



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

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Abstract

Efficient use of external inputs and water conservation are a prerequisite of sustainable agricultural productivity in semiarid West Africa. A field experiment was carried out during 3 years (2000–2002) at Saria in semiarid Burkina Faso (800 mm of annual rainfall, PET of 2000 mm per year) 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) nitrogen and the combined use of SWC and compost-N or urea-N on N flows and balances. The trial was conducted on a Ferric Lixisol with 1.5% slope and comprised nine treatments in two replications. The SWC measures 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 N exports by sorghum biomass and soil erosion-induced N losses. Large amounts of N (7 kg N ha⁻¹ per year in 2000 and 44 kg N ha⁻¹ per year 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. Sole stone rows and grass strips reduced erosion N losses to 8 and 12%, respectively, of the total annual loss. The combined application of SWC measures and nutrients inputs reduced erosion N losses to only 2–7% of the annual N loss. The application of urea-N or compost-N led to the lowest soil N mining over the 3 years, whereas the highest N mining was observed in plots without added N. We conclude that N mining in poor fertile soils of West Africa can be mitigated through an integration of local water and nutrient management practices.

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1. Introduction

Soil degradation is a major constraint to the sustainability of agricultural systems in the arid and semiarid tropics (Ryan and Spencer, 2001) and particularly in

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the semiarid zone of West Africa (Laflen and Roose, 1998; Lal, 1998). Soil erosion can accelerate soil fertility depletion, which is the fundamental biophysical cause for declining per capita food production on smallholder farms in sub-Saharan Africa (Sanchez and Jama, 2002). Erosion influences several soil properties, such as topsoil depth, soil organic carbon content, nutrient status, soil texture and structure, available water holding capacity and water transmission characteristics. 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 semiarid zone of India.

In addition to erosion, leaching, volatilisation and exportation of nutrients by edible crop products are main causes of nitrogen losses. Brouwer and Powell (1998) reported from studies in Niger on sandy soils receiving 9–10 t ha⁻¹ of manure, that there were considerable losses of locally available nutrients mainly N (91 kg ha⁻¹) and P (19 kg ha⁻¹) through leaching. More recently, Bonzi (2002) reported in Burkina Faso (Saria) that losses of N through denitrification and volatilisation in an intensified system could reach 60–70 kg ha⁻¹ per year, while N exported through sorghum crop averaged 49 kg ha⁻¹ per year.

Given the dominant role of N nutrition for crop growth, its efficient management and effective strategies to avoid losses are key elements for intensive crop production (Giller *et al.*, 1997). 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 in the north-Sudanian climate zone of Burkina Faso.

2. Materials and methods

2.1. Site description and experimental design

The experimental field was at Saria Agricultural Research Station in Burkina Faso (12°16'N, 2°9'W, 300 m altitude), characterised by a north-Sudanian climate (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–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 a Ferric Lixisol (FAO–UNESCO, 1994) with an average slope of 1.5% and a hardpan at 0.7 m depth. The textural class according to the USDA system is a sandy loam at 0.3 m (62% sand, 28% silt, 10% clay) with a gravel content decreasing from 36% at the 0–0.05 m to 30% at 0.1 m depth. The trial was conducted over three seasons (2000–2002) and combined linear SWC measures with organic or fertiliser sources of nitrogen. The experimental design was a randomised Fisher bloc with nine treatments and two replications:

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

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

The plots, of 100 m × 25 m, were isolated from the surrounding area by an earth bound 0.6 m high. In each plot, 36 subplots of 10 m × 2 m were delimited to measure sorghum grain and straw yields. These subplots were located in pairs at the following distances 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 m. Each of the three lines of sorghum per subplot was harvested separately.

The stone rows and the grass strips were installed during 1999 rainy season with a spacing of 33 m (that is three barriers per plot) along contours as recommended by previous studies (Zougmore *et al.*, 2000a,b). Each stone row consisted of two rows of stones placed in a furrow. The upslope row of large

stones was stabilised by the downslope row of small stones. Stone rows were about 0.2–0.3 m high. Grass strips were made of three rows of grass, resulting in a thick barrier of 0.3 m width.

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

2.2. Data collection

2.2.1. Erosion-induced losses 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 × 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 rainfall event. Each pit in one replicate was equipped with a water level recorder (TD-divers, Eijkelpamp) that recorded the overland flow.

