. Zonder twijfel zal dit de agrarische intensivering een grote impuls geven.

Aanbeveling

De verdere adoptie en het succes van deze efficiënte biofysische maatregelen hangt af van het boereninitiatief om gebruik te maken van lokale kennis, innovaties en de sociale realiteit tijdens de implementatie in hun individuele velden. Innovatieve boeren kunnen een belangrijke rol spelen bij de aanpassing van de maatregelen aan lokale situaties en kunnen een olievlek effect veroorzaken. Gezien het substantiële economische voordeel, bestaat er een noodzaak om een marktbeleid te ontwikkelen voor voedselgewassen, welke er voor zal zorgen dat ook deze gewassen meer competitief en kosteneffectief geproduceerd zullen worden. Hierdoor zou het inkomen van boeren kunnen verbeteren en dit zou hen kunnen stimuleren om te investeren in hun velden. Bovenstaande is welhaast voorwaarde om een sociaal economisch klimaat te creëren waarin een duurzame landbouwproductie in de Sahel ontwikkeld kan worden.

Résumé

Introduction

Le caractère erratique des pluies, la faible fertilité inhérente des sols et la grande susceptibilité des sols à l'encroûtement sont les principaux facteurs qui affectent la croissance des cultures en zone semi-aride du Burkina Faso. Les conséquences sont la faible productivité des terres entraînant de faibles rendements des cultures et des risques fréquents d'insécurité alimentaire pour la majorité des petites exploitations agricoles. Face à la forte pression actuelle sur les terres cultivables, il est de plus en plus reconnu que l'augmentation de la production alimentaire proviendrait d'une amélioration de la productivité par unité de sol, d'eau et de nutriments. Ainsi, un premier point essentiel qui devrait conduire à l'augmentation des rendements consisterait en une utilisation efficiente des eaux pluviales et des éléments nutritifs du sol. Cela suppose une réduction du ruissellement, une augmentation de l'infiltration et de la rétention d'eau dans la zone d'exploration racinaire des cultures, et une utilisation judicieuse des intrants externes. Les indications ci-dessus citées créent des conditions favorables qui permettraient d'obtenir une production agricole durable et d'atteindre des rendements potentiels des sols. La présente étude a évalué l'effet seul ou combiné des barrières semi-perméables de conservation des eaux et des sols (CES) et de la fertilisation organique ou minérale, sur l'efficacité d'utilisation de l'eau et des nutriments du sol dans un système de culture continue de sorgho en zone semi-aride du Burkina Faso. L'effet des techniques sur les bilans hydriques et minéraux a été également étudié. L'hypothèse de base était qu'on aboutirait à une interaction positive (synergie) grâce à la gestion intégrée de l'eau et des nutriments du sol. Les principales conclusions de cette recherche ont été résumées ci-dessous par technologie étudiée.

Les cordons pierreux

Sur les sols sablo-limoneux susceptibles à l'encroûtement de la zone sahélienne du Burkina, les cordons pierreux sont des mesures de CES qui réduisent efficacement le ruissellement et améliorent ainsi l'humidité du sol (Chapitre 2). Cette efficacité des cordons dépend cependant de l'espacement entre les cordons : Plus l'espacement est large, moins est l'impact sur le ruissellement et le stockage d'eau du sol. En année à saison pluvieuse irrégulière, les cordons pierreux ont induit une augmentation des rendements de 2 à 3 fois comparés à un champ non aménagé. Cela indique que les

cordons pierreux contribueraient à atténuer les effets de la sécheresse et partant, à réduire les risques d'échec des cultures pendant les années à pluviosité erratique. Les résultats ont également montré que pendant les saisons pluvieuses avec une bonne distribution des pluies, l'effet bénéfique des cordons devenait plus réduite et que le stockage important d'eau dans les champs pouvait même être néfaste pour les cultures.

