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ORIGINAL ARTICLE

Decomposition of organic amendment and nutrient release under the zai technique in the Sahel

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Abstract In the West African Sahel, farmers use the zai technique to reclaim degraded cropland. Although the nutrients released by the decomposition of the amendments are central to the success of the technique, little is known regarding the impact of the zai pits on the decomposition process and whether the nutrient release is synchronized with plant requirements. The decomposition of millet stalks and cattle manure applied in zai pits or at the soil surface was studied in Niger using litterbags, under controlled irrigation on-station in 1999 and on-farm in 1999 and 2000 at two locations (Damari and Kakassi) with contrasting soils. In addition, a satellite trial was conducted in 2000 on-farm at the same locations to study the relative contribution of termites to manure decomposition. Only at Damari did termite presence enhance manure decomposition, by a factor three for surface placement compared to the zai pits. At Damari, zai pits enhanced the decomposition when termite activity was suppressed. Whereas manure decomposition proceeded two to three times faster than that of millet stalks at Damari, the type of amendment had no effect on decomposition rate at Kakassi. Nutrient release followed the trend of organic amendment decomposition except for K. When applied prior to the rainy season, nutrient release rate of organic amendments strongly exceeded plant nutrient uptake, which could lead to important leaching losses during the first 4–6 weeks after sowing, especially for N and to a lesser extent for K. However, at harvest, total nutrient absorption by plants was generally higher than the total amount released. The results indicate a highly site-specific response of amendment decomposition to zai and the need for a better timing of amendment application to reduce potential leaching losses, possibly through a split application.

Keywords Desertification · Sub-saharan Africa · Organic amendment · Nutrient release · Nutrient uptake · Millet straw · Manure · Zai

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Introduction

In the Sahelian zone of West Africa, the traditional approach to soil fertility restoration through vegetated fallow is coming under pressure due to the expansion of cropland (Amissah-Arthur et al. 2000). This exacerbates the degradation of the environment by wind and water erosion, and by nutrient mining (Zougmoré et al. 2004a). Due to lack of fertile land and increasing population pressure, farmers are increasingly forced to use marginal, and sometimes degraded bare lands for agricultural production.

The zai is one of the indigenous practices used for rehabilitation of degraded lands in the Sahel (Roose et al. 1993). In this technique, small pits are dug into the soil to trap wind-driven sediment and collect water and sediment from surface run-off. Small amounts of organic material (twice a handful, equivalent to 300 g dry matter) are added to the pits, which are later sown with millet or sorghum. The pits are dug in alternate rows to increase the capture of runoff water. The main sources of organic amendments are crop residues (millet, sorghum and maize straw, roselle (*Hibiscus sabdariffa*) stalks) as well as other plant residues and animal manure (composted or non-composted). The technique improves the physical properties of the soil (better water infiltration and retention) as a result of the addition of organic matter and enhanced termite activity as well as plant nutrient supply through the decomposition of organic amendment in the vicinity of the rooting zone of the crops (Roose et al. 1993).

Under the conditions of the Sahel the decomposition of organic amendments is strongly dependent on the activity of the macrofauna, particularly termites (Mando and Brussaard 1999). According to Lobry De Bruyn and Conacher (1990), termites are the most important soil fauna in the semi-arid tropics and as such, they also play an important role in nutrient cycling (Bachelier 1978). The dominant termites in the Sahel, *Macrotermitinae*, are little affected by the quality of their food due to their relationship with *Termitomyces*, a symbiotic basidiomycete, which is maintained on fecal/fungal combs within the nest and is capable of digesting polyphenols (Mando and Stroosnijder 1999). They are able to induce over 70% organic amendment mass loss in 1 year under Sahelian conditions (Mando and Brussaard 1999).

Previous studies have shown that the zai technique promotes crop production on highly degraded soils and helps secure crops from the adverse effects of dry spells, which are frequent during the cropping period in the Sahel (Zougmoré et al. 2004b; Fatondji et al. 2006). The zai is implemented with locally available, low-cost tools. However, the digging of zai holes requires considerable labor input evaluated at about 300 h per hectare at spacing of 0.40 m × 0.80 m (Barro et al. 2005). In addition, Fatondji et al. (2006) have shown that the zai did not always significantly improve millet yields compared to surface application of organic amendments, depending on site and year conditions. This may in part have resulted from drought spells of variable severity, but also from variable nutrient release rates. In particular, in the zai hole, more favorable moisture conditions resulting from the water harvesting function (Fatondji et al. 2006) may enhance amendment decomposition and therefore nutrient release as compared to surface application. However, faster nutrient release may not always be desirable as the nutrients may be lost by deep drainage in case of excessive water harvesting. One may therefore question whether surface application of organic amendments would not be more suitable than pit application, especially on sandier (intrinsically very permeable) soils where the water harvesting function of the zai may be secondary compared to the chemical fertility enhancement function. However, no research has been undertaken so far to study the decomposition and nutrient release rates of different types of amendments in the zai system compared to surface application. Studying nutrient release is essential to understand how well nutrient release matches the crop nutrient requirements. Nutrient release should not largely exceed crop nutrient uptake, otherwise nutrient losses by leaching may occur, thereby reducing the nutrient use efficiency.

The objective of this work was therefore to study the decomposition and nutrient release from two sources of organic amendments applied in the zai technique in comparison to soil surface application, both under controlled water application and under rainfed conditions.

Table 1 Soil chemical and physical properties of the experimental fields prior to the experiments (0–20 cm soil depth)

Soil characteristics	Experimental sites					
	Sadoré	SD	Damari	SD	Kakassi	SD
pH (H_2O)	4.5	0.30	4.2	NA	6.4	NA
pH (KCl)	3.9	NA	3.9	0.06	5.4	0.29
Exch. base (cmol kg^{-1})	0.4	0.23	1.7	0.75	7.9	0.28
Exch. acidity (cmol kg^{-1})	0.7	0.07	1.1	0.11	0.04	0.02
ECEC (cmol kg^{-1})	1	NA	2.8	0.72	7.9	0.30
Al saturation (%)	47	11.09	29	3.12	0	–
Base saturation (%)	37	13.38	61	4.10	99	0.25
P-Bray (mg kg^{-1})	2.3	0.43	2	0.40	0.8	0.10
C org (%)	0.1	0.00	0.2	0.05	0.2	0.01
Total N (mg kg^{-1})	120	12.30	116	36.50	169	27.80
Bulk density (mg m^{-3})	1.5	NA	1.6	NA	1.8	NA
Sand (%)	93	0.44	84	NA	69	NA
Silt (%)	2.7	0.25	3	NA	6	NA
Clay (%)	5.4	0.44	13	NA	25	NA

ECEC effective cation exchange capacity

Materials and methods

Site description

The decomposition of millet straw and cattle manure was studied using litterbags in one on-station, dry-season trial and two on-farm, rainy-season trials in Niger. The on-station trial was conducted at the ICRISAT research station at Sadoré (13°15′N, 2°17′E), approx. 40 km southwest of the capital city Niamey, from March to May 1999. The mean monthly temperature at Sadoré varies between 25 and 41°C (Sivakumar et al. 1993). The soils are Arenosols (World Reference Base), classified as psammentic Paleustalf according to the US soil taxonomy (West et al. 1984). The soil is acidic with relatively high Al saturation (Table 1). The field had a gentle 2.5% slope.

