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Carbon and nitrogen dynamics in a phosphorus-deficient soil amended with organic residues and fertilizers in western Kenya

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Abstract The contribution of organic resources to the restoration of soil fertility in smallholder farming systems in East Africa is being tested as an alternative to costly fertilizers. Organic inputs are expected to have advantages over fertilizers by affecting many biochemical properties controlling nutrient cycling. Our study examined changes in soil C and N, C and N mineralization, microbial biomass C (MBC) and N (MBN), and particulate organic matter (POM) in a P-limiting soil in western Kenya after applications of organic residues and fertilizers to overcome P limitation to crops. Leaf biomass from six different tree (shrub) species was incorporated into the soil at 5 Mg ha⁻¹ for five consecutive maize growing seasons, over 2.5 years. Triple superphosphate was applied separately at 0, 10, 25, 50, and 150 kg P ha⁻¹ in combination with 120 kg N ha⁻¹ as urea. Soil inorganic N, soil organic C, mineralizable N, and total C in all POM fractions and total N in the 53- to 250- μ m POM fraction increased following addition of all organic residues compared to the control. Whether there was an advantage of organic residue incorporation over inorganic fertilizer use depended on the soil parameter studied, the organic residue and the rate of fertilization. Most differences were found in N mineralization where 14.4–21.6 mg N kg⁻¹ was mineralized in fertilizer treatments compared to 25.2–30.5 mg N kg⁻¹ in organic residue treatments. C and N mineralization and the 53- to 250- μ m POM fractions were the most sensitive parameters, correlating with most of the studied parameters. Organic

residues can contribute to improved soil nutrient cycling while the magnitude of their contribution depends on the biochemical properties of the residues.

Keywords Leaf biomass · Microbial biomass carbon · Mineralization · Particulate organic matter · Phosphorus fertilizer

Introduction

The predominance of smallholder farming systems constitutes a major constraint to soil fertility improvement in Eastern Africa. Such systems are characterized by land scarcity, low soil fertility, low income, low input of fertilizers and therefore low crop production, etc. The limited use of fertilizers in such systems has stimulated research to identify low-cost alternatives. One such alternative is the use of organic resources available to farmers. These include plant residues, green manures, animal manures and organic wastes. Organic resources can play an important role as a direct supply of nutrients, provided the nutrient release is synchronized with crop demand (Myers et al. 1994). While organic inputs often have lower capacity as a direct source of nutrients compared to fertilizers, they affect many soil properties controlling nutrient cycling, availability and crop production (Palm et al. 1997). Studies have reported that application of organic amendments can change soil water retention (Ghuman and Sur 2001), soil structure and aggregation (Acosta-Martinez et al. 1999), soil pH (Tang and Yu 1999; Paul et al. 2001), microbial biomass and activity (Chander et al. 1995; Acosta-Martinez et al. 1999), soil organic matter (Wander et al. 1994) and plant nutrient availability. However, organic resources differ in their capacity to release nutrients (Cobo et al. 2002) and the quality of the organic material is an important consideration when studying the short- or long-term effects of organic resources on nutrient availability (Palm et al. 2001).

In Eastern Africa, N and P are considered as the most limiting nutrients for crop production and strategies for improving soil fertility include the incorporation into soil

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of leaf biomass from trees and shrubs found in a farm's vicinity. Most field experiments have focused on the effect of such residues on crop yield and on the availability of the nutrient of interest, but little or no attention has been given to other soil indicators of nutrient cycling (Jama et al. 1997; Gachengo et al. 1999). In an experiment designed to study the contribution of organic residues in comparison to inorganic fertilizers initially on the control of a pest weed (striga, *Striga hermonthica* Del.) and then on P-availability improvement in a P-limiting soil in western Kenya, it was found that some organic residues reduced striga emergence (Gacheru and Rao 2001) whereas soil labile P in some residue treatments was higher than that seen with an equivalent rate of P fertilizers (Nziguheba et al. 2000). We then hypothesised that repeated incorporations of organic residues may have affected many other soil indicators of short- or long-term nutrient cycling. The main objectives of the present study were: (1) to assess changes in soil organic C (SOC), C and N mineralization, microbial biomass C (MBC) and N (MBN) as affected by organic residues and inorganic fertilizers; (2) to determine the effect of organic residue quality on these parameters; and (3) to study the distribution of C and N in soil organic matter fractions after organic residue amendments.