When rainfall was high enough to generate overland flow, runoff was quantified by pumping out and measuring the water collected in each runoff-pit. This data was compared with the runoff volume determined by TD-divers placed in the pit. 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 was called sample fraction (SF). The fine sediments, after decantation and filtration of the barrel content, were dried and weighted. Coarse sediments in the pit after each runoff

event were also dried and weighted. The total soil loss per rainfall event was the dried fine sediment times SF plus the collected coarse sediment. At each rainfall event, a fraction (1/SF) of the coarse sediment was added to the dried fine sediment from each treatment, thoroughly mixed and sampled for the determination of N concentration (automatic colorimetry). Runoff water was analysed for dissolved NO₃⁻-N and NH₄⁺-N. Each year at the onset of the rainy season, soil samples were taken at 0–0.15 and 0.15–0.3 m depths in triplicate from each treatment to determine the concentration of N.

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

2.2.2. Nitrogen export by harvested sorghum

At the maturity of sorghum, two entire plants (straw plus panicle) were sampled in each plot at 1 m downslope and 0.1, 4, and 12 m upslope of the middle barriers. The eight plant samples per plot were pooled, dried and ground to 0.2 mm for total N analysis. The amount of N exported through sorghum was calculated by multiplying the total harvested dry matter (TDM) of sorghum by the N concentration of the shoots.

2.2.3. Nitrogen loss through leaching

Four porous ceramics tubes (Tensionics, SDEC-France) were installed in each plot at 0.5 m depth to extract soil solution for the quantification of leaching-N (Moutonnet et al., 1993). Soil solution was extracted at 14-day intervals during the entire rainy season and conserved in sterilised tubes for the determination of N-NO₃⁻ and N-NH₄⁺. The calculation of the amount of leached N required the volume of water drained below the rooting depth of sorghum. 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 (Zougmore and Mando, 2004b). In 2001 and 2002, soil moisture was measured weekly by time domain reflectometry method (TDR-TRIME-FM) at depths of 0–0.2, 0.2–0.4, 0.4–0.6 and 0.6–0.8 m. Estimates of soil drainage were based on the magnitude of infiltration water and the variation of soil water storage over the considered soil depth. This approach had been used previously in

the Sahel by Stroosnijder and Koné (1982) and Mando (1997). The amount of leached N for a given week was therefore the drainage volume multiplied by the corresponding N concentration.

2.2.4. Other N losses

Setting up a full N balance required the determination of all fluxes (Van den Bosch et al., 1998). Nitrogen exports through harvested sorghum products, erosion losses and leached N were measured through the experiment as previously described. Gaseous N losses (denitrification and volatilisation) were estimated using the following regression model developed by IFA and FAO (Lesschen et al., 2003):

$$\text{OUT4} = (0.025 + 0.000855P + 0.01725F + 0.117C) + 0.113F$$

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

2.2.5. N inputs

Following the treatments defined above, organic and fertiliser N inputs were applied at a dose equivalent to 50 kg N ha^{-1} per year. For the study region, annual atmospheric depositions (rain and dust) were estimated to average 5 kg ha^{-1} (Pieri, 1985; van der Pol and Traoré, 1993). Non-symbiotic fixation of nitrogen was ignored.

2.3. Data analysis

All data were analysed using STATITCF package (Gouet and Philippeau, 1986), performing ANOVA and Newman–Keuls tests to examine differences between treatments at $P < 0.05$.

3. Results

3.1. Effect of water and nutrient management on sorghum N

There were significant treatment effects on annual N exportation through sorghum for the three successive years, which reflected differences in sorghum

TDM yields (Table 1). Nitrogen exports were highest in treatments that combined stone rows or grass strips with compost-N or urea-N application (T_{SRC} , T_{SRU} , T_{GSC}), whereas they were lowest in treatments without N input (T_{SR} , T_{GS} , T_0). For the 3 years, the exportation of N by sorghum accounted for 82–87% of the 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 . Averaged among the 3 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 1).

3.2. N losses through erosion and leaching

For the 3 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} , Table 1). The lowest erosion and runoff mediated N losses were recorded in plots with added compost (T_{SRC} , T_{C}). In 2000 and 2001 with less erosive rainfall events, the N losses through runoff and erosion did not exceed 7 kg ha^{-1} . However, in 2002, when an intensive rainfall event occurred, N losses 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} .

