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Nitrogen dynamics in tropical soils of Mali, West Africa

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Abstract Soil samples were collected from a loamy sand and a clayey soil near Cinzana, Mali, for the purpose of documenting the seasonal dynamics of soil inorganic N after 9 years under five crop-management systems. The cropping systems were: continuous grain sorghum (*Sorghum bicolor*) or millet (*Pennisetum glaucum*) without residue return, continuous grain with stalk residue returned to the field every second year, grain in rotation with cowpea (*Vigna unguiculata*), and grain in rotation with the green manure crops, sesbania (*Sesbania rostrata*) and dolichos (*Dolichos lablab*). A sharp increase in soil N was observed early in the rainy season in both soils. Extractable N concentration in loamy sand and clayey soils, respectively, peaked between 15–22 kg and 33–51 kg N ha^{-1} in the upper 10 cm of soil. In the clayey soil, the higher soil N concentrations associated with the early season flush lasted 8 weeks after the onset of rain. Nitrogen addition through rotational crops and crop residue was low. Significant improvement of cereal grain yield may not be possible solely by rotation with sesbania and dolichos green manure or cowpea without additional nutrient input. Earlier cereal planting, where feasible, is recommended to improve synchrony of soil N mineralization and crop demand.

Keywords Nitrogen dynamics · Crop management · Green manure · Millet · Sorghum

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Introduction

After P, N is the most limiting nutrient for grain crops in the Sahel (Warren et al. 1997). Knowledge of soil N dynamics is essential for effective crop management and fertilizer recommendations. Rainfall patterns in Mali, West Africa, exhibit distinct dry and rainy seasons. Rains usually begin in May and cease in October. A sharp increase in inorganic soil N has been shown to occur in the early part of the rainy season, followed by an almost equal decline in many locations (Greenland 1958). Nitrogen mineralization and nitrification are usually very slow in the field during the dry season, but dramatically increase once the rains commence (Roy and Singh 1995). Following rewetting of dried soil, N is often rapidly mineralized during the first 1–2 weeks and approaches steady-state conditions thereafter (Beauchamp et al. 1986; Bonde and Rosswall 1987; Cabrera 1993; Franzluebbers et al. 1995). The wetting and drying of soil is the essential cause of the N flush.

Birch (1960) and Sorenson (1974) explained that, with the onset of the rains, the increase in inorganic soil N is due to rapid mineralization of labile organic matter and microbial biomass killed by dry conditions. A common factor that explains the consistency of the flush of CO_2 and N mineralization is microbial death and subsequent mineralization after rewetting dry soil (Birch 1958). Inubushi and Wada (1987) found that air-drying and rewetting soil not only increased the easily mineralizable soil N pool, but also increased the size of a more stable pool that mineralized more slowly. Mineralization is followed by rapid nitrification of NH_4^+ accumulated during the dry season (Wild 1972), unless conditions limit this process. During the rainy season, after the initial N increase and decline, soils are warm and moist, with conditions still favorable for nitrification. Until the soil dries sufficiently to inhibit bacterial activity, soil NO_3^- and NH_4^+ continue to be produced, but not at the intense rate of the initial early-season flush.

Recommendations for crop N fertilization are often based on extractable inorganic soil N measurements made before the growing season. Residual inorganic soil N, predominantly NO_3^-, is a useful tool for predicting crop N needs in lower rainfall areas, but is generally less successful in more humid regions because of NO_3^- losses via leaching and denitrification (Schmitt and Randall 1994). This procedure does not take into account N that may become available during the growing season due to microbial mineralization of soil organic N. In the laboratory, N mineralization is underestimated because it does not account for the flush of N mineralization that occurs when dry soil is rewetted in the field (Birch 1958; Cabrera 1993). Excessive N application due to an underestimation of potentially mineralizable N may result in soil N runoff or leaching into groundwater, while overestimation may result in less than optimum N application and crop yield.

Accurate prediction of the quantity of N that is mineralized from soil organic matter during a growing season should result in more efficient use of N fertilizer and manure. Fertilizer recommendations can then be matched more closely with crop requirements to optimize economic yield and decrease the potential of environmental contamination.

The objective of this research was to determine the effect of five long-term crop-management systems on seasonal NH_4^+ and NO_3^- concentrations in two soils near Cinzana, Mali, and to relate these results to crop yield.

Materials and methods

Experimental site and design

This study was conducted in research plots at the Cinzana Research Station in Mali, West Africa (13 ° 15′ N, 5 ° 57′ E, altitude approximately 280 m). The Cinzana Station is on the river terrace of the Bani River, a tributary of the Niger River, in the Segou area.

The station lies between the 600 and 800 mm isohyets (lines of equal precipitation). Rainfall is monomodal, with the rainy season beginning in May and usually ending in October. In general, half the rain falls in July and August. The long-term average annual rainfall from 1961 through 1990 was 619 mm. The average annual rainfall from 1990 through 1998 was 697 mm, with a high of 849 mm and a low of 579 mm. Rainfall in 1998 totaled 843 mm. The most common mid-slope and toe-slope soils of the Cinzana region were used in this study. Soil characteristics are summarized in Table 1.

Table 1 Selected properties of the loamy sand and clay soil research locations at the Cinzana Research Station, Mali

Parameter	Soil site	
	Mid-slope soil	Toe-slope soil
Classification[a]	Typic Plinthustalf	Oxyaquic Haplustept
Texture	Loamy sand 0–9 cm loamy sand 9–19 cm sandy loam 19–41 cm sandy clay loam 41–76 cm sandy clay 76–100 cm sandy clay loam	Clay 0–100 cm clay
Organic C (0–10 cm)	1.84 g kg^{-1}	9.16 g kg^{-1}
pH[b]	5.6	6.2

[a] National Soil Survey Laboratory (1990)
[b] Average pH of samples collected in 1998

The sandy soil of the mid-slope is classified as a fine, kaolinitic isohyperthermic Typic Plinthustalf. The soil is acidic, with low available P and low exchangeable Ca, Mg, and K content (Kouyate et al. 1998). The clayey soil is located on a toe-slope nearer the Bani river. The soil is classified as a very fine, kaolinitic isohyperthermic Oxyaquic Haplustept. A 1990 soil analysis reported that the surface soil was slightly acidic and had relatively high organic matter content and exchangeable Ca, but was low in available P (Kouyate et al. 1998).