Materials and methods

Site description and experimental design

The field experiment was conducted in the highlands of western Kenya (latitude 0°06'N, longitude 34°34'E, altitude 1,420 m, mean annual rainfall 1,800 mm). The area has two growing seasons: a long rainy season (LR) from March to August and a short rainy season (SR) from September to January. The soil is classified as a very fine, isohyperthermic Kandiodalfic Eutrudox (USDA). The top 0.15-m layer, sampled at initiation of the experiment has pH (soil/water 1:2.5)=5.4, total organic C=14 g kg⁻¹, total N=1.7 g kg⁻¹, exchangeable Ca=3.9 cmol kg⁻¹, exchangeable Mg=1.5 cmol kg⁻¹, exchangeable K=0.13 cmol kg⁻¹, exchangeable acidity=0.6 cmol kg⁻¹, bicarbonate extractable inorganic P=1.7 mg kg⁻¹, bulk density=1.1 g cm⁻³, 420 g kg⁻¹ clay and 330 g kg⁻¹ sand. P is often the primary limiting nutrient of crop production in this area (Sanchez et al. 1997).

The experiment was established during the SR of 1995. The field was tilled with hand hoes to a depth of 0.15 m at

the beginning of each rainy season. Treatments consisted of leaf biomass from six tree or shrub species [*Calliandra calothyrsus* Meissner, *Senna spectabilis* (DC) H.S. Irwin and Barneby, *Croton megalocarpus* Hutch, *Lantana camara* L., *Sesbania sesban* (L.) Merr, and *Tithonia diversifolia* (Hemsley) A. Gray] (Table 1) and inorganic fertilizers. The specific tree or shrub species were selected for their availability in the area. Each rainy season, fresh leaves of each of the species were picked in the vicinity of the experiment and applied separately to the soil at a rate of 5 Mg ha⁻¹ on a dry matter basis. The inorganic fertilizer treatments consisted of a uniform application of 120 kg N ha⁻¹ as urea and the application of triple superphosphate in separate plots at different rates: 0 kg P (120N 0P), 10 kg P (120N 10P), 25 kg P (120N 25P), 50 kg P (120N 50P), or 150 kg P ha⁻¹ (120N 150P). Urea was split applied with one-third of the rate applied at planting and the remaining 5 weeks later. K was added each season in all treatments as a blanket application of 100 kg K ha⁻¹. All residues and fertilizers were broadcast and incorporated by hand hoes into the top 0.15 m, at planting, for five consecutive maize growing seasons, two per year in the two rainy seasons, in plots of 7×7.5 m. Each treatment was replicated 4 times in a randomized complete block design. Total N added in residues at each season ranged between 136 and 183 kg N ha⁻¹, and total P between 8 and 14 kg P ha⁻¹. With an average C content of 45% in all residues, a total amount of 11.3 Mg C ha⁻¹ was applied by the end of the experiment, in each of the organic residue treatments. Maize (*Zea mays* L.) hybrid 511 was planted each short season and hybrid 612 or 614 during the LRs, in rows at a spacing of 0.75 m between rows and 0.25 m between plants in the row. Two seeds were sown per hole and later thinned to one per hole. Weeding took place whenever appropriate. The above-ground maize biomass was removed from the field at each harvest.

The amounts of rainfall received during the cropping seasons was 496, 1,287, 975, 1,086, and 1,272 mm for the SR 1995, LR 1996, SR 1996, LR 1997 and SR 1997, respectively.