Nitrogen losses through leaching were not significantly different among treatments over the 3 years (Table 1). However, urea-N treatments showed higher leaching-N than compost-N treatments when compared in pairs ($T_{\text{SRU}}/T_{\text{SRC}}$, $T_{\text{GSU}}/T_{\text{GSC}}$, $T_{\text{U}}/T_{\text{C}}$). In 2001, the lowest N losses through leaching were recorded in treatments without SWC measures (T_{U} , T_0 and T_{C}), whereas the largest 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 amounts of 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 (Zougmore and Mando, 2004b), N losses through leaching averaged $3\text{--}9 \text{ kg ha}^{-1}$ per year, whereas they were only $1\text{--}6 \text{ kg ha}^{-1}$ per year 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.

Table 1
Effect of water and nutrient management on N fluxes through harvested sorghum, soil erosion and leaching at Saria, Burkina Faso^a

Treatment	Sorghum total dry matter (kg ha ⁻¹)			N export through sorghum total dry matter (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
<i>T</i> 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
<i>T</i> _{SRM} / <i>T</i> _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
<i>T</i> _{GSM} / <i>T</i> _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
<i>T</i> _{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
<i>T</i> _{G_{SU}}	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
<i>T</i> _{G_{SC}}	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
<i>T</i> _{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
<i>T</i> _{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
<i>T</i> _{SR_C}	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

*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*_{G_{SU}}: grass strips + urea-N; *T*_{G_{SC}}: grass strips + compost-N; *T*_{SR}: stone rows, no N input; *T*_{SRU}: stone rows + urea-N; *T*_{SR_C}: stone rows + compost-N.

^a Treatments with the same letter are not statistically different at *P* = 0.05.

In 2000, erosion and leaching accounted on average for 14% of the total N loss compared to 7% in 2001. In 2002, in addition to high amounts of N exported through the harvested sorghum TDM, a single major rainstorm caused a large loss of N through runoff and erosion (Table 2).

3.3. Effect of water and nutrient management on N flows and balance

In 2000, the N balances for all treatments were negative and ranged from -26 to -60 kg ha⁻¹ per year (Table 2). A first group of treatments with highly

negative N balances (<-40 kg ha⁻¹ per year) comprised *T*₀ (control), *T*_{SR} (stone rows alone), and *T*_{GS} (grass strips alone). These treatments did not receive organic or mineral N inputs. A highly negative N balance of -60 kg ha⁻¹ per year was also observed in treatment *T*_{G_{SC}}, where N exports through TDM removal and leaching were the highest in this year. Treatments that combined SWC measures and organic-N or mineral-N in the decreasing order *T*_{SRU}-*T*_{SR_C}-*T*_{SRM}-*T*_{G_{SU}}-*T*_{G_{SM}} formed the second group with N balances larger than -40 kg ha⁻¹ per year. In this year, N loss through erosion did not exceed 7 kg ha⁻¹ per year but loss of N through

Table 2
Effect of water and nutrient management on N flows and balances in 2000 at Saria^a (kg ha⁻¹)

	<i>T</i> ₀	<i>T</i> _{SRM}	<i>T</i> _{GSM}	<i>T</i> _{GS}	<i>T</i> _{G_{SU}}	<i>T</i> _{G_{SC}}	<i>T</i> _{SR}	<i>T</i> _{SRU}	<i>T</i> _{SR_C}
IN1, chemical fertiliser	0	50	0	0	50	0	0	50	0
IN2, organic fertiliser	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
Full balance 2000 (input-output)	-57	-30	-26	-44	-29	-60	-54	-48	-38

^a Treatments are explained in Table 1.

Table 3

Effect of water and nutrient management on N flows and balances in 2001 at Saria^a (kg ha⁻¹)

	T_0	T_U	T_C	T_{GS}	T_{GSU}	T_{GSC}	T_{SR}	T_{SRU}	T_{SRC}
IN1, chemical fertiliser	0	50	0	0	50	0	0	50	0
IN2, organic fertiliser	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
Full balance 2001 (input–output)	–57	–18	–29	–43	–28	–30	–49	–50	–43

^a Treatments are explained in Table 1.

leaching reached 9 kg ha⁻¹ per year. Nitrogen loss through erosion and leaching totalled both 8–21% of the N outflow.

The same trend was observed in 2001 with lower negative balances ranging from –18 to –57 kg ha⁻¹ per year (Table 3). Nitrogen 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 per year followed by T_{SRC} , T_{GSC} , and T_{SRU} , where N exports through sorghum were high (90–118 kg N ha⁻¹ per year) (Table 4). Treatments T_{SR} , T_{GS} and T_C showed negative N

balances of –50 kg ha⁻¹ per year while the least negative N balances were observed in treatments T_U , and T_{GSU} (–43 and –32 kg ha⁻¹ per year, 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, erosion effects were particularly large. Indeed, the amounts of N lost through erosion were 3–20 times higher than those in 2001, and corresponded to 2–43% of the total outflow of N.