The experiment was conducted from March to May 1999; a period when mean monthly temperature varies between 35 and 41°C. The experimental field had been kept free of any weeds through repeated weeding during four successive years and was consequently severely degraded by wind and water erosion. The field had developed extensive erosion crusts (Casenave and Valentin 1989), locally known as “Gangani”, characteristic of severely degraded land.

The rainy season trials, to which we will hereafter refer to as ‘main trials’, were conducted at two sites in 1999 and 2000:

(1) Damari (13°12′N, 2°14′E) is located 45 km southwest of Niamey and 7 km from Sadoré, with a long-term average annual rainfall of 550 mm and mean monthly temperatures similar as for the ICRISAT research station. The experimental field was located on a formerly cultivated upper glacis, eolian sand over laterite with a 2% slope, severely eroded by wind and water. Like on the research station, the soil is acidic, very sandy although with more clay and high Al saturation (Table 1). The soil is classified as kanhaplic Haplustult (US soil taxonomy; cf. Soil Survey Staff 1998). The selected field had been left under fallow for 3 years prior to the experiment. Except for small patches of loose sand deposits, which are remnants of the former field and were still cropped by the farmer, the field presented large areas of bare soil, which were selected for the trial.

(2) Kakassi (13°50′N, 1°29′E) is located 80 km northwest of Niamey, and has a long-term average annual rainfall of 450 mm. The mean monthly temperatures of the region vary between 25 and 38°C. The field at Kakassi was located on an extended plateau with approximately 2% slope, which was severely eroded by wind and water. It was formerly cropped, but had been abandoned by

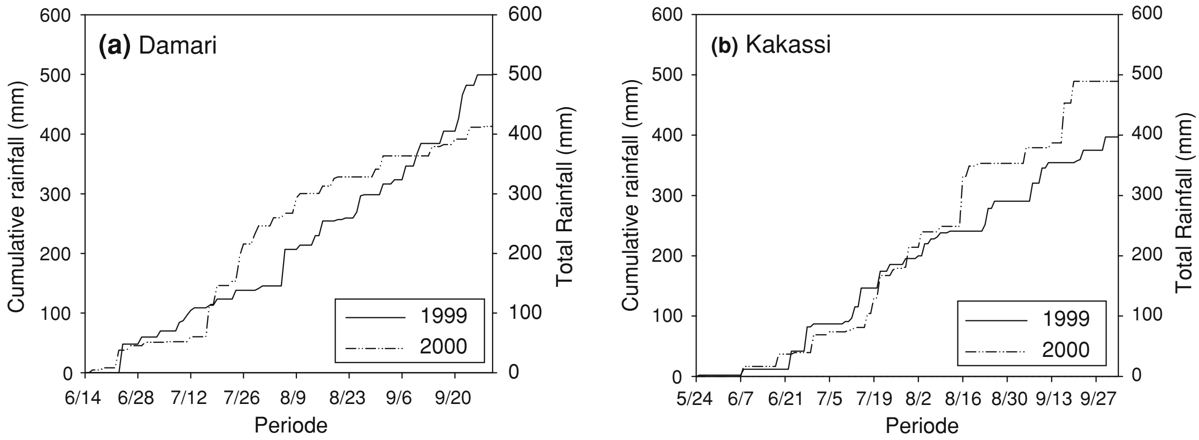

Fig. 1 Cumulative rainfall; Damari and Kakassi, rainy seasons 1999 and 2000 (Dry spells are visible as *horizontal lines*)

the farmer several years prior to the experiment due to loss of fertility. The soil has an almost neutral pH with no exchangeable aluminum, relatively high clay content and 99% base saturation (Table 1). It is classified as vertic Haplustept according to the US soil taxonomy (Soil Survey Staff 1998).

Concomitant with the lower rainfall, the vertic soil properties at the Kakassi site reduce soil permeability and increase the risk of mid-season droughts compared to Damari. At 0.8 mg kg^{-1}, available P (P-bray) was particularly low at Kakassi (two times less than Damari). Both sites have low N and C contents (Table 1). All the characteristics reported here are indications of the advanced stage of soil degradation at the two experimental sites. Except for P, Kakassi is, however, intrinsically more fertile than Damari, as reflected in the higher CEC, base saturation, total N and pH.

In 1999, the total annual rainfall was higher at Damari (499 mm) than at Kakassi (397 mm). It was also more evenly distributed at Damari (Fig. 1). In 2000 rain at Damari (425 mm) was lower than at Kakassi (490 mm). In 2000, frequent dry spells of more than 1 week occurred at both sites.

Experimental layout and data collection

The litterbag experiments were conducted in the same fields and at the same time as the millet crop response studies (Fatondji et al. 2006), both on-station as well as on-farm. Under both conditions, the experimental design was a randomized complete block design (RCBD) with four replicates.

(1) *On-station*: In the on-station study conducted during the dry-season at Sadoré, the effect of amendment type (millet straw and cattle manure) and rate of application (1, 3 and 5 t ha^{-1}) on the growth and development of pearl millet (*Pennisetum glaucum* L. R. Br) were evaluated under controlled irrigation in zai pits only. The field was sprinkler-irrigated uniformly throughout the experiment at a weekly rate of 20 mm starting 7 days before sowing. Irrigation rate and schedule of application were determined based on previous observations and accumulated experience on ICRISAT research station at Sadoré. According to our observations weekly application of 20 mm was enough to provide optimum humidity to millet crop grown on the station during the off-season. Organic amendment application was done 5 days before sowing. A local millet variety ‘Sadoré local’ was hill-sown after the second irrigation on zai pockets at a density of 10,000 pockets per ha and thinned to 3 plants per hill 3 weeks after emergence.