The plots sampled for this study were established in 1990 for a crop-management study. The experimental design was a randomized complete block design with five crop-management systems, with each system replicated five times. The five crop-management systems studied were: continuous cereal without residue return, continuous cereal with residue returned to the field every second year, cereal in rotation with cowpea (*Vigna unguiculata*), cereal in rotation with sesbania (*Sesbania rostrata*), and cereal in rotation with dolichos (*Dolichos lablab*). Sorghum (*Sorghum bicolor*, var. CSM 219E) was grown on the clay soil and millet (*Pennisetum glaucum*, var. Toroniou C1) was the cereal grown on the loamy sand.

The plot size was 18.5×7.5 m. Ten rows of crops were grown in each plot. The outer two rows and outer two plants of each row were excluded from harvest. Ridges (~30 cm high) were formed by a tractor. Cereal seeds were planted on top of the ridges with the use of hand hoes at a spacing of 0.8 m (millet) and 0.5 m (sorghum). The distance between ridge crests, or crop rows, was 0.75 m. Legumes were planted with 0.5 m between pockets (hills) in rotation years.

Sorghum during the sampling year was planted on the clay soil on 13 July 1998. Plots were weeded manually on 8 August and pockets were thinned to two plants per pocket on 13 August. The crop was 50% headed by 28 September and manually harvested on 3 November 1998. Millet was planted on the loamy sand soil on 23 July 1998. Pockets were thinned to two plants per pocket on 19 August and plots were manually weeded on 20 August. The crop was 50% headed by 28 September and manually harvested on 16 November 1998.

Fertilizer was applied in 1990, the first year of the crop-management study, in the form of diammonium phosphate (18 kg N ha^{-1}, 20 kg P ha^{-1}) and urea (23 kg N ha^{-1}). In 1991, the first legume crops received 13 kg P ha^{-1} as single superphosphate before planting. In 1995 and 1998, the loamy sand soil received 300 kg Tilemsi rock phosphate ha^{-1} before planting. The clay soil received 300 kg Tilemsi rock phosphate ha^{-1} before planting in 1996. Sorghum or millet residue was returned to appropriate plots 2 weeks prior to cereal planting.

Soil and plant sampling

Soil was collected to a depth of 10 cm at least once each week from May 1998 until crop harvest in November. Each sample was a composite of 12 soil cores (10 cm deep), with a diameter of about 2.5 cm, collected from each plot. Samples to a depth of 30 cm in 10-cm increments were collected at the beginning of the season for soil total N determination. Subsamples of the field moist soil were oven-dried at 105 °C for 24 h to determine soil moisture content. Air-drying of bulk soil samples began within 2 h of collection. Samples were passed through a 2-mm sieve before being stored in a cool, dry area.

Three plants were randomly selected at harvest and cut just above the soil surface. Plants were divided into grain, leaves, and stalks. Plant parts were chopped with a machete into 3- to 4-cm pieces and then dried at 65 °C in a forced-draft oven for about 48 h. Each sample was then mixed and divided until a 50- to 70-g random subsample was obtained. Plant samples were ground and stored in a dry area away from sunlight until analyzed.

Soil and plant analysis

Ammonium and NO_3^- were measured using 2 M KCl as an extractant. A 7-g sample of air-dried, sieved soil was shaken for 30 min in 28 ml of 2 M KCl, and NH_4^+ and the NO_3^- plus NO_2^- concentrations were analyzed in the filtered extracts using autoanalyzer techniques (Technicon Instruments Corp. 1977a, 1977b). Total N was determined after digestion in concentrated H_2SO_4 with a K_2SO_4-Cu-Se catalyst (Bremner 1996; Technicon Instruments Corp. 1977a). Soil organic C was measured by dry combustion in a medium-temperature resistance furnace (Nelson and Sommers 1982). Soil Ca, Mg, and Na were measured by atomic absorption and K by atomic emission after extraction with 1 M ammonium acetate (Thomas 1982). Soil pH was determined in 1:1 soil:water.

Plant samples were initially ground through a 20-mesh screen with an electronic mill and were then ground with a high-speed mill to pass a 0.5-mm screen. Samples were prepared for analysis by wet digestion in a heated block with concentrated H_2SO_4 and 30% H_2O_2 (using Se and Li as catalysts), as described by Linder (1994), and expanded to include essential micronutrients by Lowther (1980). Nitrogen concentrations of digests were determined by autoanalyzer techniques (Technicon Instruments Corp. 1977a).

Statistical analysis

Soil differences over time and crop-management effects were evaluated by two-way ANOVA with means separated by Tukey's Studentized range test with α=0.10, unless otherwise indicated.

Results and discussion

Nitrogen dynamics in soils

Soil inorganic N concentrations and rainfall distribution for 1998 are shown in Fig. 1. Soils received an unseasonable rainfall of 105 mm on 4 May and about