Une méthode pour déterminer l'écartement économiquement optimal entre cordons a été développée dans le chapitre 3, et appliquée durant trois années successives aux saisons pluvieuses contrastées. Cette étude a montré que l'écartement économiquement optimal dépendait de la méthode d'aménagement des cordons, du coût de transport des moellons et du type d'organisation du travail d'aménagement. Les résultats ont montré que dans la zone sahélienne du Burkina Faso, pour un paysan qui peut construire les cordons en utilisant son propre petit matériel et en disposant de cailloux à proximité du champ, l'écartement optimal se situait entre 23 m et 45 m. Dans le cas le plus commun d'un paysan qui bénéficiait de l'aide d'une ONG pour le traçage des courbes de niveau et le transport des moellons, l'écartement était situé entre 30 et 43 m. Dans le scénario où les aménagements étaient réalisés en communauté comme c'est souvent le cas avec les projets de développement, l'augmentation des rendements n'arrivait pas à couvrir les coûts de construction à cause du coût élevé de l'investissement en main d'œuvre ; D'autres bénéfices autres que purement économiques (ex : environnementaux) non pris en compte dans cette étude pourraient justifier ce type de projet.

Au chapitre 4, il est montré que dans un système de culture continue de sorgho sans fertilisation en zone sahélienne, les cordons pierreux ont induit un effet négatif sur la fertilité du sol. En effet, cinq ans après l'installation des cordons, on a observé une baisse du pH et des teneurs du sol en carbone, en azote et en phosphore. Cela indique la nécessité d'accompagner les aménagements de cordons pierreux d'un apport de fertilisants.

Les bandes enherbées

En raison de l'importance des superficies aménagées en cordons pierreux grâce aux projets étatiques et aux ONG, la disponibilité et l'éloignement des sites de moellons deviennent de plus en plus des facteurs limitants pour une continuelle adoption et mise en oeuvre de la technique. De ce fait, l'utilisation alternative des bandes enherbées comme mesure semi-perméable est encouragée par la vulgarisation. Au chapitre 5, il a été clairement montré que les cordons pierreux réduisent le ruissellement et les transports solides plus efficacement que les bandes enherbées à *Andropogon gayanus*. Cependant, les différences d'efficacité entre cordons et bandes enherbées deviennent plus petites lorsque les deux mesures sont combinées à un apport d'amendement organique. En effet, en moyenne, les cordons pierreux ont réduit le ruissellement de 10% plus que les bandes enherbées quand ils étaient combinés à un apport de compost, 28% quand ils étaient combinés à un apport d'urée et 19% quand les cordons pierreux ou les bandes enherbées étaient appliqués sans aucun apport de fertilisant. Trois ans après l'installation des mesures semi-perméables, l'érosion a été réduite par les cordons pierreux de seulement 4% plus qu'avec les bandes enherbées quand tous deux sont combinés à un apport de compost, 19% quand ils sont combinés à un apport d'urée et 13% quand ils sont appliqués sans fertilisation. De façon générale, l'aménagement de cordons pierreux ou de bandes enherbées a induit une réduction plus efficace du ruissellement et de l'érosion qu'une parcelle non aménagée, indiquant que tout comme le cordon pierreux, la bande enherbée joue un rôle majeur dans la collecte d'eau de pluie, améliore le stock d'eau du sol (Chapitre 6) et limite les pertes de sédiments et de nutriments du sol par ruissellement (Chapitre 7). Cependant, la compétition des bandes pour la lumière, l'eau et les éléments nutritifs affecte la productivité des cultures (Chapitre 5). Un important bénéfice des bandes enherbées est la possibilité d'utilisation à des fins domestiques des sous produits (paniers, chapeaux, toits de maison, etc.) et aussi comme fourrage pour le bétail sans cependant diminuer leur efficacité anti-érosive.

Fort de ce qui précède, nous concluons que la bande enherbée pourrait être une intéressante mesure anti-érosive alternative au cordon pierreux en zone semi-aride d'Afrique de l'Ouest.