(2) *On-farm experiments*: The effect of mode of placement of the amendment (at the soil surface vs. in zai pits) and amendment type (millet straw and cattle manure at a rate of 3 t ha^{-1}) on pearl millet yield was studied at Damari and Kakassi. When applied at the soil surface, the amendment was slightly incorporated (5 cm) to prevent it from being transported by wind and runoff. When applied in the zai pit, it was not initially covered. The decomposition and nutrient release was studied using litterbags. The organic amendment was applied 36 and 27 days before sowing in 1999 at Damari and Kakassi, respectively,

and 20 and 18 days before sowing in 2000. The bags were installed in the fields before the onset of the rain, which was at a different date in 1999 than in 2000. A local millet variety, 'Sadoré local' at Damari and 'Darinkoba' at Kakassi, was sown in both years at a density of 10,000 pockets ha^{-1}. All pockets were thinned to 3 plants approximately 3 weeks after sowing.

To study the impact of termite activity on amendment decomposition, two satellite trials were conducted at Damari and Kakassi during the 2nd year (2000). In these trials, termite activity was controlled through pesticide application. A RCBD with four replications was used. Mode of amendment placement (zai pit vs. flat) and pesticide treatment (with vs. without pesticide treatment) were tested for manure only (300 g dry matter/pocket). The insecticide Phipronil (*Rhone-Poulenc* 200 g l^{-1} ai) was applied in the respective plots before sowing, directly on the pockets at a rate of 2 l ha^{-1} (Planchon and Bruge 1999). Additional applications were necessary at both locations 7 days after cattle manure application and 29–30 days later to avoid the reactivation of termites. The organic amendment was applied 21 and 14 days before sowing at Damari and Kakassi, respectively. The same local millet varieties used in the main trials were sown at the same density at both sites. In all experiments, the zai pits are 25 cm in diameter and 15–20 cm deep. The pits were renewed every year and the same holes were used.

Amendment decomposition

Litterbags (200 × 200 × 50 mm) made of 2 mm mesh size iron netting were used to monitor amendment decomposition. For the on-station experiment, the bags were filled with either 50 g of millet straw or with 100 g of cattle manure, all sun-dried. For the on-farm trials, the bags were filled with 100 g of sun-dried amendments. The millet straw had been collected from experimental fields at Sadoré and cut in pieces of 10 cm, whereas the cattle manure was collected from a barn on the same station and comprised a mixture of urine with the feces, which increases N and K content. With 1.7% N in 1999 and 2.5% N in 2000 (Table 2), the quality of the manure was above the 1.2% N reported by Esse et al. (2001) for cattle manure collected in farmers corralled fields at Chikal, a village 170 km north of Niamey, the capital city of Niger.

The filled litterbags were installed on the date of amendment application in all trials. In the on-station trial, 1 l bag was installed in six randomly selected zai pits in each plot for all treatments. Three replications out of four were used. In the on-farm experiments, litterbags were placed on the soil surface and fixed with iron rings or in zai pits, depending on the treatment. On each of eight randomly selected planting hills or zai pits per plot, 1 l bag was installed in three out of four replications.

Two litterbags per plot were collected on each sampling date. The litterbag collection was done at a 3 weeks interval starting 3 weeks after sowing, except for Damari in 1999, when the first sampling was delayed for 2 weeks because of late crop establishment. The remaining amendment in each litterbag was sun dried, cleaned of sand manually with a soft brush, dried at 65°C for 48 h, weighed and ground to pass a 1 mm mesh size. The organic amendment weight was corrected for sand content after ignition at 550°C using the method proposed by Kurzatkowski et al. (2004).

Five grams of the organic amendment of each of the two bags from a given plot were mixed to make a sub-sample. The sub-samples were analyzed for total N, P and K after digestion using the Kjeldahl method (Houba et al. 1995). Total N was quantified using the colorimetric method (Bertholet reaction) and an autoanalyzer (Houba et al. 1995). Total P was determined with the colorimetric method based on the phosphomolybdate complex, reduced with ascorbic acid, and total K was determined with flame emission spectrophotometry (Houba et al. 1995). Before filling the litterbags, cattle manure and millet straw were sampled and analyzed to determine the initial content

Table 2 Organic amendment chemical characteristics

Organic amendment	N (%)	P (%)	K (%)	C/N
1999				
Millet straw	0.83	0.10	0.98	50
Manure	1.74	0.82	0.86	20
2000				
Millet straw	1.18	0.10	1.57	50
Manure	2.53	0.94	1.72	21

of N, P and K. Decomposition was assessed by the weight loss of the organic amendment. It is expressed as a percentage of organic amendment remaining relative to the amount initially applied. Nutrient release was calculated as the difference between the initial nutrient content in the amendment and the quantity remaining at sampling time. Due to logistical constraints, the decomposition pattern and the nutrient content in the samples of the litterbags of 5 t ha^{-1} millet straw and those of 3 t ha^{-1} cattle manure in the on-station trial could not be determined. Data obtained from the litterbags were extrapolated to obtain the quantity released per hectare based on total amendment applied per hectare.

To study plant nutrient uptake in both trials, two pockets were sampled three times during the experiment. The litterbag collection and plant sampling dates were matched to allow comparing nutrient release and nutrient uptake except for the second litterbag collection when no plant samples were taken. Plant samples were analyzed for N, P and K using the same methods as for the amendments.

Statistical analyzes

The amendment decomposition and nutrient release data were analyzed statistically using two different approaches. The first approach was based on repeated measures using the AREPMEASURES procedure of GENSTAT® v.9 (Lawes Agricultural Trust 2007). The analysis was done individually per site and per year. The means were used to create the graphs showing the decomposition trend over time. The second approach was based on the fitting of an exponential decay function (Olson 1963) to the amendment decomposition and nutrient release data:

$$C_t = C_0 \exp^{(-kt)} \quad (1)$$

where C_0 and C_t (%) are respectively the percentage amendment or nutrient present initially or remaining at time t, t = time (days), and k ($days^{-1}$) the decay constant. In the formula 'C_0' was set to 100% and k was fitted to the observed data of each plot. An analysis of variance was carried out on the value of the k parameter. The analysis was done for each site and year, followed by a pooled analysis over years and sites.

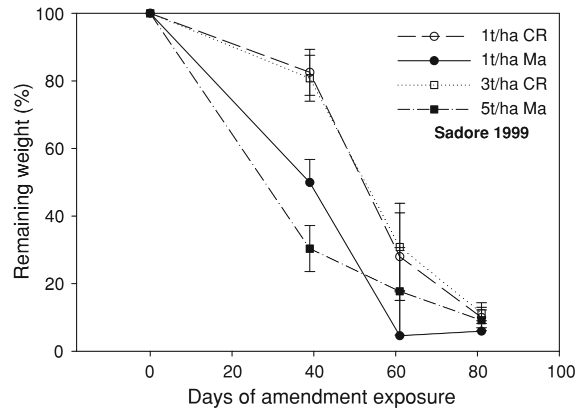

Fig. 2 Effect of amendment type and rate of application on the decomposition rate of manure and crop residue in zai pits under controlled water supply; on-station, Sadoré 1999. *CR* millet straw, *Ma* cattle manure, *Error bars* standard error of difference between means

Results

Amendment decomposition

On-station experiment—organic amendment decomposition in zai pits

At the end of the period of organic amendment exposure (81 days), only 8% of the manure and 11% of the millet straw remained (Fig. 2), the differences not being statistically significant. However, whereas the decomposition of the manure seemed to proceed more gradually, the decomposition of the crop residue was initially very slow (0–39 days—40 vs. 82%; $P < 0.001$), followed by a very rapid decay during the next 42 days, irrespective of the rate of application. The decomposition of the manure applied at a rate of 1 t ha^{-1} was initially slower than at a 5 t ha^{-1} application rate (but not statistically significant) followed by more rapid trend.