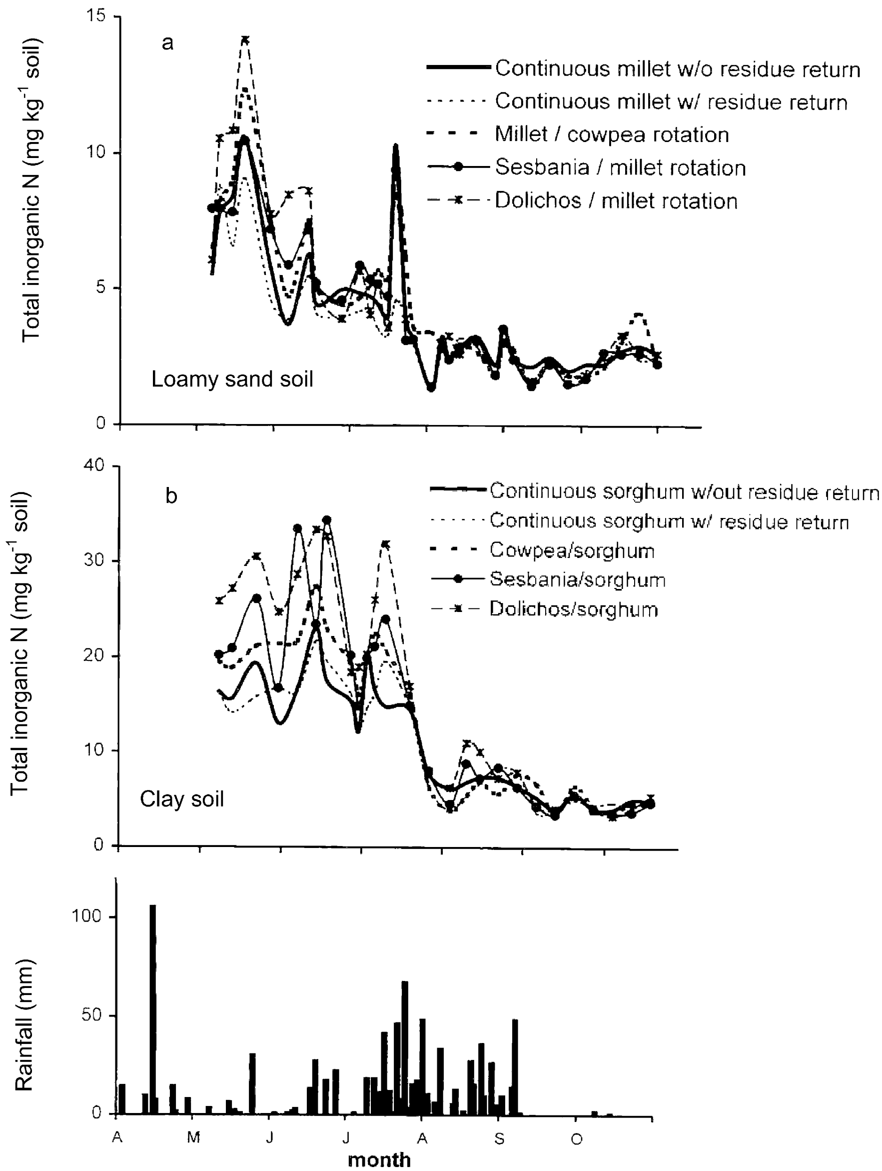

Fig. 1 Total inorganic N in the upper 10 cm of loamy sand (**a**) and clay (**b**) soils and rainfall (**c**) for Cinzana Mali in 1998. *Each point* on the *X*-axis indicates the middle of the month

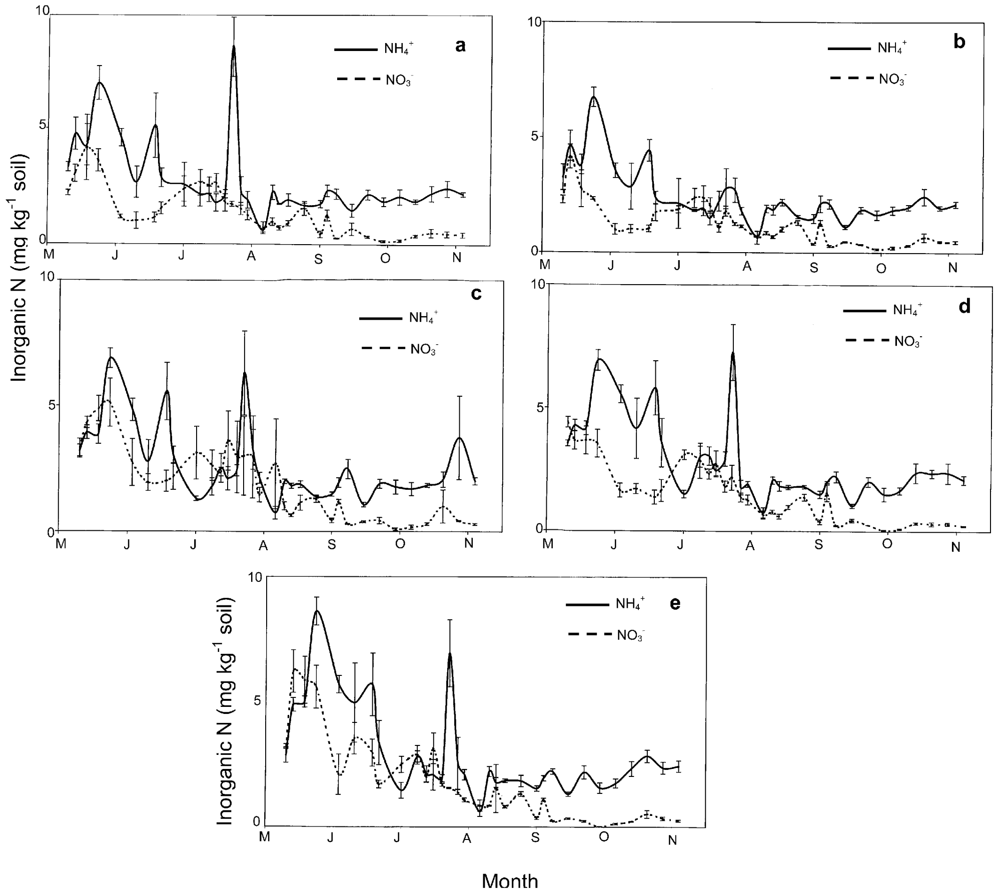

Fig. 2a–e Inorganic NH_4^+-N and NO_3^--N in the upper 10 cm of loamy sand soil under different cropping systems. **a** Continuous millet without residue return, **b** continuous millet with residue return, **c** cowpea/millet rotation, **d** sesbania/millet rotation, **e** dolichos/millet rotation. *Error bars* represent standard errors

29 mm of rainfall on 26 May before the first day of sampling. On 8 June, 12 days after the first sampling, soil inorganic N increased to the season's peak in all crop-management systems in loamy sand soil and then rapidly declined. Inorganic N again began to increase after 18 June and peaked in early July and August, but the magnitude and amplitude of peaks varied for different soil crop-management systems (Fig. 1a). Soil inorganic N decreased continuously after 28 July in clay soil and until 6 August in loamy sand soil, regardless of crop-management system. This decrease occurred during the wettest time of the growing season. After 6 August, inorganic N fluctuation was minimal or statistically insignificant (Fig. 1a). Much of the mineralized N apparently may have moved below the 10-cm sampling depth in this soil before millet was planted.