Plant and soil analyses

Plant analyses

The quality parameters of the plant residues used are given in Table 1 and were determined following the methods recommended by Palm and Rowland (1997). Fresh leaves

Table 1 Selected characteristics of organic materials applied in a field experiment in western Kenya during five consecutive maize growing seasons^a. PP Soluble polyphenols

Treatment	Lignin (g kg ⁻¹)	PP (g kg ⁻¹)	N (g kg ⁻¹)	Soluble C (g kg ⁻¹)	Total P (g kg ⁻¹)	Lignin/N	PP/N	(Lignin+PP)/N
<i>Calliandra</i>	115±40	77±13	37±5	36±3	1.6±0.2	3.3±1.7	2.1±0.5	5.4±2.1
<i>Senna</i>	142±34	23±11	36±5	39±1	2.3±0.3	2.9±2.1	0.7±0.4	4.4±1.5
<i>Croton</i>	125±24	48±6	27±1	30±4	2.0±0.3	4.6±0.8	1.8±0.2	6.4±0.9
<i>Lantana</i>	138±23	52±11	31±6	35 ^b	2.6±0.4	4.7±1.4	1.8±0.7	6.5±2.1
<i>Sesbania</i>	57±7	38±8	37±3	46±5	1.9±0.3	1.6±0.2	1.0±0.2	2.6±0.1
<i>Tithonia</i>	127±76	39±9	35±3	36 ^b	2.8±0.3	3.8±2.4	1.1±0.2	4.9±2.3

^aValues are means from five consecutive seasons, ±SD

^bThe value was determined in one season only

of each species were air-dried and ground to pass a 0.5-mm sieve. N and P contents were determined following a sulphuric acid Kjeldahl digestion (Anderson and Ingram 1993). Lignin was determined according to the acid detergent fibre method of Van Soest (1963), and total soluble polyphenols (PP) according to Anderson and Ingram (1993). The water-soluble fraction of the materials was determined based on the cold water method of TAPPI (1988). Total C in this filtrate was determined as a measure of soluble C following the potassium dichromate method of Nelson and Sommers (1982). All residues had a C/N ratio ranging between 12 and 17, which is lower than the general threshold of 25 used as an index for predicting N immobilization/mineralization. The incorporation of these residues would be expected to result in net N mineralization (Myers et al. 1994; Palm and Rowland 1997).

Soil analyses

Soil analyses were done on soil samples taken from the top 0.15-m layer at the harvest of maize grown during the fifth rainy season (SR97). Soil samples were air-dried, and sieved to 2 mm prior to analyses. Soil pH was measured in a 1:2.5 soil/water suspension.

Soil inorganic N was calculated as the sum of NH_4^+ and NO_3^- extracted with 2 M KCl after 1 h of shaking (Anderson and Ingram 1993). Potentially mineralizable N was determined following the anaerobic mineralization procedure described by Drinkwater et al. (1996). Soil was anaerobically incubated for 7 days and mineralizable N calculated as the difference between NH_4^+ extracted with 2 M KCl after incubation and NH_4^+ extracted before incubation.

MBC and MBN contents were determined by the chloroform fumigation–extraction method of Tate et al. (1988). Dry soils were re-wetted to 60% water filled pore space and pre-incubated for 7 days prior to chloroform fumigation. Soils were then exposed to alcohol-free chloroform for 24 h and C and N extracted thereafter with 0.5 M K_2SO_4 on fumigated and unfumigated samples. Chloroform released C and N was calculated as the difference between C and N extracted in fumigated and unfumigated samples and was converted to MBC and MBN using respective conversion factors of 0.35 and 0.4 (Sparling and West 1989).

Soil C mineralization was estimated by measuring the CO_2 evolution (Anderson 1982) during the pre-incubation period of samples used for MBC and MBN determination. CO_2 evolved from the soil after 1 day of pre-incubation (1 day) or throughout the pre-incubation (7 days) was trapped using 0.5 M NaOH and determined by back-titration with 0.15 M HCl after precipitation with excess BaCl_2 .

SOC was determined by wet oxidation with acidified dichromate coupled with heating at 150°C for 30 min, and total N by Kjeldahl digestion (Anderson and Ingram 1993).