For the 3 years, the highest negative N balance was observed in the control treatment (–71 kg ha⁻¹ per year) while the least values were observed in treatments T_{GSU} , T_U and T_C (–32 kg ha⁻¹ per year) (Fig. 1).

Table 4

Effect of water and nutrient management on N flows and balances in 2002 at Saria^a (kg ha⁻¹)

	T_0	T_U	T_C	T_{GS}	T_{GSU}	T_{GSC}	T_{SR}	T_{SRU}	T_{SRC}
IN1, chemical fertiliser	0	50	0	0	50	0	0	50	0
IN2, organic fertiliser	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

^a Treatments are explained in Table 1.

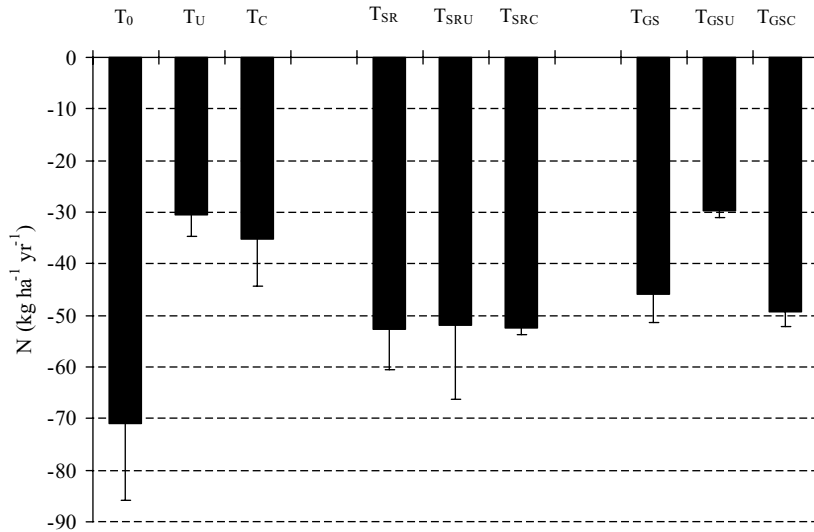


Fig. 1. Mean annual N balance per treatment over the three cropping seasons (2000–2002) at Saria. Treatments explained in Table 1.

4. Discussion

4.1. Effect of water and nutrient management on N exports by sorghum harvests

The higher availability of water and nutrients in treatments that combined SWC measures and compost-N explained the greater TDM and subsequent N exports in these treatments compared to no N input treatments. A previous study indicated that SWC measures increased the use of soil major nutrients (N, P, K) by reducing runoff and increasing soil water storage in the crop-rooting zone (Zougmore and Mando, 2004b). The input of K and micronutrients 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 (Biielders et al., 2002). Results obtained by Hafner et al. (1993) on N-deficient soils in Niger (Sadoré) reported that crop residue plus fertiliser application increased both the number of diazotrophic and total bacteria in comparison to mineral fertiliser application alone; this increase of bacterial populations was accompanied with an increase of N gain of about 6 kg N ha^{-1} per year.

The application of urea-N in plots with SWC measures improved N uptake by sorghum plants, as confirmed by the larger quantities of N contained in harvested sorghum (Table 1). Several studies (Vanlauwe et al., 2000; Bationo and Buerkert, 2001) also reported that urea-N application improved the uptake of available P and K by West African cereals, which by feedback can improve N uptake. This explains the greater N exports in treatments which combined SWC measures and urea-N application compared to those without added N.

Also, outflows of N through sorghum products were strongly related to the amounts of TDM produced per treatment, which explained the larger quantities of N exported through sorghum in compost-N and urea-N treatments compared to treatments without added N. 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 also extracts considerable quantities of nutrients from the soil. The application of 50 kg ha^{-1} per year through urea-N or compost-N was below the N exports through sorghum harvest products, which means that the soil N stock undoubtedly contributed to crop biomass production in all treatments regardless of whether or not they received N inputs.