Through the majority of the 1998 season, there was no significant difference in soil inorganic N concentration between the crop treatments in loamy sand soil (Fig. 1a). Inorganic N concentrations from the crop-management systems were statistically different only near the beginning of the rainy season. The dolichos green manure rotation exhibited more rapid N accumulation, a higher maximum accumulation, and a retarded N reduction, compared with other systems. Continuous millet systems generally had the lowest N concentrations.

On clay soil, inorganic N was higher than in loamy sand soil during the first part of the rainy season, and significant (α=0.05) differences in soil inorganic N concentrations between crop-management systems were observed (Fig. 1b). Green manure rotation systems showed higher inorganic soil N than continuous sorghum systems before August. The dolichos and sesbania green manure systems alternately had the highest soil inorganic N concentrations. The dolichos green manure rotation exhibited greater soil inorganic N than the continuous sorghum system from 27 May through 10 June and over 24–28 July. Soil from the sesbania green manure rotation had a significantly higher inorganic N concentration than the continuous sorghum treatments on 25 June.

No difference (α=0.05) in soil inorganic N concentration was observed between the continuous sorghum system with and without residue return (Fig. 1b). The cowpea rotation system usually had more inorganic N than the continuous sorghum systems, but differences were never statistically significant (α=0.05).

Soil N dynamics closely followed seasonal rainfall events. For example, inorganic N concentrations peaked on 8 June, which was during a soil-drying cycle that followed unseasonably heavy rainfall events in early to late May (Fig. 1). Soil inorganic N concentrations also remained fairly constant from late July until September, which corresponded with a time of almost continuous

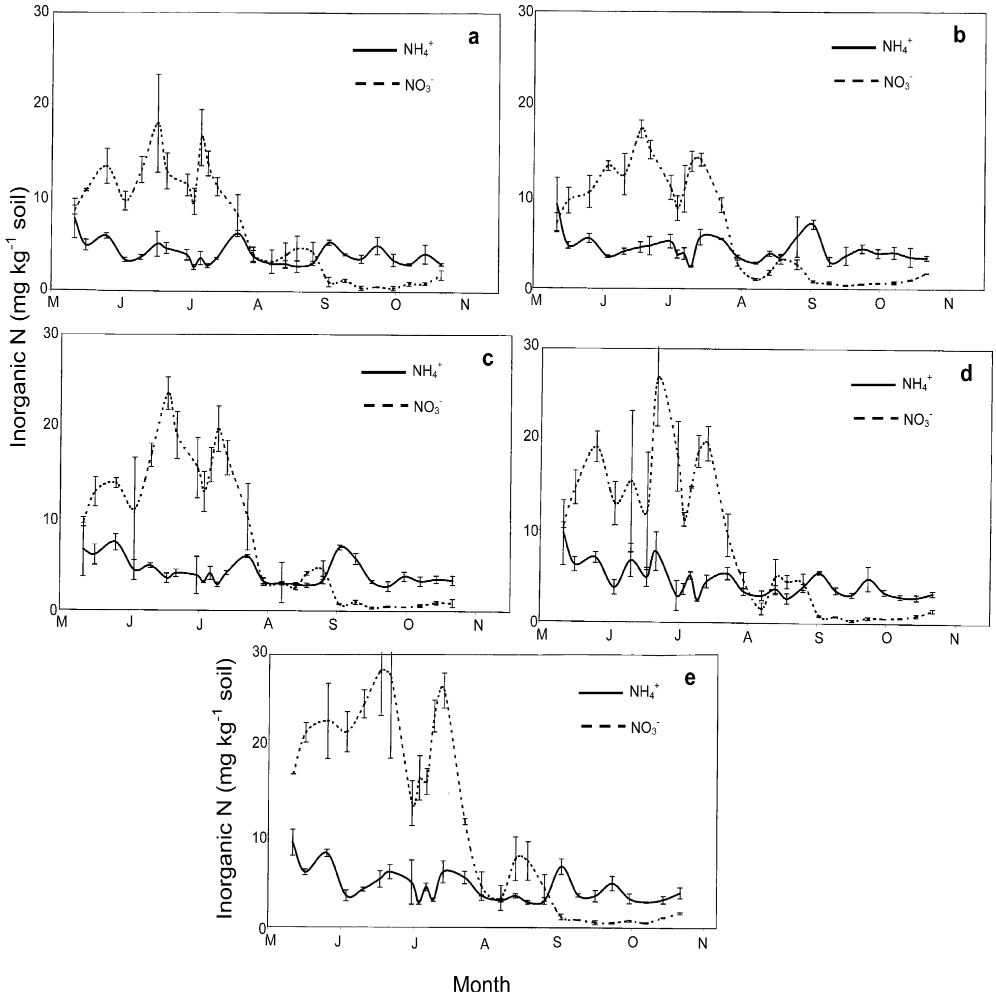

Fig. 3a–e Inorganic NH_4^+-N and NO_3^--N in the upper 10 cm of clay soil under different cropping systems; **a** continuous sorghum without residue return; **b** continuous sorghum with residue return; **c** cowpea/sorghum rotation; **d** Sesbania/sorghum rotation; **e** dolichos/sorghum rotation. *Error bars* represent standard error. Labels on the X-axis indicate the middle of the month

rainfall, with short drying periods between rainfall events (Fig. 1; Blanton-Knewtson 2000). Wetting and drying cycles are essential for N mineralization and N flushes. Also, after several drying and wetting cycles, the quantity of N mineralized is usually diminished (Birch 1958).