On-farm experiments

Effect of planting technique and organic amendment type

In general in both years, decomposition was faster in Damari than in Kakassi (except for millet straw in 1999 which was similar at both sites; Fig. 3; cf. also Table 3A). Also, decomposition was strongly affected

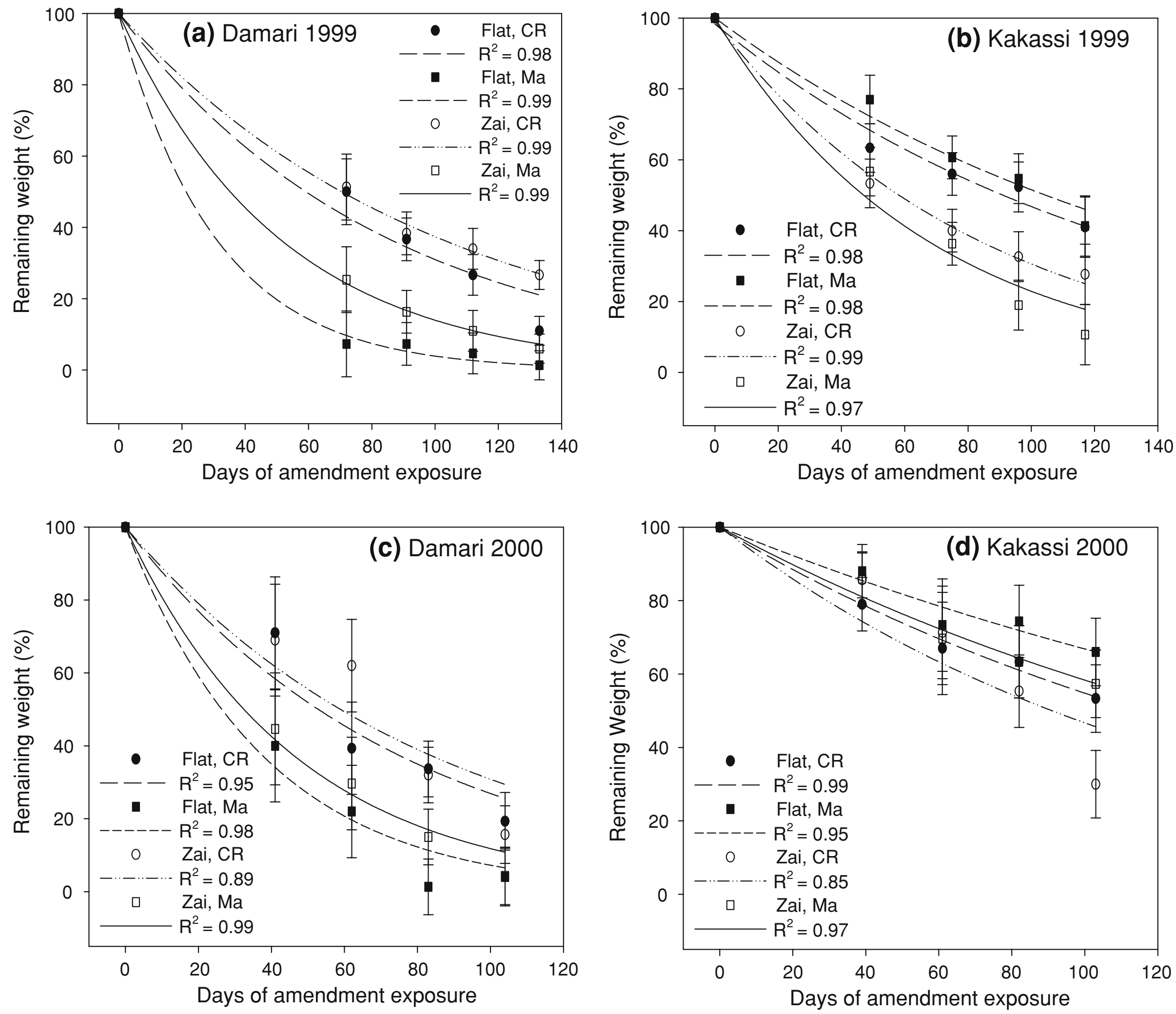

Fig. 3 Effect of amendment type and placement (Zai vs. surface application) on the decomposition of manure and crop residue at Damari and Kakassi, rainy seasons 1999 and 2000—*Flat* soil surface exposure, *CR* millet straws, *Ma* cattle manure; *Error bars* are standard error of difference between means

by amendment type and mode of application in Damari, but only by the mode of application (zai or surface) in Kakassi (Fig. 3). Manure decomposition was on average faster than that of millet straw in Damari, regardless of the mode of placement (Fig. 3a, c). The decomposition coefficient of cattle manure was higher than that of millet straw by a factor of two ($P < 0.001$; Table 4). An interaction between amendment type and mode of placement was observed only at Damari (Table 4), where the decomposition coefficient of cattle manure placed on the soil surface was 48% higher than in the zai ($P = 0.048$). No such differences were observed for millet straw decomposition.

At Kakassi, amendment type did not affect the decomposition rate (Fig. 3b, d). In contrast to Damari, decomposition coefficient in the zai was higher than on soil surfaced placement ($P = 0.002$), but also there was no significant interaction between amendment type and mode of placement (Table 4).

