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Soil macrofaunal-mediated organic resource disappearance in semi-arid West Africa

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Abstract

A field experiment to investigate the interaction of soil fauna and organic resource quality in the applied organic material mass loss was conducted on a Eutric Cambisol in southern Burkina Faso during the 2000 rainy season. Plots were treated with the pesticides Dursban and Endosulfan or left untreated (main treatments). Sub-treatments consisted of surface-placed maize straw, *Andropogon* straw or cattle dung. Organic materials were applied at a rate equivalent to the application of 40 kg N ha^{-1}. Litterbags and direct estimation methods were used to follow the litter mass loss of the different organic materials. Without soil macrofauna, 96% of *Andropogon* straw, 70% of cattle dung and 34% of maize straw were not broken down 3 months after application, whereas in the presence of soil fauna only 19% of *Andropogon* straw, 8% of cattle dung and 5% of maize straw remained 3 months after application. Soil depth (surface-placed or buried) had little or no influence on organic resource disappearance in the absence of soil fauna. The interaction between organic resource quality and soil macrofauna had a large influence on the timing of organic material disappearance. Termite density was strongly correlated with the remaining organic material, with organic material being preferred over easily decomposable organic resources. In semi-arid low-input agricultural systems, soil fauna (termites) determine the rate of decomposition of organic resources.

Keywords: Litter mass loss; Soil fauna; Termites; Organic matter

1. Introduction

The beneficial effect that soil faunal communities have on the sustainability of low-input agricultural systems based on organic fertilisation is largely ignored in soil fertility management (Lavelle et al., 1994; Wardle et al., 1999). Soil organisms fulfil a number of functions including decomposition of organic matter, nutrient cycling, bioturbation and suppression of soil-borne diseases and pests (Brussaard et al., 1997).

According to their size, soil organisms are usually classified into microflora, microfauna, mesofauna and macrofauna (Swift et al., 1979). Within these major categories, soil organisms are often grouped according to their functional attributes that often transcend morphological and taxonomic boundaries (Beare et al., 1997). Brussaard (1998) distinguished the following

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three guilds of soil organisms:

1. (1) Root biota which consist of organisms that live in association with the living plant, either beneficially or detrimentally affecting plant growth, e.g. nitrifying bacteria and mychorrizas.
2. (2) Decomposers which involve microflora and micro/mesofauna which mineralise nutrients and/or act as regulators of numbers and activities of microorganisms and microbial feeders. This group also includes meso- and macrofauna that comminute litter entering the soil without physically reworking the mineral part of the soil.
3. (3) Ecosystem engineers consisting of meso- and macrofauna which create microhabitats for the other soil biota by reworking the soil. Earthworms and termites are considered the most important ecosystem engineers in soil because of their far-reaching and lasting effects on other species and their ability to modulate soil physical and chemical properties. The latter group is considered as the most important faunal component in the semi-arid zone (Lavelle et al., 1994). Furthermore, the contribution of the soil fauna to the decomposition of organic material and nutrient release appears to be high under constrained environmental conditions (Tian et al., 1997).

The decomposition of organic residues is related to their C/N ratio, their lignin and polyphenol content (Woomer and Swift, 1994; Janssen, 1996; Tian et al., 1997). Comminution (breakdown) of organic material by soil fauna increases the exposure of substrate to the microflora, which may lead to an enhanced decomposition and nutrient release (Scheu and Wolters, 1991). It is well known that soil fauna play a key role in the communition and decomposition of organic material, but to what extent organic resource quality and soil faunal interactions can affect organic material mass loss has not been well investigated under semi-arid conditions. The aim of this paper is to assess the interaction of organic resource quality and soil fauna in the mass loss of organic materials of contrasting qualities under semi-arid conditions in West Africa. It was hypothesised that the contribution of soil fauna to the disappearance of organic resources will be different depending on the quality of the organic material.