La gestion des nutriments du sol

Au Chapitre 5, il est indiqué que l'application de compost seul a réduit le ruissellement plus que l'application d'urée seule. Après deux années successives de bonne pluviosité, l'application de compost seul a réduit le ruissellement et les transports solides autant que les cordons pierreux. L'effet des fumures organique ou minérale sur le bilan hydrique du sol est discuté au Chapitre 6. En année avec une bonne distribution des pluies, l'application de compost seul a amélioré le stock d'eau du sol plus que l'application d'urée seule. Cependant, le stock d'eau était plus faible avec l'application de compost qu'avec l'application d'urée en année à pluviosité erratique. Cela est dû à la consommation plus élevée d'eau (par transpiration des plantes) liée à la plus importante biomasse de sorgho avec l'application du compost. L'application de compost seul ou d'urée seule a amélioré l'efficacité d'utilisation de l'eau plus que les cordons pierreux ou les bandes enherbées (Chapitre 5). Les résultats au Chapitre 7 indiquent que l'application de compost réduit les transports de sédiments, de matière organique et de nutriments plus que l'application d'urée. Les teneurs en éléments nutritifs des sédiments érodés et de l'eau de ruissellement étaient toutefois très élevées dans ces deux traitements. On a observé une plus grande perte d'azote par lixiviation avec l'application d'urée qu'avec l'application de compost (Chapitre 8).

La synergie des techniques de gestion d'eau et de nutriments

L'effet synergique des mesures de CES et des apports de nutriments est ressorti dans plusieurs chapitres comme le meilleur moyen de réduire le ruissellement et l'érosion du sol, et d'améliorer l'efficacité d'utilisation des éléments nutritifs par le sorgho. En effet, durant les trois années d'étude, la combinaison des cordons pierreux ou des bandes enherbées avec l'application de compost a induit les plus faibles ruissellements. Les mêmes tendances étaient observées pour les transports de sédiments et les pertes d'éléments nutritifs par érosion hydrique, avec toujours une meilleure performance de l'application de compost par rapport à celle de l'urée. Ainsi, l'amélioration de l'état hydrique et minéral du sol a induit une augmentation de l'utilisation des éléments nutritifs du sol par les plantes ; Cela est confirmé par les exportations plus élevées d'azote par les plants dans les parcelles ayant reçu un apport azoté comparées aux parcelles sans apport azoté. De même, tout au long de la période d'étude, les plus fortes valeurs d'efficacité d'utilisation de l'eau et des nutriments ont été observées dans les traitements combinant les mesures de CES avec l'application de nutriments (Chapitre 5, 6 et 9). Les faibles différences d'efficacité d'utilisation de l'eau et des nutriments constatées entre les traitements combinant les mesures de CES avec l'application de nutriments (compost, urée) et les traitements avec seulement des apports de nutriments, indiquent qu'en année à bonne pluviosité, l'apport de nutriments plus que la rétention d'eau par les mesures de CES, a été plus déterminante dans l'amélioration dans la production agricole. Ainsi, la croissance du sorgho s'en est renforcée, conduisant ainsi à une augmentation significative des rendements en grains et en paille (Chapitres 5 et 9). Comparé au témoin, l'augmentation de rendement du sorgho résultant de la combinaison des mesures de CES avec la fertilisation a atteint en moyenne 148% pour la combinaison cordons pierreux-compost et 136% pour la combinaison bandes enherbées-compost ; L'augmentation était de 55% pour la combinaison cordons pierreux-urée et 24% pour la combinaison bandes enherbées-urée (Chapitre 9). La combinaison des deux mesures semi-perméables de CES avec la fertilisation a induit des interactions positives et des bénéfices économiques. Les gains étaient plus élevés dans les combinaisons avec les bandes enherbées qu'avec les cordons pierreux, ces derniers ayant un coût d'installation plus élevé que celui des bandes enherbées. Ces bénéfices économiques pourraient augmenter la capacité des paysans à investir dans la gestion de leurs terres pour une meilleure production agricole.