Mineralization and nitrification in the two soils from May to October 1998 under the different crop-management systems are shown in Figs. 2 and 3. The NH_4^+ and NO_3^- concentrations were similar in the loamy sand soil from 26 May until the 8 June collection, when NH_4^+ in all treatments increased significantly, while NO_3^- began to decline (Fig. 2). On 16 July, the soil NO_3^- concentration was significantly higher than that for NH_4^+ in the cowpea rotation plots (Fig. 2c) and the sesbania (Fig. 2d) and dolichos (Fig. 2e) green manure plots.

Ammonium and NO_3^- concentrations after 16 July were both around 2.0–3.5 mg N kg^{-1} soil until 6 August, when the NH_4^+ concentration tripled. The continuous millet plots without residue return had the highest NH_4^+ increase on this date, followed by the cowpea rotation and green manure rotation plots.

Soil NO_3^- concentrations began to decline after 30 July in all treatments and continued until 21 September. From 21 September until harvest, soil NO_3^- concentrations averaged less than 0.5 mg NO_3^--N kg^{-1} soil. A minimal flush of inorganic N in the continuous millet with residue return system on 6 August (compared with other systems) may have been caused by N immobilization. Decreasing NO_3^- may have been due to increasing crop uptake and/or leaching.

Seasonal changes in NH_4^+ and NO_3^- concentrations in clay soil were almost the opposite of those in the loamy sand soil (Fig. 3). Nitrate concentrations were generally much greater than NH_4^+ concentrations, so that the seasonal fluctuations of inorganic N in the clay soil mostly followed that of NO_3^-. Soil NO_3^- concentrations in all treatments increased from its first measurement until its peak in early July, followed by a period of decreasing NO_3^- concentration and then another peak in late July nearly as great as previously. Soil NH_4^+ concentrations changed little during the course of the season, indicating much more rapid nitrification in the clay soil. Nitrate concentrations were greater in cowpea and green manure treatments, especially dolichos, compared with continuous sorghum treatments. Lower pH in the sandy soil likely inhibited nitrification. In an incubation study, increasing soil pH to 6.5 resulted in complete nitrification of $NH_4{}^+$ (data not shown).

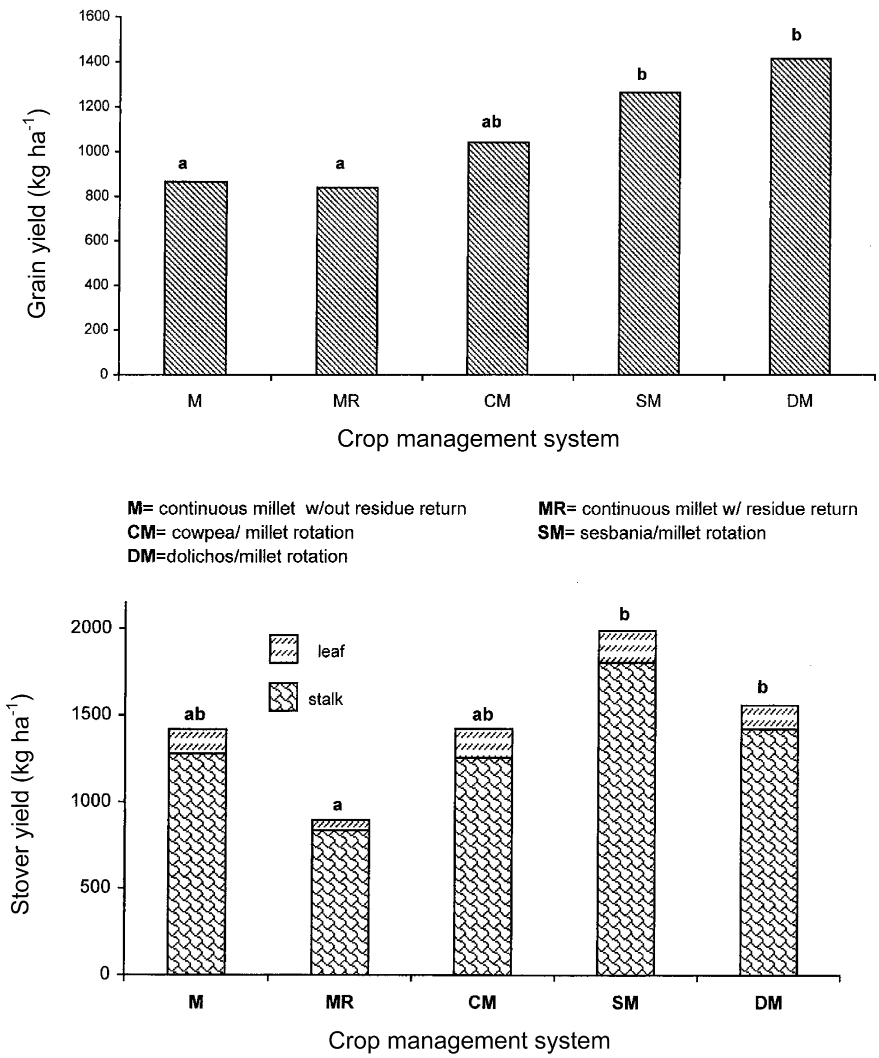

Fig. 4 Millet grain and stover yield on loamy sand soil in 1998. *Means with the same letter* are not significantly different at α=0.10

Yield response to crop-management systems

Millet yield and N content on loamy sand soil are shown in Figs. 4 and 5. The dolichos and sesbania green manure rotation treatments had significantly greater grain yield than the continuous millet treatments. The grain yield of millet in rotation with cowpea was not significantly different from either the continuous millet or the green manure rotations.

Millet in rotation with dolichos and sesbania green manures had, respectively, 64% and 46% higher grain yield than continuous millet without residue return. Dolichos and sesbania green manures also tended to have greater inorganic soil N during the growing season. Millet in rotation with cowpea had 20% greater grain yield than continuous millet without residue return, but this was not statistically significant. The grain yield of continuous millet with residue returned was 3% less than the grain yield of millet without residue return, but the difference was not significant.

The highest millet stover yields were from millet in rotation with dolichos (1,560 kg ha^{-1}) and sesbania (1,900 kg ha^{-1}) green manures (Fig. 4). These yields were greater than that from continuous millet with residue return (896 kg ha^{-1}). Residue return appeared to be more detrimental to millet stover yield than it was to grain production. As might be expected, stalks constituted by far the greatest proportion of stover yield.