2. Methods

2.1. Site description

The study was conducted at Kaibo (11°N–12°N) in 2000 in southern Burkina Faso, located in the north soudanian climatic zone. Annual rainfall ranges from 750 to 1000 mm with a mean temperature of 28 °C. The rainy season is from June to September with an average rainfall of 935 mm for the last 47 years. Leptosols, Vertisols, Fluvisols, Regosols, Luvisols, Lixisols and Cambisols are the most dominant soil types (BUNASOL, 1989; Mulders and Zerbo, 1997). The experiment was laid out on a Eutric Cambisol. The top soil (0–10 cm) characteristics are shown in Table 1. Nutrient depletion and water erosion are the main land degradation forms.

2.2. Experimental design

A split plot design with four replications was laid out. The site was previously under fallow for 6 years. The main treatment was the use of insecticides, to establish plots with fauna (F) and plots without fauna (NF). Dursban (with chloropyrifos as active ingredient applied at the rate of 400 g a.i. ha^{-1}) and Endocoton (with endosulfan as active ingredient applied at the rate of 450 g a.i. ha^{-1}) were applied four times (just before the set-up of the experiment and 3, 6 and 10 weeks after the organic material application and sowing). The plots were 24 m × 20 m and 10 m apart.

Table 1
Characteristics of the top soil (0–10 cm) (Eutric Cambisol, Kaibo, southern Burkina Faso)

Parameters	Values
Clay (%)	15 ± 2
Silt (%)	33 ± 4
Sand (%)	51 ± 5
Carbon (%)	0.83 ± 0.14
Nitrogen (%)	0.05 ± 0.01
Phosphorus (%)	0.017 ± 0.003
Potassium (%)	0.063 ± 0.012
Exchangeable calcium (μmol kg^{-1})	5.0 ± 1.0
Exchangeable magnesium (μmol kg^{-1})	1.4 ± 0.3
Exchangeable potassium (μmol kg^{-1})	0.2 ± 0.06
Exchangeable sodium (μmol kg^{-1})	0.1 ± 0.02
pH (H_2O)	7.0 ± 0.4
pH (KCl)	5.3 ± 0.4

Table 2
Chemical properties of materials applied

Organic materials	Carbon (C) (%)	Nitrogen (N) (%)	Phosphorus (P) (%)	Potassium (K) (%)	Lignin (L) (%)	C/N ratio	L/N ratio
Andropogon straw	49	0.32	0.03	0.24	0.13	153	0.41
Cattle dung	38	0.95	1.06	0.36	0.49	40	0.52
Maize straw	45	0.77	0.18	1.20	0.16	59	0.21

Sub-treatments consisted of maize straw (SM), *Andropogon* straw (SA) and cattle dung (CD). Table 2 shows chemical properties of the applied organic resources. The size of sub-plots was 10 m × 5 m separated by guard row of 2.5 m × 2 m. The blocks were separated by an alley of 4 m. All the organic materials were applied at the same time before sowing at rates equivalent to the application of 40 kg N ha^{-1}.

The plots were sown with sorghum (*Sorghum bicolor* L. Moench) variety SARIASO 14 at a density of 31,250 seedlings ha^{-1}. During the growing season, the field was weeded twice using hoes. The crop was harvested 4 months after sowing.

2.3. Data collection

2.3.1. Litter disappearance and counting of soil macrofauna

Litter mass loss was measured using the litterbag technique and direct estimation of litter disappearance. Litterbags (18 cm × 15 cm) of mesh size 1 or 4 mm were placed at two depths (0–3 cm; 30–35 cm). The litterbags were constructed from soft-wire net. Each litterbag was filled with 100 g (on dry matter basis) of the same organic material as the sub-treatment on which it was placed. *Andropogon* straw was introduced into the litterbag without any pre-treatment. For cattle dung, dung in the form of dried cake was used in order for it to be retained in the litterbag even when the mesh size was 4 mm. Long stems of maize straw were chopped into pieces not longer than 8 cm before introduction into litterbags.

Surface-placed litterbags were kept in place with earth around each litterbag. The use of litterbags with mesh size 1 mm placed in the treated plots aimed to exclude most soil meso- and macrofaunal activity from the litterbag and the mesh size of 4 mm aimed to allow all soil fauna to access the organic material inside the litterbag. Two hundred and eighty-eight litterbags were used for the experiment. Twelve litterbags were placed in each sub-plot, i.e. six on the surface (0–3 cm) and six buried at 30–35 cm. The litterbags were placed at sowing.