At Kakassi, organic amendment decomposition was faster in 1999 than in 2000 (Table 3A, B) regardless of amendment type and placement. Under zai, the decomposition rate was similar at both sites in 1999, but it was 2.5 times faster in Damari than in Kakassi in 2000. On the other hand, with surface application, the decomposition rate of all amendments

Table 3 Effect of experimental sites, organic amendment type (A) and mode of placement (B) on decomposition coefficient in both experimental years—decay constant k (days^{-1})

Treatments		Years	
Sites—A	Amendment type	1999	2000
Damari	Millet straw	0.011	0.014
	Manure	0.027	0.026
Kakassi	Millet straw	0.011	0.008
	Manure	0.012	0.005
SED (±)		0.0016	0.0029
F-test probability			
Site (S)		<0.001	0.005
Amendment type (AT)		<0.001	0.013
Interactions (S × AT)		<0.001	<0.001
Sites—B	Amendment placement		
Damari	Zai	0.016	0.017
	Flat (soil surface)	0.022	0.022
Kakassi	Zai	0.015	0.007
	Flat (soil surface)	0.008	0.005
SED (±)		0.0016	0.0029
F-test probability			
Site (S)		<0.001	0.005
Placement (Pl)		0.917	0.384
Interaction (S × Pl)		<0.001	0.032

SED standard error of difference between means

was about four times faster at Damari than at Kakassi (on average over both years; Table 3B).

Effect of amendment placement and pesticide treatment

Termites were observed to be more abundant at Damari, and the presence of these decomposer organisms is consistent with the faster decomposition at this site. This was assessed with a termite exclusion experiment using pesticides. At Damari, pesticide application significantly slowed weight loss ($P < 0.001$; Table 5) on average over the two modes of application (Fig. 4a). There was a statistically significant interaction between placement and pesticide application ($P < 0.001$). Recorded weight loss in soil surface placement after 3.5 months was 34% for pesticide-treated plots and 92% for non-treated plots ($P < 0.001$). For the zai-placed manure the respective weight loss difference was negligible.

At Kakassi, in contrast, we observed no effect of pesticide application or placement on organic amendment decomposition (Table 5), the decomposition rate on pesticide treated plots at Damari was similar to the average decomposition rate at Kakassi (Table 5), which points at the fact that very little if any termites were present at the latter site.

Table 4 Mode of amendment placement and type on decomposition coefficient k (days^{-1}) at Damari and Kakassi, averaged over 2 years (1999 and 2000)

Treatments		Experimental sites	
Placement	Amendment type	Damari	Kakassi
Zai	Millet straw	0.011	0.011
	Manure	0.021	0.011
Flat (soil surface)	Millet straw	0.013	0.008
	Manure	0.032	0.006
SED (±)		0.0026	0.0017
F-test probability			
Placement (P)		0.006	0.002
Amendment type (AT)		<0.001	0.52
Interaction (P × AT)		0.048	0.391

SED standard error of difference between means

Table 5 Effect of experimental sites, termite control and mode of organic amendment placement on decomposition coefficient—decay constant k (days^{-1})

Treatments		Decomposition coefficient
Sites	Termite control	
Damari	+ Pesticide	0.006
	− Pesticide	0.014
Kakassi	+ Pesticide	0.006
	− Pesticide	0.006
SED (±)		0.0008
F-test probability		
Sites (S)		0.003
Pesticide (P)		<0.001
Interactions (S × P)		<0.001

SED standard error of difference between means

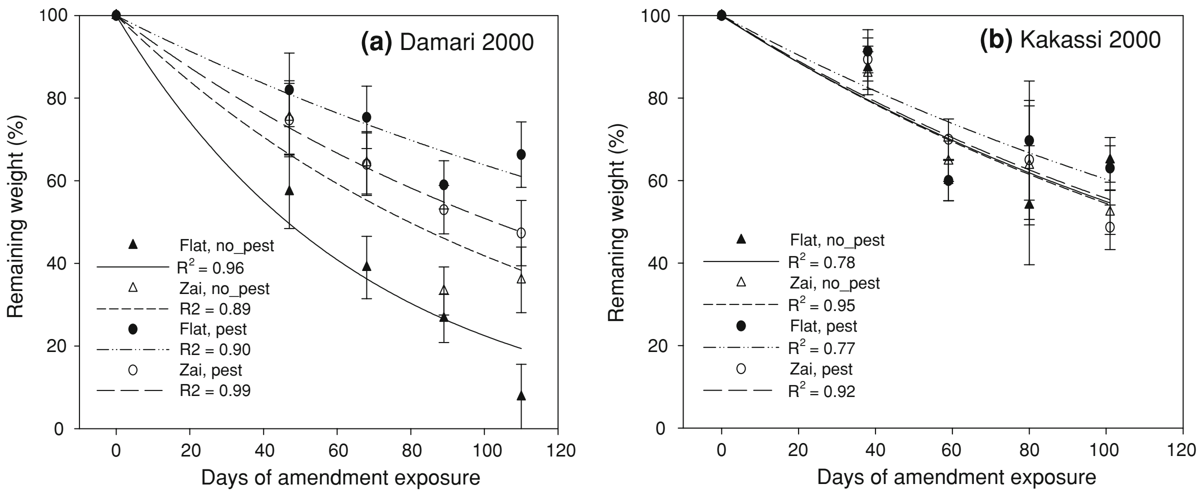

Fig. 4 Effect of pesticide application and placement (in Zai pit vs. surface application) on cattle manure decomposition at Damari and Kakassi; rainy season 2000—pest is equivalent to insecticide application; *Error bars* are standard error of difference between means

Nutrient release

On-station experiment—effect of organic amendment type and application rate

The effect of the treatments on N, P and K release was similar to that of organic amendment decomposition and proportional to the initial content in the amendment. Nitrogen, P and K release was almost complete for all treatments at the end of the exposure period (Fig. 5). In general, nutrient release from manure was faster than from millet straw. Differences between the types of amendment were observed mainly at first sampling, which were statistically significant, particularly for K release ($P < 0.001$). Organic amendment application rate also affected N and K release up to the first sampling date, with higher amendment rates releasing significantly ($P = 0.043$) more N compared to the lower rates. In terms of K release there was an interaction between the amendment type and rate of application ($P = 0.007$). The lower rate of crop residue release more rapidly K compared to the higher rate whereas the higher rate of manure released K more rapidly than the lower rate (Fig. 5).

On-farm experiment—effect of organic amendment type and placement

Nutrient release followed amendment decomposition. At Damari in 1999, N, P, and K release was slower in the zai pit than in soil surface placement, which was statistically significant for N and P. In contrast at Kakassi in the same year, N, P and K release were significantly faster in the zai pit (Table 6). At Damari, nutrient release from cattle manure was faster than from millet straw, which was statistically significant (except for N in 2000; Table 6). At Kakassi, manure released P significantly faster than millet straw in 1999 and N in 2000. In general, K release rate was higher than that of N and P at all sites in both years, which reflects the high solubility of this element.

Effect of pesticide treatment and organic amendment placement

The overall tendency is a reduction in the rate of nutrient release following pesticide application, regardless of the mode of application (Table 7). But first order interactions where observed at Damari, where significantly faster N, P and K release was observed with soil surface application without termite control as compared to zai pit application with or without termite control or soil surface application with termite control. At Kakassi, no interactions were observed between the treatments in terms of nutrient release, but N release was faster without than with termite control. Nutrient release in the zai pit was also faster than with surface-applied amendment. These differences were statistically significant (Table 7).