The amounts of N removed in grain and stover for the different management systems on sandy soil are shown in Fig. 5. Millet in rotation with sesbania green manure removed more N in the grain than did continuous millet treatments; and the N content of millet grain in the cowpea rotation was not significantly different from any other treatment. In general, if cereal yield is increased without increasing soil N availability, then crop N removal is not altered. In this study, differences in crop N removal were observed, so it may be concluded that there were differences in soil N availability between the crop-management systems. If millet stover were returned to the field, the highest amount of N would be returned by millet in rotation with sesbania (14.5 kg N ha^{-1}) and the least by continuous millet with residue return (5.0 kg N ha^{-1}). Very little N was returned to the soil since 1990 in

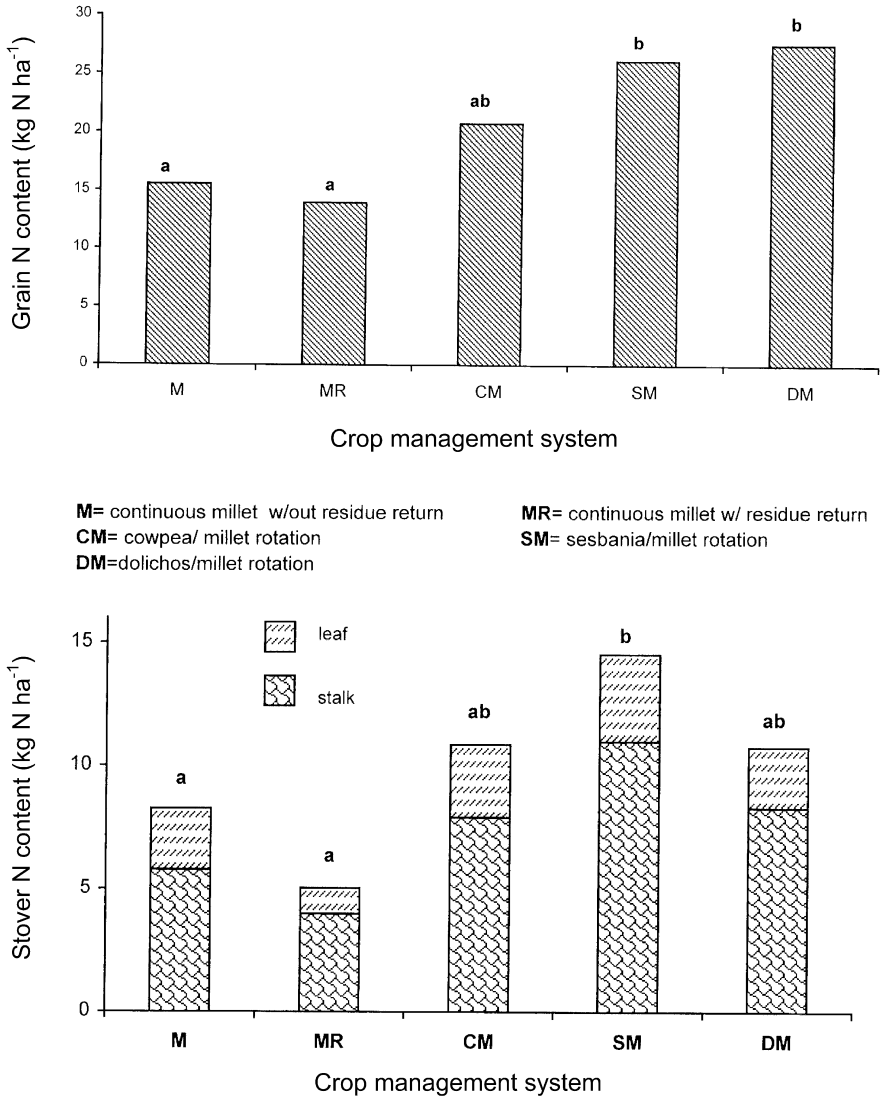

Fig. 5 Nitrogen content of millet grain and stover on loamy sand soil in 1998

the management system where residue from continuous millet plots was returned every second year. Millet yield would probably increase if N availability were increased. Additional N likely was needed and could be provided as a supplement of inorganic N fertilizer or organic N sources. Leaves, as might be expected, represented a greater proportion of stover N removal than they did stover biomass (Figs. 4, 5).

Sorghum yield and crop N removal in clay soil are shown in Figs. 6 and 7. Dolichos and sesbania green manure and cowpea rotation systems did not have significantly greater yield than continuous sorghum without residue return (Fig. 6). Continuous sorghum with residue return had lower grain yield than other management systems, possibly due to N immobilization. Sorghum in rotation with sesbania and dolichos green manure, respectively, had 29% and 10% more grain yield than continuous sorghum. Sorghum in rotation with cowpea had 18% more grain yield than continuous sorghum. However, none of these differences were statistically significant. Soil inorganic N concentrations for treatments with legumes in rotation, especially dolichos and sesbania, frequently were greater than those for continuous sorghum on this soil (Fig. 1).

Stover yield was least for continuous sorghum with residue return and greatest in the cowpea rotation (Fig. 6). Continuous sorghum, with residue returned to the soil 2–3 weeks before planting, produced 42% less grain than continuous sorghum without residue return. This difference was statistically significant and was likely related to less soil N availability due to immobilization where stalk residue was returned shortly before planting. Grain N removal was significantly reduced for continuous sorghum with residue return and was also lowest for stover N content (Fig. 7).