After the experiment was set up, four litterbags (two mesh sizes, two depths) from each sub-plot were removed every month. Soil material was washed away from the remaining organic material, which was air-dried and weighed. Soil fauna in each litterbag were collected and conserved in 70% alcohol until identification and counting.

Direct estimation of the remaining surface-placed organic material was carried out at harvest using the method adapted from Stott et al. (1990). In the four replications, remaining organic materials were removed from a delimited 1 m^2 microplot. Plot borders were excluded during sampling. Soil debris was gently washed away and organic material air-dried and weighed. Data were subjected to ANOVA.

2.3.2. Soil faunal contribution to organic material disappearance

Soil faunal contribution to organic material mass loss was calculated using the following formula adapted from Mando and Brussaard (1999):

$$\text{Soil faunal contribution to mass loss (\%)} = \frac{A - B}{100 - B} \times 100$$

where A is the percentage of organic material remaining in the absence of soil fauna (percentage of organic material remaining in the litterbag with mesh size 1 mm placed in the treated plots), and B is the percentage of organic material remaining in the presence of soil fauna (percentage of organic material remaining in the litterbag with mesh size 4 mm placed in the untreated plots).

3. Results

3.1. Effect of soil fauna on organic material disappearance

Table 3 and Fig. 1a–f show that litterbag mesh size was by far the most important factor influencing organic material disappearance, followed by the length of exposure (sampling period) and the nature of the organic material. In the case of litterbags with mesh size 1 mm, there was no significant difference in loss of organic material between the treated plots and the untreated plots for the entire period of the experiment and for all the treatments except the surface-placed maize straw (Fig. 1a–f). There was no significant difference in the amount of organic material remaining in the 4-mm mesh litterbags between treated and untreated plots in the first month, although the general trend shows higher mass loss in untreated plots than in treated plots except in buried *Andropogon* and buried maize straw. Three months after placement, 5–19% of the organic material remained in untreated plots compared with 8–47% in the treated plots.

Table 4
Percentage of surface-placed organic materials remaining at harvest (4 months after application) using direct estimation of litter mass loss

Treatments	Non-treated	Pesticides
Andropogon straw	0.2 ± 0.07	41 ± 4.4
Maize straw	2.3 ± 0.13	43 ± 1.3
Cattle dung	0.0 ± 0.00	32 ± 0.9

±: Standard deviation.

Significant differences were noted in the organic material remaining in the 1- and 4-mm litterbags. In treated as well as in non-treated plots, organic material remaining in the 4-mm litterbag in *Andropogon* straw and cattle dung treatments was less than in the 1-mm litterbags 3 months after placement.

When comparing the impact of pesticide and mesh size on organic material disappearance, significant differences were observed in all treatments, suggesting that small mesh size was more efficient in suppressing soil faunal activities in the litterbags than pesticides. However, direct estimation of organic resource disappearance showed that the organic material mass loss was significantly ($P < 0.001$) reduced when pesticides were applied (Table 4).

Table 3
Repeated measurement ANOVA of organic material remaining.

Source of variation	d.f.	*F*-value	*P*-value
Pesticide	1	29.07	<0.001
Mesh size	1	515.49	<0.001
Organic resource	2	59.10	<0.001
Depth of placement	1	9.51	0.003
Sampling period	1	116.41	<0.001
Pesticide × mesh size	1	5.67	0.02
Pesticide × organic resource	2	1.74	NS
Mesh size × organic resource	2	2.60	NS
Pesticide × depth of placement	1	24.07	<0.001
Mesh size × depth of placement	1	3.89	NS
Organic resource × depth of placement	2	7.62	0.001
Sampling period × pesticide	2	1.45	NS
Sampling period × mesh size	2	21.41	<0.001
Sampling period × organic resource	4	0.71	NS
Sampling period × depth of placement	2	0.90	NS
Pesticide × mesh size × organic resource	2	2.98	NS
Pesticide × mesh size × depth of placement	1	1.74	NS
Mesh size × organic resource × depth of placement	2	3.95	0.024
Sampling period × pesticide × depth of placement	2	5.26	0.007
Sampling period × mesh size × organic resource	4	8.12	<0.001
Sampling period × pesticide × mesh size × organic resource × depth of placement	4	3.47	0.01

P-value: probability level, d.f.: degrees of freedom, NS: $P > 0.05$.