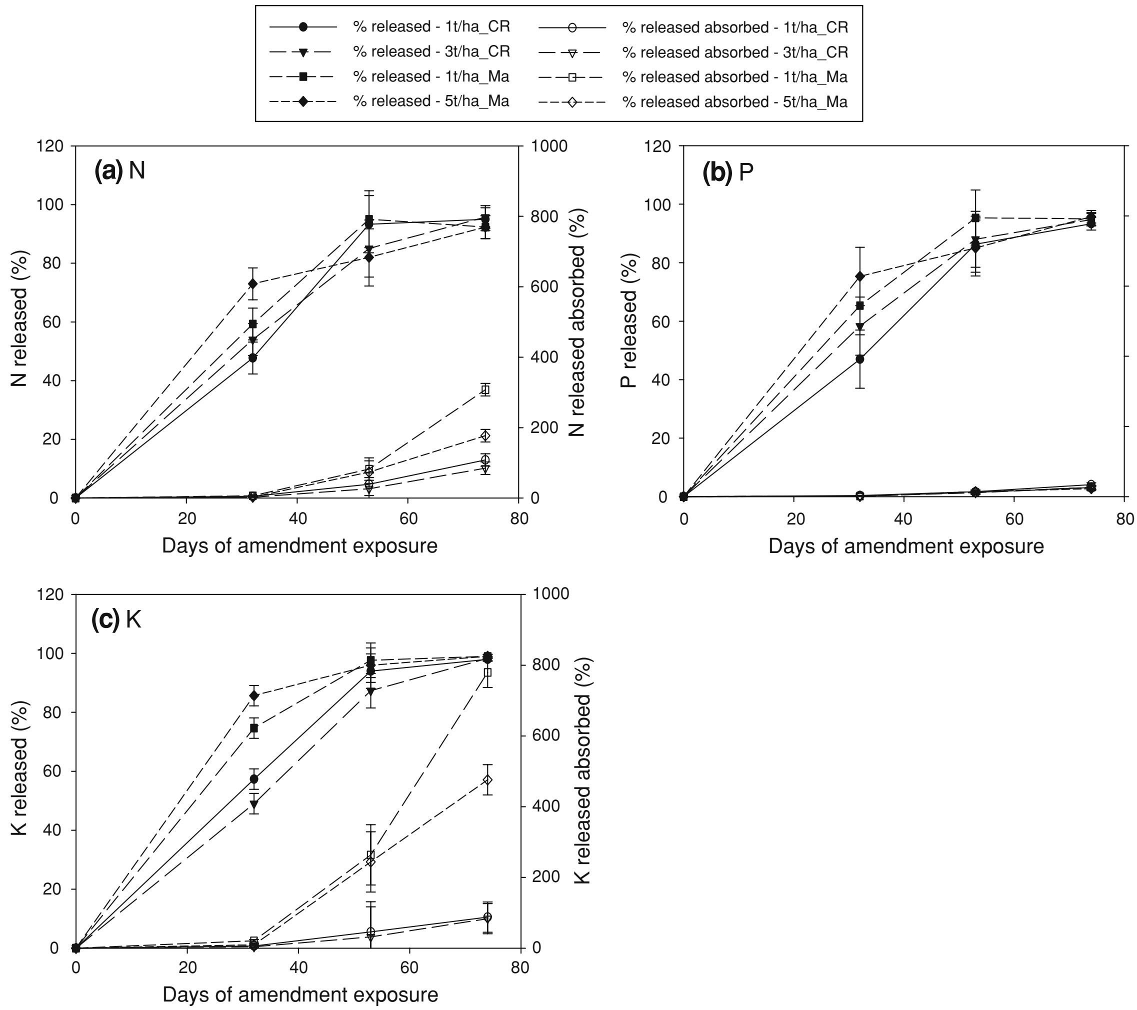

Fig. 5 N, P and K release from various amendments and percentage of released nutrients absorbed by millet in Zai pits at Sadoré 1999 – *CR* is millet straw, *Ma* is cattle manure – *Error bars* are standard error of difference between means

Percentage of N, P and K absorbed as affected by organic amendment type and placement

Figures 5 and 6 present nutrients absorbed by millet expressed as a percentage of the amount released by the amendment decomposition, for the on-station experiment at Sadoré and at Damari in 1999. Figure 5 shows that 39 days after litter application (34 days after sowing) only 3% of the N released from millet straw and 4% of that released from manure were absorbed by the millet plants on average, whereas 51 and 66% of the N contained in the straw and manure were released, respectively. The same trend is shown in Fig. 6, where 72 days after litter application at Damari, which corresponds to 36 days of plant growth, nitrogen absorption by millet corresponded to as little as 9% of the N released in the zai pit and 8% of the N released after soil surface application. Nitrogen absorption increased rapidly thereafter to reach 113 and 115% of the amount of nutrients released during amendment decomposition 1.5 month later in the zai and on soil surface application, respectively. Percentages of released absorbed nutrients in excess of 100% necessarily imply sources of nutrients other than the nutrients released by the added amendments. The same trend was observed for P and K but for P plant uptake never exceeded the amount released from cattle manure. Potassium

Table 6 Effect of mode of amendment type and placement on rate of nutrient release at Damari and Kakassi in both experimental years (1999 and 2000)—decay constant k (days^{-1})

Factors	1999						2000					
	Damari			Kakassi			Damari			Kakassi		
	N	P	K	N	P	K	N	P	K	N	P	K
Placement												
Zai	0.017	0.020	0.036	0.018	0.020	0.046	0.033	0.034	0.054	0.022	0.018	0.051
Flat (soil surface)	0.025	0.029	0.041	0.011	0.012	0.034	0.040	0.037	0.059	0.022	0.018	0.039
SED (±)	0.0028	0.0027	0.0037	0.0018	0.0019	0.0033	0.0045	0.0046	0.0078	0.0020	0.0040	0.0028
F-test probability	0.029	0.013	0.233	0.007	0.004	0.009	0.229	0.517	0.577	0.931	0.898	0.005
Amendment type												
Millet straw	0.015	0.021	0.030	0.016	0.013	0.042	0.034	0.020	0.045	0.031	0.017	0.044
Cattle manure	0.027	0.028	0.047	0.014	0.018	0.038	0.039	0.051	0.069	0.013	0.019	0.047
SED (±)	0.0028	0.0027	0.0037	0.0018	0.0019	0.0033	0.0045	0.0046	0.0078	0.0,020	0.0,040	0.0028
F-test probability	0.006	0.046	0.003	0.412	0.037	0.314	0.26	<0.001	0.023	<0.001	0.725	0.247