Soil fractionation

To determine soil organic matter associated with soil particle size, soil samples were fractionated into different particle-size separates by wet sieving after soil dispersion with a sodic resin (Feller et al. 1991; Gavinelli et al. 1995). Air-dried soil (50 g) was passed through a 2-mm sieve and shaken end-to-end at 125 reciprocations min^{-1} for 16 h with 200 ml of deionized water and 30 g of cation exchange resin (Amberlite IR-120) saturated with Na. Soil size fractions were separated by wet sieving successively through 250- and 53- μm sieves using tap water. The fraction <53 μm was further separated into 0- to 5- μm and 5- to 53- μm fractions by sonication and sedimentation. All fractions >53 μm were separated into organic and mineral fractions by flotation in water. In this study, only the organic fractions >53 μm (POM) and the fractions <53 μm are presented: [250- to 2,000- μm organic fraction (O250), 53- to 250- μm organic fraction (O53), 5- to 53- μm fraction (5–53), and 0- to 5- μm fractions (0–5)]. Mineral fractions >53 μm are not presented because they were not affected by any treatment. Total C and N in the fractions were determined using a CN analyser–mass spectrometer [Roboprep (Europa Scientific) VG Micromass 622, UK]. Given that the fractionation is time consuming, only two inorganic treatments (i.e. 120N 10P, 120N 150P) were considered in addition to the control and organic residue treatments.

Statistical analysis

ANOVA was conducted using the general linear model procedure (GLM) of SAS (SAS Institute 1995). Differences among treatment means were determined by the least significant difference (LSD). Mention of significant differences refers to $\alpha=0.05$ unless otherwise mentioned. Simple Pearson correlation analysis was carried out between plant characteristics and studied soil parameters.

Results and discussion

Soil pH, organic C, total N and inorganic N

Soil pH values ranged from 4.9 to 5.3 (Table 2). These values were lower than the pH value of 5.4 measured at the beginning of the experiment (see [Site description and experimental design](#)). Conyers et al. (1995) reported seasonal fluctuations in pH due to changes in soil temperature and water potential with corresponding effects on microbial activity and proton budgets. In our study, rainfall fluctuations, particularly heavy rains with periods of flooding during the SR97, could have affected some processes controlling soil pH such as N mineralization and nitrification. For example, the $\text{NH}_4^+/\text{NO}_3^-$ ratio decreased from an average of 2.0 at the harvest of maize grown in SR95 to an average of 0.8 at the harvest in SR97 (data not shown), a decrease that would contribute to the observed decrease in soil pH.

Table 2 Soil pH, soil organic C (SOC), inorganic N and total N as affected by organic and inorganic amendments in a field trial cropped with maize in western Kenya. 120N 0P 120 kg N, 0 kg P; 120N 10P 120 kg N, 10 kg P; 120N 25P 120 kg N, 25 kg P; 120N 50P 120 kg N, 50 kg P; 120N 150P 120 kg N, 150 kg P ha⁻¹; LSD least significant difference ($P < 0.05$)

Treatment	Inorganic N (mg kg ⁻¹)	SOC (g kg ⁻¹)	Total N (g kg ⁻¹)	pH (1:2.5 water)
Control	12.5	11.5	1.69	5.1
120N 0P	16.3	14.2	1.70	5.0
120N 10P	14.7	14.2	1.69	5.0
120N 25P	16.9	14.6	1.71	5.0
120N 50P	14.8	12.7	1.52	4.9
120N 150P	16.3	13.8	2.00	5.1
<i>Calliandra</i>	20.7	15.2	1.89	5.1
<i>Senna</i>	22.4	14.4	1.93	5.1
<i>Croton</i>	17.7	14.3	1.90	5.2
<i>Lantana</i>	19.0	15.7	1.91	5.3
<i>Sesbania</i>	17.8	14.8	1.74	5.0
<i>Tithonia</i>	21.0	14.2	1.86	5.2
LSD	2.8	1.8	0.33	0.1