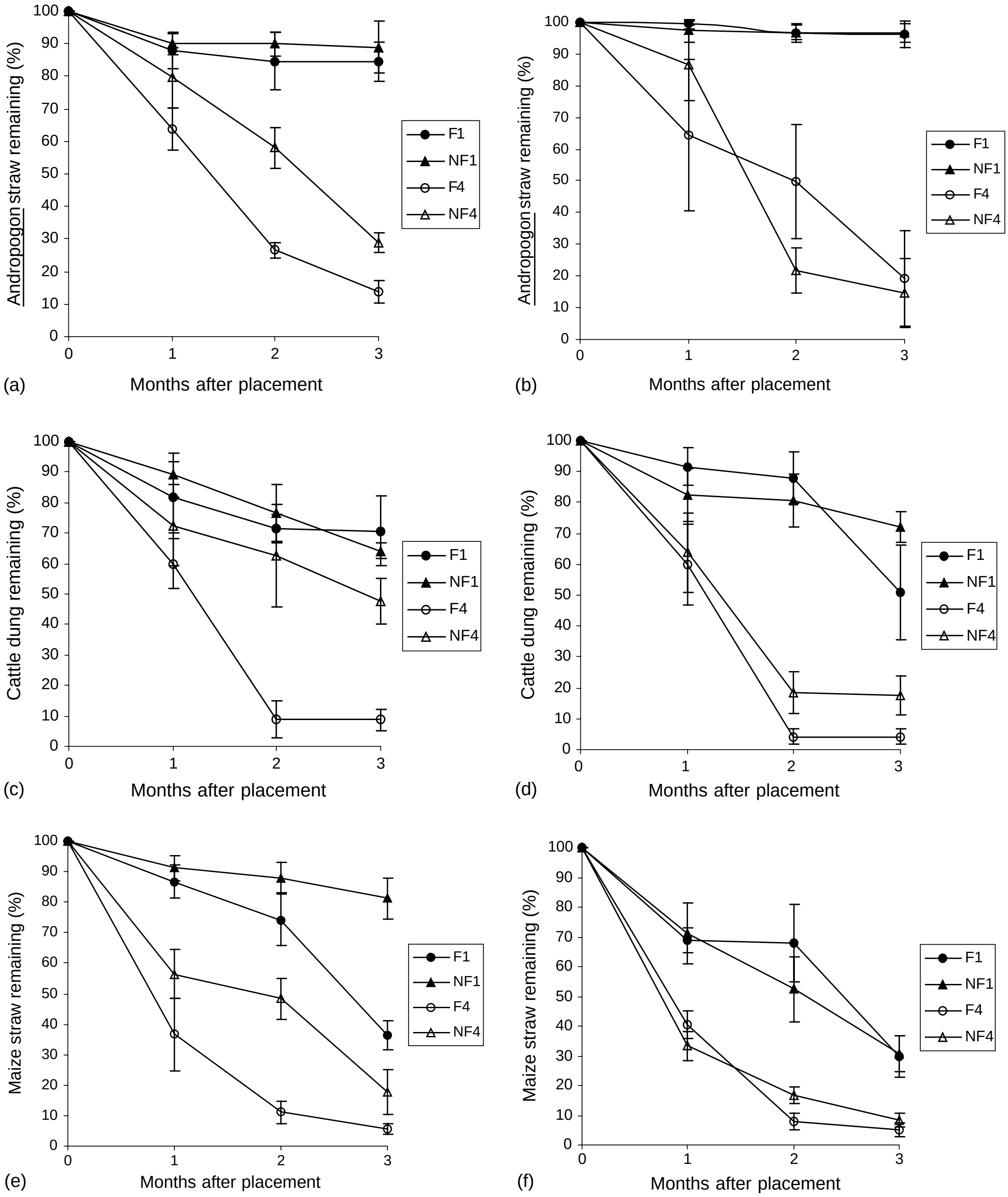

Fig. 1. Percentage mass loss of organic materials over 3 months, August, September and October 2000: (a) surface-placed (0–3 cm) *Andropogon* straw; (b) buried (30–35 cm) *Andropogon* straw; (c) surface-placed (0–3 cm) cattle dung; (d) buried (30–35 cm) cattle dung; (e) surface-placed (0–3 cm) maize straw; (f) buried (30–35 cm) maize straw. F1: With fauna, litterbag mesh size 1 mm; F4: with fauna, litterbag mesh size 4 mm; NF1: without fauna (pesticide-treated), litterbag mesh size1 mm; NF4: without fauna (pesticide-treated), litterbag mesh size 4 mm; bars represent standard deviations.