SED standard error of difference between means

Table 7 Effect of mode of amendment placement and pesticide application on rate of nutrient release at Damari and Kakassi, 2000—decay constant (k days^{-1})

Treatments		Damari			Kakassi		
Pesticide	Placement	N	P	K	N	P	K
+ Pesticide	Zai	0.011	0.014	0.033	0.013	0.026	0.047
	Flat	0.010	0.012	0.026	0.010	0.021	0.041
− Pesticide	Zai	0.013	0.014	0.028	0.016	0.030	0.053
	Flat	0.023	0.022	0.039	0.013	0.017	0.039
SED (±)		0.0016	0.0027	0.0048	0.0014	0.0034	0.0023
F-test probability							
Pesticide (Pe)		<0.001	0.046	0.315	0.032	0.995	0.201
Placement (Pl)		0.009	0.148	0.661	0.024	0.009	0.001
Interactions (Pe × Pl)		0.003	0.032	0.039	0.851	0.158	0.060

SED standard error of difference between means

absorption was particularly high under manure treatment. The same trend was observed at Kakassi in 1999, 22 days after planting, even though 1.5 month later the percentage of amendment-released nutrients absorbed by the millet plants was very high. Percentage of released N absorbed ranged from 130% for crop residue to 218% for manure, whereas for P it ranged form 71% for cattle manure to 185% for crop residue. The same trend was observed in both years.

Discussion

Organic amendment decomposition

Whether at Sadoré under controlled water supply, or at Damari under natural rainfall conditions, cattle manure decomposition was initially faster than millet straw. Results from Sadoré indicated that this is not influenced by the application rate in the case of CR and only slightly in the case of manure. In addition,

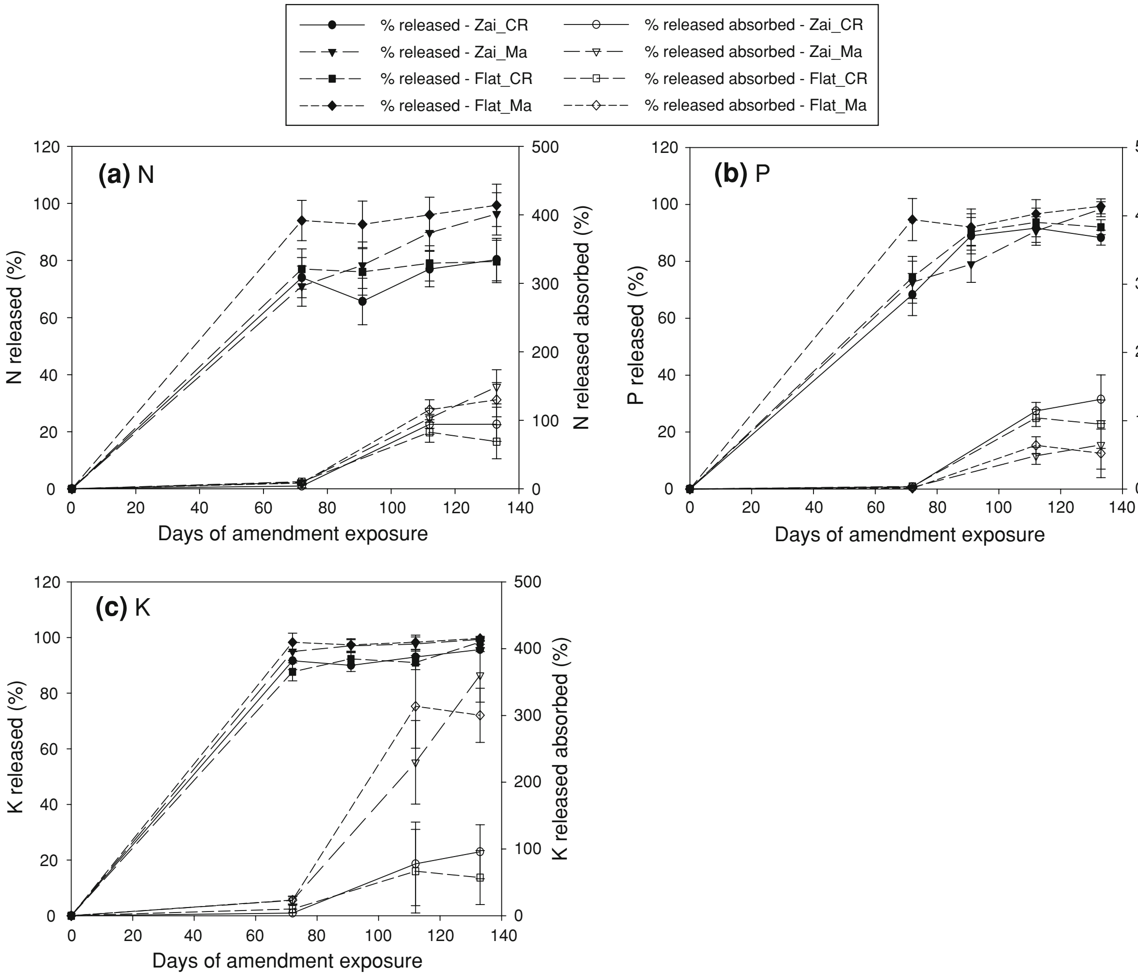

Fig. 6 N, P and K release from cattle manure and millet straw applied in Zai pits or at the soil surface and percentage of released nutrients absorbed by millet at Damari in 1999—*CR* is millet straw. *Error bars* are standard error of difference between means

the pesticide satellite trial conducted at Damari clearly revealed the significant contribution of termites to the overall amendment decomposition at this site. The lower initial decomposition rate of the millet straw may therefore be due to its lower nutrient content as well as to a preference of the termites for manure compared to millet straw. Microbial decomposition of organic amendments is controlled by their chemical and physical characteristics such as N concentration, C:N ratio and lignin:N ratio (Thomas and Asakawa 1993). The low initial N content of millet straw and its high C:N ratio (50) compared to that of cattle manure (20) reflect the low organic amendment quality of millet straw, which may have contributed to its lower microbial decomposition in the present study.

According to Mando and Stroosnijder (1999), the dominant termite species in the Sahel is *Macrotermitinae*, which are little affected by the quality of their food because of their symbiotic relationship with basidiomycete fungi. On the contrary, Ouedraogo et al. (2004) reported a preference of termites for maize straw compared to manure in Burkina Faso. They also reported on the presence of several termite species in their field experiment. In the present experiments, the species composition of the termites was not determined, nor was the contribution of termites to millet straw decomposition evaluated during the satellite trials. However, we visually observed more intensive activities of termites on cattle manure than on millet straw, which is in contradiction with the results of Ouedraogo et al.