Legume green manure and legume rotation tended to increase soil N availability on both soils, but significantly increased crop yield and N uptake only on the sandy soil. Much of the mineralized N in both soils appeared to have leached or denitrified prior to the time of primary crop

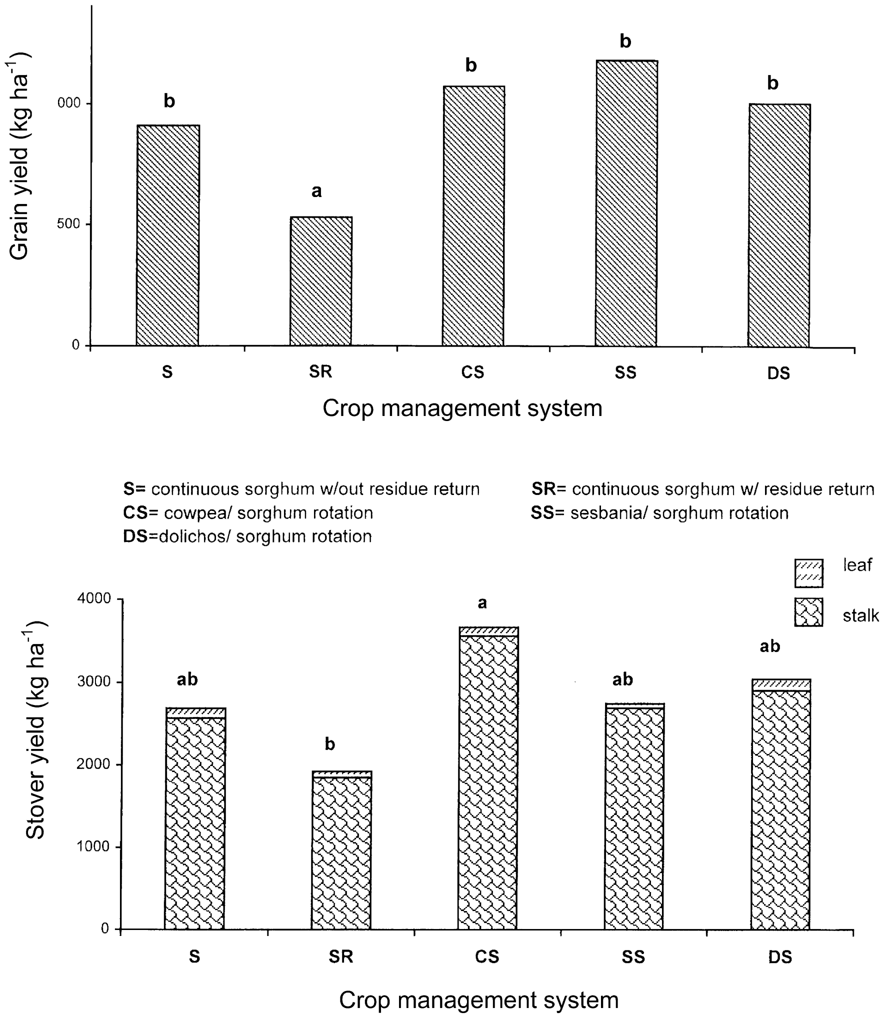

Fig. 6 Sorghum grain and stover yield on clay soil in 1998

demand for N. Simply improving the efficiency with which nutrients are recycled may not alone supply the soil N necessary to raise grain production, especially where overall biomass production is low (Giller et al. 1997).

In many cases, organic input might more correctly be termed nutrient transfer, especially in situations where low amounts of nutrients are returned in crop residue. Plant N uptake just before cereal heading is a relatively good estimate of plant N uptake for the growing season. Maximum millet N uptake at anthesis in 1998 was 43 kg N ha^{-1}, while maximum sorghum N uptake at anthesis was 65 kg N ha^{-1}. Sesbania and dolichos green manure, grown every second year on loamy sand and clay soils at Cinzana, respectively returned averages of 12.6 kg and 35.3 kg N ha^{-1} for sesbania and 14.9 kg and 27.8 kg N ha^{-1} for dolichos. Comparing these values with above data, it is evident that green manure incorporation alone cannot supply the N requirement of grain crops in this region, even at current yield levels.

Nitrogen dynamics and synchrony of crop requirements should be considered. Early in the rainy season, soil N availability was relatively high, but plant N requirements were low. With the planting dates used in this study, the plant N requirement increased as the crop reached its fourth to sixth week, but the soil N availability was less than adequate. Earlier planting might allow better synchrony of soil N availability and crop N demand. The negative effects of millet and sorghum residue return likely could be avoided by incorporating the materials in early May, rather than shortly before planting.

Crop management and total soil N

Four cycles of a biannual rotation had occurred in this study by 1998. Total soil N in loamy sand and clay soils in July 1998 to a depth of 30 cm is shown in Tables 2 and 3.

In loamy sand soil, the continuous millet system without residue return had the highest average total N concentration (206 mg N kg^{-1}) at a depth of 0–10 cm, while millet in rotation with dolichos exhibited the lowest concentration (161 mg N kg^{-1}; Table 2). Green manure rotations in the loamy sand soil increased grain yield, but did not increase total soil N after four rotation cycles.