3.2. Effects of location on organic material disappearance

Table 3 shows that the depth of placement (soil surface or buried) significantly affected organic material disappearance but less than mesh size, sampling period, the nature of organic material or pesticide. No significant effect of the interaction between mesh size and depth of placement on organic material disappearance was observed (Table 3). The depth of organic material placement also had no significant influence on organic material mass loss from the litterbags with mesh size 1 mm except in the maize straw treatment where the disappearance seemed to be faster when buried than surface-placed (Fig. 1e and f).

In general, the disappearance of organic material from the buried litterbags with mesh size 4 mm was as fast as the mass loss of organic material applied (in mesh size 4 mm) on the soil surface in the presence of soil fauna. In the treated plots, the mass loss was faster when the material was buried than surface-placed. Indeed, the interaction between pesticide and soil depth significantly affects organic material disappearance (Table 3).

3.3. Organic material location and soil faunal contribution to disappearance

Fig. 2 shows soil faunal contributions to the disappearance of organic material at the two depths from surface-placed and buried litterbags. Soil faunal contribution to *Andropogon* straw disappearance was highest when buried followed by cattle dung and maize straw. When placed on the soil surface, soil faunal contribution was more important in maize straw during the first month. In the second and the third month, the same trend as when the material was buried was observed. In cattle dung plots, the contribution of soil fauna to mass loss was intermediate between the two other treatments.

3.4. Organic resource quality effects on soil macrofauna composition

The seven most important groups of soil macrofauna found in the litterbags were termites, ants, Coleoptera, Myriapoda, Arachnida, Dermaptera and earthworms. Termites accounted for 78% of total soil fauna (Tables 5 and 6). Two groups of termites were collected: the *Macrotermes* spp. and *Trinervitermes* spp. *Macrotermes* spp. accounted for 90% of the termites. High density of termites was noted during the first 2 months in maize and *Andropogon* straw. However, an increase in termites was only observed in cattle dung during the third month. Strong correlations between percentage remaining organic material and termites were noted in all treatments (Fig. 3a–f). No significant correlation between remaining organic resource and other soil fauna was noted.

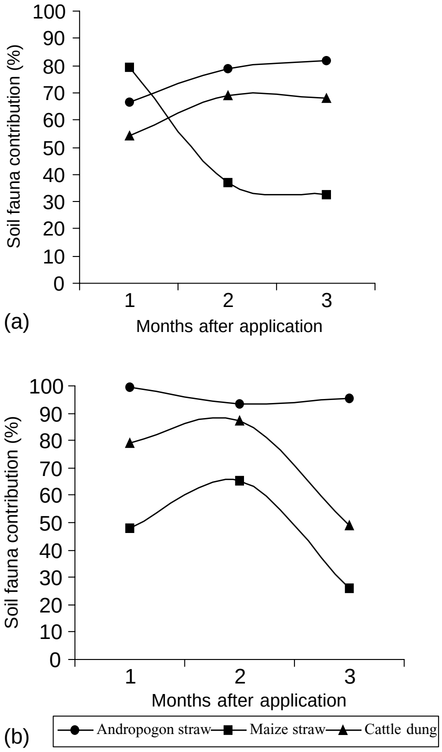

Fig. 2. Soil faunal contribution to organic material mass loss as affected by soil depth (location) in 2000 at Kaibo, Burkina Faso: (a) surface-placed; (b) buried.