4.2. Effect of water and nutrient management on erosion and leaching of N

Annual losses of N through soil erosion largely depended on the magnitude of annual runoff and sediment loss (Zougmore and Mando, 2004b). If sediment loss on gentle slopes could be considered as negligible, this did not apply to nutrient losses particularly for N, as small runoffs transport fine soil particles, which are richest in N, and also carry high amounts of N dissolved in water. Cogle et al. (2002) pointed out that since the fine soil fraction containing most of the nutrients is preferentially eroded, a disproportionate loss of soils nutrients can occur and leads to pronounced soil degradation. Several studies (Quansah and Ampontuah, 1999; Zougmore and Mando, 2004a) have demonstrated that nutrient losses through soil erosion were higher during small intensive rainfall events than during heavy and highly erosive rain events. The results of this study also indicated that water and nutrient management induced a significant reduction of nutrient losses. On average, these reductions reached 40–70% of the control, thus showing a great effect of soil management. These findings indicate that on gentle slopes (>3%), erosion-induced nutrient losses can remain harmless (N losses lower than N input by atmospheric deposition) with proper management while poor management can lead to severe losses. Therefore, nutrient balance studies should take into account a management factor when estimating erosion-induced losses of soil nutrients in semiarid West Africa. Indeed, N losses through erosion represented 43% of the total output in the worst case (T_0) of this study (during rainy seasons with exceptional rainfall events), whereas water and nutrient management practices (T_{SRC} , T_C) significantly reduced N losses by only 2% of the total N outflow.

During 2001, a year with several small and well-distributed rainfalls, the reduced runoff by stone rows and grass strips may have induced an increased N concentration in drainage water of plots with SWC measures compared to that of plots without SWC measures. This explained the larger N losses through leaching in plots with SWC measures compared to plots without barriers in 2001. Such an 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 (Zougmore and Mando, 2004b). The greater amounts of drainage water in addition to its higher N concentration explained the larger N losses through leaching in treatments that received compost-N or urea-N compared to treatments without N input in 2002. These results confirmed those of Bonzi (2002) who reported similar values of N leaching at Saria on the same soil type. He concluded that treatments with different types of fertility management did not show significant differences of N leaching and that treatments with application of mineral fertilisers only induced slight increases of N leaching.

Overall, the results of this study indicated that the amount of N loss through leaching was strongly related to the magnitude of drainage water but also to the type of soil, water and nutrient management.

4.3. Effect of water and nutrient management on the soil N balance

From the 3-year results of this study, it appears as if the export of N through the harvested sorghum TDM was the major factor explaining the negative balances in all treatments regardless of the level of N input. The application of organic-N or urea-N induced a major increase in sorghum TDM production. Consequently higher amounts of N were exported from the plots with N input compared to plots without N input (Table 1). Smaling et al. (1997) came to similar conclusions from nutrient balance calculations in Kenya and Mali where they found that most nutrients leave the system through the harvested crop. The magnitude of these exports outweighed the total N input.

Nutrient outputs generally exceed nutrient inputs in West African cropping systems (Bationo et al., 1998). Therefore, nutrient balances are usually negative, indicating soil mining. For instance, van der Pol and Traoré (1993) reported that farmers in Mali extract, on average, 40% of their agricultural revenue from the soil mining. Continuous and intensive cropping without restoration of the soil fertility have depleted the nutrient base of most soils in this region. Using the average straw-N/grain-N ratio (1.43) determined at Saria by Bonzi (2002) for the same variety of sorghum, an estimation of the amounts of N exported

through crop residues revealed that on average, N exports 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 , 113% for T_C and 145% for T_{GSU} , respectively. Despite the large exports N through sorghum in plots which combined SWC measures and N inputs, these treatments could better replenish soil N by residue recycling than treatments without added N.

In 2001, average N balances were less negative than in 2000, most likely because of the low losses of N through erosion and leaching.

5. Conclusions

Under the climatic and edaphic conditions of this study, stone rows or *Andropogon gayanus* grass strips combined with mineral-N or organic-N led to larger sorghum growth which subsequently caused a significant increase in nutrient exports from the soil compared to untreated controls.

On gentle slopes, soil erosion-induced significant loss of N through both fine sediments transport and runoff water. Nutrient losses through soil erosion were an important contributor to the generally negative N balances. They could represent up to half of the total N export if neither N nor soil water conservation management options are used. Integrated water and nutrient management tremendously reduced unproductive N losses.

The application of SWC measures alone or combined with urea-N or compost-N induced negative N balances. Nitrogen losses through sorghum exports and soil erosion were the two main factors explaining these negative balances.

The recycling of crop residues produced under integrated water and nutrient management options may reduce actual soil negative N balance by 90%.

It is therefore concluded that continuous N mining in poor fertile soils of semiarid West Africa could be mitigated through the application of integrated water and nutrient management practices.

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