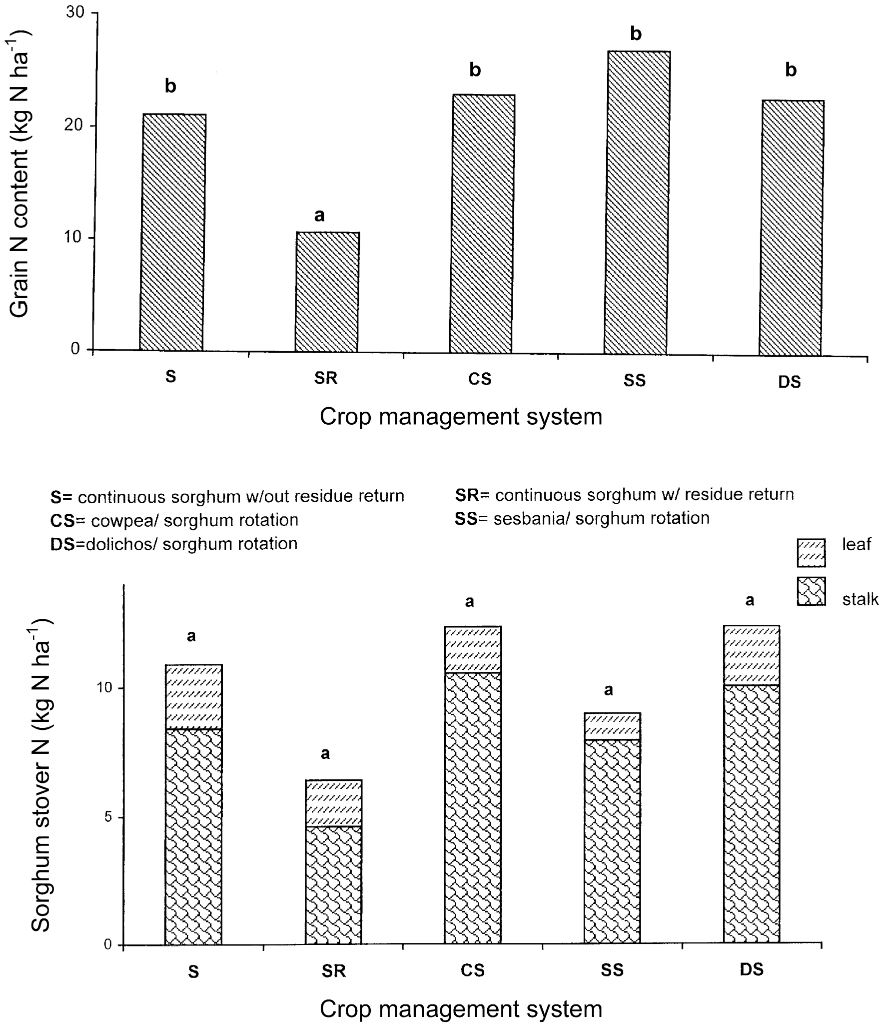

Fig. 7 Nitrogen content of sorghum grain and stover on loamy sand soil in 1998

Table 2 Total N to 30 cm depth from different crop management systems on loamy sand soil in 1998 at Cinzana, Mali. *LSD* Least significant difference

Depth (cm)	Crop management system					$LSD_{0.05}$	$LSD_{0.10}$
	Millet without residue	Millet with residue	Cowpea/millet	Sesbania/millet	Dolichos/millet		
	(mg N kg^{-1})						
0–10	206	182	184	168	161	48	41
10–20	205	187	186	163	168	39	34
20–30	178	202	188	186	181	62	54
$LSD_{0.05}$	57	53	38	37	46		
$LSD_{0.10}$	52	48	35	34	42		

Total N was lowest in the upper 20 cm of soil under sesbania and dolichos rotations, which contrasted with the findings of Kouyate et al. (1998) that millet yield following green manure increased over the years because of improved soil N reserves.

In the clay soil, the average soil total N concentrations at depth intervals of 0–10 cm and 10–20 cm were 614 mg and 619 mg N kg^{-1}, respectively, while that at a depth of 20–30 cm was 528 mg N kg^{-1} soil (Table 3). At a soil depth of 10–20 cm, total N concentration was significantly higher under continuous sorghum with residue return than under continuous sorghum without residue and sorghum in rotation with dolichos. Total soil N under sorghum in rotation with cowpea and sesbania did not differ from other management treatments at a soil depth of 10–20 cm. At a soil depth of 20–30 cm, total N ranged over 439–570 mg N kg^{-1} and no statistical differences between management systems were observed.

Total N concentration was higher in the upper 20 cm of clay soil under continuous sorghum with residue return,

Table 3 Total N to 30 cm depth from different crop management systems on clay soil in 1998 at Cinzana, Mali. *LSD* Least significant difference

Depth (cm)	Crop management system					$LSD_{0.05}$	$LSD_{0.10}$
	Sorghum without residue	Sorghum with residue	Cowpea/ sorghum	Sesbania/ sorghum	Dolichos/ sorghum		
	(mg N kg^{-1})						
0–10	560	664	656	604	588	100	85
10–20	587	691	622	608	588	118	101
20–30	570	569	439	505	562	156	132
$LSD_{0.05}$	106	126	50	158	72		
$LSD_{0.10}$	83	99	40	125	57		

Table 4 Organic C at 0–10 cm depth in loamy sand and clay soils in 1998. *LSD* Least significant difference

Crop management system	Organic C (g kg^{-1})
Loamy sand soil	
Continuous millet without residue return	2.2
Continuous millet with residue return	1.7
Cowpea/millet rotation	1.9
Sesbania green manure/millet rotation	1.8
Dolichos green manure/millet rotation	1.6
$LSD_{0.10}$	0.4
Clay soil	
Continuous sorghum without residue return	8.4
Continuous sorghum with residue return	9.6
Cowpea/sorghum rotation	9.5
Sesbania green manure/sorghum rotation	8.8
Dolichos green manure/sorghum rotation	9.5
$LSD_{0.10}$	1.5

compared with other systems; and this is in agreement with previous research (Juo and Lal 1977). Increased total N was partially due to increased organic N after years of residue return. Organic matter is more protected from decomposition in a clay soil than in a sandier soil and, thus, the effects were more pronounced at this site compared with the sandy site. Grain yield, stover yield, and plant density were often lowest for continuous sorghum with residue return from 1991 to 1997 (Kouyate et al. 1998). Nitrogen export from the field was then lower, even in years without residue return.

Effect of crop management on soil organic C

Differences in soil organic C between crop-management treatments generally were not statistically different because of the large spatial variability within each treatment (Table 4). An increase in soil organic C due to increased organic matter return, such as that described by Geiger et al. (1992), was not evident in the loamy sand or clay soils after four rotations of residue return, green manure incorporation, or cowpea rotation. The only difference noted was in the loamy sand with the dolichos green manure treatment exhibiting less soil organic C than continuous millet without residue return.

Conclusions

Sesbania and dolichos green manures resulted in greater inorganic soil N, compared with continuous millet or sorghum on loamy sand and clay soils. Inorganic N was highest for the first 2 months of the rainy season, especially in the clay soil, and then declined rapidly. Cereals were not planted until July and their period of maximum N demand was not synchronous with soil N mineralization. Green manure treatments increased millet grain and stover yield and crop N uptake on the loamy sand soil, but no differences in yield or N uptake for different management systems were generally observed for sorghum on the clay soil. Nitrification appeared inhibited in the coarse soil, likely because of acidity. Earlier cereal planting is recommended to improve the synchrony of soil N mineralization with the advent of the rainy season and maximum crop N demand.

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