Ants were dominated by *Monomonium* spp., *Camponotus* spp., *Dorolys* spp. and *Pachycondula* spp. and were often associated with high densities of other organisms like termites. The Coleoptera mainly belonged to Staphynilidae, Elateridae and Scarabaeidae. Myriapoda were Diploda and Chilopoda. Spiders were the most dominant component of Arachnida. Dermaptera were mainly found in *Andropogon* and

Table 5
Total numbers of individuals of the main soil macrofaunal groups present in the 4 mm litterbags for 1–3 months after placement in non-treated plots (no pesticides)

	Organic materials																	
	Andropogon straw buried			*Andropogon* straw surface-placed			Maize straw buried			Maize straw surface-placed			Cattle dung buried			Cattle dung surface-placed		
	1[a]	2[a]	3[a]	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Termites	434	507	18	539	137	1	326	325	1	1286	143	62	0	0	422	11	78	125
Ants	205	4	22	1	20	0	11	8	40	9	1	72	4	1	53	2	2	1
Coleoptera	15	15	16	21	8	0	14	12	13	17	0	2	12	2	2	8	3	2
Myriapoda	6	4	3	4	1	0	9	20	17	5	0	0	3	2	12	3	0	0
Arachnida	2	8	9	3	1	0	2	4	5	0	1	3	2	33	1	0	0	1
Dermaptera	0	1	6	0	3	0	0	1	1	7	2	0	0	2	1	0	0	0
Earthworms	0	0	0	1	0	0	0	0	1	0	1	0	0	1	1	1	0	0
Others	2	4	3	0	2	0	0	6	1	1	3	4	0	3	3	0	0	0

[a] Time in months.

Table 6
Total numbers of individuals of the main soil macrofaunal groups present in the litterbags as affected by mesh size and pesticides

	1 mm[a]		4 mm[a]	
	Treated[b]	Non-treated[b]	Treated[b]	Non-treated[b]
Termites	0	0	18	4415
Ants	8	8	17	456
Coleoptera	5	10	26	162
Myriapoda	10	8	16	89
Arachnida	9	8	7	75
Dermaptera	2	2	10	24
Earthworms	0	0	0	6
Others	1	3	5	32

[a] Mesh size.
[b] Pesticides.

maize straw. Earthworms found were mainly *Millsonia inermis*, which live at 30–40 cm depth but come to the soil surface to feed on organic residues. As a result, few earthworms were collected, but the presence of their casts in the litterbags confirmed their activities. The other soil macrofauna counted were some Orthoptera represented by *Gryllus* spp. and snails collected mainly in *Andropogon* straw. Few ants (*Monomonium* spp.) and Arachnida were encountered in the litterbag with mesh size 1 mm. However, some Coleoptera, Dermaptera and Myriapoda were still found in the 4 mm litterbags placed in the treated plots (pesticides) but their numbers were far less than in the 4-mm litterbag placed in the untreated plots (Table 6).

4. Discussion

4.1. Soil fauna as a key element in the decomposition process of semi-arid zones

When soil fauna were excluded, organic material remaining was up to 99% for recalcitrant organic material compared with less than 20% in the presence of soil fauna. In the absence of soil fauna, recalcitrant organic material disappearance was apparently not effective in 1 year.

When pesticides were applied, the organic material remaining in the 1 mm litterbags did not change significantly confirming that abiotic and microbial impact on slowly decomposable organic resource decomposition is very low in the absence of soil fauna. From a methodological point of view, mesh size seems to be more effective than pesticide application in suppressing soil faunal activities (comparing F1 and NF4, Table 6). The confinement conditions in litterbags may have reduced pesticide action due to reduced penetration into the litterbags during the different pesticide applications. This was confirmed by the direct estimation of organic material mass loss.

The results indicate a strong correlation between organic resource mass loss and the dynamics of termites with low quality organic material being preferred over easily decomposable material. The present study confirms the findings of previous studies, which have shown that soil faunal activity is a key element in the decomposition of organic residues under semi-arid