Conclusion

L'amélioration de la productivité des terres cultivables pour une augmentation de la production alimentaire et une réduction des risques d'insuffisance alimentaire pour les petites exploitations agricoles en Afrique de l'Ouest est un énorme challenge. Cette étude a analysé et expliqué les processus en jeu dans l'effet seul ou combiné des barrières semi-perméables et des apports de nutriments sur le ruissellement, les pertes en terre et sur les bilans hydrique et minéraux du sol dans un système de culture à base de sorgho. Les résultats de cette thèse indiquent que le contrôle du ruissellement et de l'érosion du sol à travers l'application de mesures de CES localement adaptées et acceptées, a augmenté le stockage d'eau du sol et amélioré la disponibilité en eau pour les plantes. La disponibilité en éléments nutritifs du sol a été améliorée grâce à l'utilisation de apports de nutriments (organique ou minérale). La gestion intégrée de l'eau et des nutriments à travers la combinaison des mesures de CES avec l'application d'azote (ressources organique ou minérale) a amélioré l'efficacité d'utilisation de l'eau et des éléments nutritifs du sol par le sorgho ; cela a permis une intensification de la production agricole. L'avantage majeur de cette synergie est le bénéfice économique substantiel de 145000 FCFA à 180000 FCFA ha^{-1} an^{-1} quand on applique du compost sur des champs aménagés avec des cordons pierreux ou des bandes enherbées. Ce gain pourrait contribuer à réduire la pauvreté et permettrait en outre aux paysans d'acquérir des intrants agricoles tels que le matériel de transport (Charrette, brouette), les engrais, les semences améliorées, etc., qui à n'en point douter, viendront renforcer l'intensification de l'agriculture.

Recommandation

Une adoption et un succès davantage plus accrus de ces pratiques techniquement efficaces dépendent aussi des initiatives paysannes à intégrer leur savoir faire ainsi que les innovations et réalités sociales lors de la mise en œuvre dans leur champs individuels. Pour ce faire, les paysans innovateurs pourraient jouer un rôle majeur dans l'adaptation de ces pratiques aux différentes conditions locales. Ils pourraient également favoriser une adoption plus grande des pratiques par effet ''tache d'huile'' dans leurs zones. Au vu des bénéfices économiques substantiels, le développement d'une politique de marché spécifique pour les cultures alimentaires de base s'avère une nécessité impérieuse ; le but est de rendre ces produits plus compétitifs et plus rentables de façon à améliorer les revenus des paysans, ce qui pourrait les stimuler à investir dans le capital sol. Ce sont là quelques exigences préalables pour créer des conditions socio-économiques favorables à une production agricole durable au Sahel.

Curriculum Vitae

Robert Bellarmin Zougmoré was born on 13 May 1967 in Tenkodogo, Burkina Faso. He spent 6 years at the military school of Ouagadougou where he obtained two basic military diplomas. He finished his high school at *Lycée Zinda* in 1986, Ouagadougou, where he obtained his *BAC-D* in mathematics and natural sciences. He entered the University of Ouagadougou (*Institut des Sciences de la Nature*) and obtained after two years study a bachelor in chemistry and biology. He then studied agronomy in the Instute for Rural Development and obtained the degree of Master in rural development techniques in 1990. He was graduated in 1991 as Engineer of rural development with specialisation in agronomy. In the same year, he was employed at the National Research Institute for Agriculture (INERA, Burkina Faso) as a research assistant in the area of soil and water conservation. From 1992 to 2002, he coordinated INERA research activities on soil and water conservation for the IFAD special program of soil and water conservation and agroforestry (CES/AGF) in the Central Plateau of Burkina Faso. Part of the studies reported in this thesis was carried out in the framework of this project. He was also involved in research programs of several networks (Cover crops network, Nutrient monitoring network, InterCRSP, Réseau Erosion, Fallow research program in West Africa). He was admitted as a PhD student in the Erosion and Soil and Water Conservation Group of Wageningen University in 2000. Robert Zougmoré is married and at the moment, is father of one son. E-mail: rb_zougmore@hotmail.com