(2004). In addition, there were no observations regarding the presence or absence of termites at different times during the decomposition process. Ouedraogo et al. (2004) showed that the largest numbers of termites were observed towards the end of the manure decomposition process whereas it occurred at 50% decomposition for the maize straw. Although the present study suggests a strong contribution of termites to crop residue decomposition after an initial lag time, further studies are required to clarify the contribution of termites of different species to the decomposition of amendments of different composition. In addition, as the presence of termites should normally enhance millet straw comminution and therefore make it more accessible to microorganisms, further studies should take into account the interaction between macrofaunal and microbial degradation.

The satellite trial data from Kakassi (Table 5) shows that the contribution of termites to manure decomposition was minimal, which seems to indicate that microbial decomposition dominated at this site. The fact that the decomposition constant was similar for both amendments at Kakassi is rather surprising given the higher C:N ratio of straw. However, crop residue was not part of the treatments tested in the pesticide satellite trial, so a contribution of termites to straw decomposition at Kakassi cannot be excluded. This would have to be verified in the future to better understand the role of amendment type in the decomposition process under the conditions of the study.

Because of the water harvesting function and a more protected environment against wind and direct insolation, zai pits are likely to offer a more continuously moist environment, favoring microbial decomposition. This may explain why at Kakassi, decomposition in the zai pits proceeded faster than for surface-applied organic amendment (Tables 3, 4).

At Damari, the overall decomposition is much larger for soil surface application than in the zai pits. At this site, runoff water may have added to the effect of termite activity in case of surface applied amendments by entraining the organic amendment after their comminution by termites. Runoff data collected at this site showed that the average run-off coefficient was 33%. At Kakassi no such effect was observed, not because runoff was limited but due to lesser activities of termites. This could explain why apparent decomposition proceeded faster for surface applied amendment at Damari and would argue in favor of slightly burying the amendments in case of surface application.

Nutrient release

The decomposition rate of various organic amendments determines the nutrient availability to the crops. In most cases, nutrient release response to the treatments was similar to that of amendment decomposition but K release was faster than organic amendment decomposition. Fast K release has been observed in earlier studies by Thomas and Asakawa (1993), and Esse et al. (2001), in the decomposition of tropical legumes and manure.

The comparison of nutrient uptake by millet and nutrient release following amendment decomposition (Figs. 5, 6) reveals that the rate of nutrient release is not well synchronized with the crop nutrient uptake. After 6 weeks, less than 10% of the released N had potentially been taken up by millet, whereas on average 82% of the amendments were already decomposed at that time. This also holds for P and K. However, this poor synchronization between nutrient release and uptake is most problematic for N, for which the risk of losses by leaching is highest. Mobility of P in soils is generally considered low, whereas K can be partially retained on the exchange sites of the clay and soil organic matter. In order to achieve a better synchronization between nutrient release and uptake, it may be useful to perform a split application of the amendments. Although a single late application of the amendments (after millet sowing) may also achieve a better synchronization, it will not improve soil surface properties prior to sowing, which may have detrimental effects on millet growth. It has also been shown that delayed application of millet straw reduces its positive impact on millet growth and yields, possibly because of reduced P mobilization (Akponikpe et al. 2008). Hence, the early application of a small amount of amendment will enhance the soil physical properties, enhance soil P mobilization and supply adequate amounts of nutrients for emergence and early growth of millet, whereas the second application (e.g., 4–6 weeks after sowing) would contribute an essential fraction to the total crop nutrient uptake. Whether early application of the amendment is of interest at Kakassi remains to be tested, as termite activity is negligible at this site and the soil is, based on crop yields, intrinsically more fertile despite the low P (Fatondji et al. 2006).

In the absence or under limited influence of termites such as at Kakassi, nutrient release in the zai was faster than on the flat. However, the water collected in the pit may exacerbate the risk of nutrient leaching. At Damari, soil surface application of the amendments favored nutrient release compared to zai pit application, especially in the case of manure. However, some of these may have been entrained by run-off water and thus lost for the crop. Thus, in the zai pit excess runoff water collected in the pit could lead to nutrient leaching whereas with surface placement it might lead to losses by run-off.

Organic amendment application such as mulch is an effective means for soil reclamation particularly when termites are present (Mando and Brussaard 1999), but nutrient loss through run-off may be critical. Therefore considering the risk of nutrient leaching following water harvesting in the zai pit at Damari, a slight burial of the surface-applied amendment may be an advantage.

Conclusions and recommendations

In general, organic amendment quality plays a role in the decomposition and nutrient release, with manure decomposing faster and more complete than millet straw except in Kakassi. In the absence of termites, organic amendment decomposition was favored in the zai compared to soil surface application, illustrating that zai offers more favorable conditions for microbial decomposition in situations with water deficits because of moisture conservation for longer period. When termites are present the amendment decomposition enhancing effect of zai was masked. This may be due to the entrainment of surface applied organic amendment by runoff water after comminution by the termites, whereas in the zai pit all the amendment is retained.

Significant termite activity was observed only at the two sandier sites (Sadoré and Damari). Although higher clay content tends to favor mount-building or subterranean termites (Meyer 1960), Lee and Wood (1971) observed no termite mounts and galleries in cracking soil despite high clay content. They conclude that the shrink-swell seasonal disturbance prevents termites from constructing stable structures. Considering its vertic properties, the soil at Kakassi can be considered as a cracking clay soil. Although the benefits of the zai are generally attributed to a large extent to the beneficial effects of termite activity on soil physical properties, this would not hold in the case of Kakassi. Water harvesting (Fatondji et al. 2006) and nutrient supply would be central to the effect of zai at this site.

Nutrient release was fast soon after organic amendment application, when plants are still too young to benefit from it. This would support arguments in favor of a split application of the amendments at sites such as Damari and Sadoré. At Kakassi, a single application a few weeks after sowing may be sufficient, as termites are absent.

Because of the poor synchronization between crop nutrient uptake and nutrient release, possibly large losses by leaching may occur, especially for N and in zai pits. In case of surface application, nutrient losses may also occur by entrainment with runoff. In this latter case, a partial burial of the amendment would be recommended.

Amendment decomposition and nutrient release are enhanced in the zai pit due moisture conservation. Therefore, the zai technique should be used under dryer conditions. Surface or broadcast applied amendments are exposed to wind and water erosion and are rapidly comminuted by termites. In such cases, nutrients are easily lost and not available to the standing crop. Incorporating the amendment could remedy this problem, but in the dry regions of the Sahel, the upper soil layer dries very quickly even during the rainy season. Under such conditions, decomposition may not proceed continuously and the zai pit might be preferred.

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