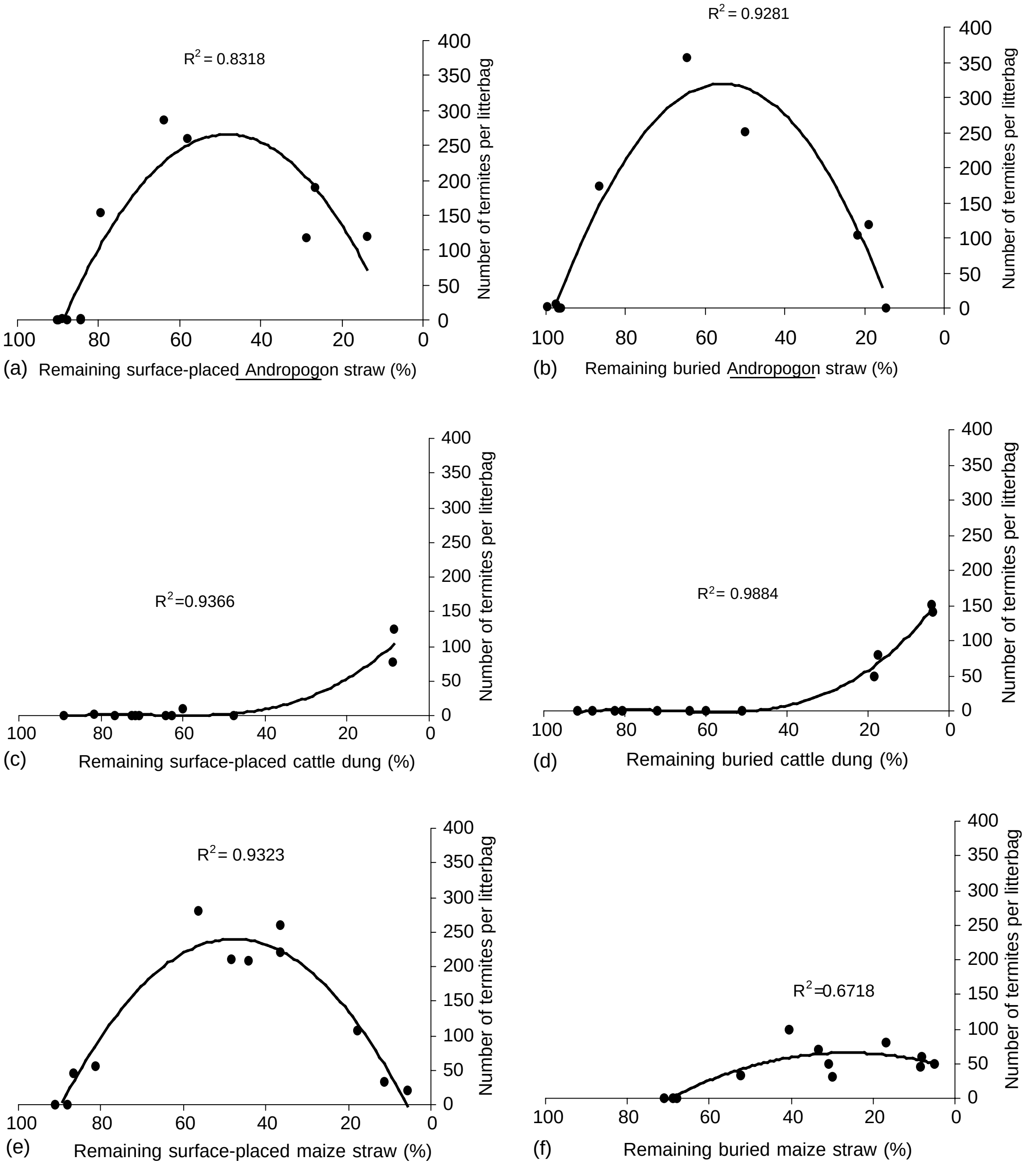

Fig. 3. Correlations between termite density and the remaining surface-placed or buried organic resources, August–October 2000, Kaibo, Burkina Faso. The decline in termite number is likely due to resource depletion; (a) surface-placed *Andropogon* straw; (b) buried *Andropogon* straw; (c) surface-placed cattle dung; (d) buried cattle dung; (e) surface-placed maize straw; (f) buried maize straw.

conditions (Tian et al., 1993; Mando and Brussaard, 1999). To the best of our knowledge, our study is the first in which low quality organic resource mass loss can be ascribed to one group of soil fauna, i.e. termites.

Organic resources are a major natural source of plant nutrients and play a key role in the reconstitution of soil organic matter, especially in low-input agricultural systems. Therefore, how their quality affects the contribution of soil fauna to decomposition is important for the management of crop residues, manure and other organic resources at farm level. The study showed that organic resource disappearance was very slow in the absence of soil fauna in an annual crop production cycle under semi-arid conditions. Soil macofauna, dominated by termites mediated the disappearance of these organic materials depending on their quality. Termites prefer recalcitrant organic material. Further research should focus on termite activity in organic resource comminution and incorporation into soil for better plant nutrition and improved soil physical properties.

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References

Beare, M.H., Reddy, M.V., Tian, G., Srivastava, S.C., 1997. Agricultural intensification, soil biodiversity and agroecosystem function in the tropics: the role of decomposer biota. Appl. Soil Ecol. 6, 87–108.

Brussaard, L., Behan-Pelletier, V.M., Bignell, D.E., Brown, V.K., Didden, W., Folgarait, P., Fragoso, C., Freckman, D.W., Gupta, V.V.S.R., Hattori, T., Hawksworth, D.L., Klopatek, C., Lavelle, P., Malloch, D.W., Rusek, J., Söderström, B., Tiedje, J.M., Virginia, R.A., 1997. Biodiversity and ecosystem functioning in soil. Ambio 26, 563–570.

Brussaard, L., 1998. Soil fauna, guilds, functional groups and ecosystem processes. Appl. Soil Ecol. 9, 123–135.

BUNASOL, 1989. Etude morpho-pédologique de la province du Boulgou. Rapport + cartes. Bureau National des Sols, Ouagadougou, 295 pp.

Janssen, B.H., 1996. Nitrogen mineralisation in relation to C:N ratio and decomposability of organic materials. Plant soil 181, 39–45.

Lavelle, P., Dangerfield, M., Fragoso, C., Eschenbrenner, V., Lopez-Hernandez, D., Pashanasi, B., Brussaard, L., 1994. The relationship between soil Macrofauna and tropical soil fertility. In: Woomer, P.L., Swift, M.J (Eds.). The Biological Management of Tropical Soil Fertility. Wiley-Sayce, Sussex and Exter, pp. 137–139.

Mando, A., Brussaard, L., 1999. Contribution of termites to the break down of straw under Sahelian conditions. Biol. Fertil. Soil 29, 332–334.

Mulders, M.A., Zerbo, L., 1997. Explications additives du rapport de Kaibo V5. Aménagement et gestion de l'espace sylvo-pastoral du Sahel. Antenne Sahélienne de l'Université Agronomique de Wageningen, Pays Bas/ Université de Ouagadougou, Burkina Faso. Document de Projet No. 42, 7 pp. + carte.

Scheu, S., Wolters, V., 1991. Influence of fragmentation and bioturbation on the decomposition of ^{14}C labelled beech leaf litter. Soil Biol. Biochem. 23, 1029–1034.

Stott, D.E., Stroo, H.F., Elliott, L.F., Papendick, R.I., Unger, P.W., 1990. Wheat residue loss from fields under no-till management. Soil Sci. Soc. Am. J. 54, 92–98.

Swift, M.J., Heal, O.W., Anderson, J.M., 1979. Decomposition in Terrestrial Ecosystems. Blackwell Scientific Publications, Oxford, 372 pp.

Tian, G., Brussaard, L., Kang, B.T., 1993. Biological effects of plant residues with contrasting chemical compositions under humid tropical conditions: effects on soil fauna. Soil Biol. Biochem. 25, 731–737.

Tian, G., Kang, B.T., Brussaard, L., 1997. Effect of mulch on earthworms activity and nutrient supply in the humid tropic. Soil Biol. Biochem. 29, 369–373.

Wardle, D.A., Yeates, G.W., Nicholson, K.S., Bonner, K.I., Watson, R.N., 1999. Response of soil microbial biomass dynamics, activity and plant litter decomposition to agricultural intensification over a seven year period. Soil Biol. Biochem. 31, 1707–1720.

Woomer, P.L., Swift, M.J., 1994. The Biological Management of Tropical Soil Fertility. Wiley-Sayce, Sussex and Exeter, 243 pp.