Croton, *Lantana* and *Tithonia* additions resulted in higher pH than the fertilizer treatments receiving 0–50 kg P ha⁻¹, with the *Lantana* treatment providing the highest soil pH, significantly higher than the values obtained using inorganic fertilizers and *Senna*, *Calliandra*, and *Sesbania* residues. Among the residue treatments, *Sesbania* resulted in the lowest pH. Increases in soil pH with some organic residue amendments have been reported in laboratory studies (Phan 2000; Paul et al. 2001). However, organic residues differ in their ability to change soil pH. Tang and Yu (1999) reported that the concentration of organic anions in residues and the degree of decomposition of plant residues were important parameters influencing the direction (increase or decrease) and magnitude of changes in the pH of amended soils. No organic anions were measured in our study. However, pH values correlated positively with the lignin/N ratio of the residues (Table 3), a residue property that affects decomposition and N release from residues (Palm and Rowland 1997).

The concentration of SOC was higher in soils treated with organic residues and fertilizers compared to the control, with the exception of 120N 50P treatments (Table 2). Few significant differences were observed in SOC among treated soils. Higher SOC was observed in *Lantana* treatments compared to the fertilizer treatments receiving 50 and 150 kg P ha⁻¹, and in *Calliandra* treatments compared to 120N 50P treatments. There were no significant differences in SOC among residue treatments.

Differing results have been obtained on the sensitivity of SOC to changes in soil management. Powlson et al. (1987) reported a 5% increase in SOC after 18 years of annual incorporation of barley straw (*Hordeum vulgare* L.), representing 4–7% of the 37.8 Mg C ha⁻¹ added. Goyal et al. (1999) observed a 54% increase in SOC after 11 years of addition of a combination of wheat straw (*Triticum*

aestivum L.), totalling 33.5 Mg C ha⁻¹, and fertilizers to a sandy loam soil in India. Changes in SOC in residue-treated soil, in our study, were very small and in general lower than the random error of 10% (Landon 1991). Of the 11.3 Mg C ha⁻¹ added in 2.5 years, 2.9–24.9% was recovered in SOC. The lack of large changes in SOC in this study may be attributed to the small amount of residues added during the shorter time frame of the experiment. Although the magnitude of changes in SOC differed among residues, we did not find any significant correlation between SOC and residue quality parameters (Table 3). Continuous cropping without fertilization but with removal of crop residues in the control treatment resulted in a 17% reduction in the initial 14 g SOC kg⁻¹. The observed increase in SOC in the fertilizer treatments compared to the control, despite removal of above-ground biomass, could be attributed to the contribution from root biomass induced by better maize growth than in the control (Nziguheba et al. 2000).

After five fertilizer N or organic residue additions, total soil N did not change significantly in amended soils compared to the control (Table 2).

All organic residues increased inorganic N compared to the control (Table 2). Inorganic N in *Calliandra*, *Senna* and *Tithonia* was higher than in the fertilizer treatments. Among organic residues, *Sesbania* and *Croton* treatments resulted in lower inorganic N than *Senna* and *Tithonia*. Inorganic N was increased by fertilizer treatments except 120N 10P and 120N 25P. The increase in inorganic N in all organic residues compared to the control suggests an improvement of N availability by organic residue additions. In addition, larger inorganic N concentrations in *Calliandra*-, *Senna*- and *Tithonia*-treated soils compared to fertilizer-treated soils would indicate a better improvement of soil N status by organic residues than by fertilizers. Difference in cumulative maize yield during the five seasons was not significantly different between fertilizers and organic residues (Nziguheba et al. 2000) and thus would not explain

Table 3 Correlation coefficients (r) between soil biochemical properties measured at the harvest of crop 5 and some characteristics of organic residues applied to the soil ($n=6$)^a. C min Mineralized C; MBC microbial biomass C; O250-C C concentration in 250- to 2,000- μ m organic fraction; O250-N N concentration in O250; O53 53- to 250- μ m organic fraction; NS not significant

	pH	C min (1 day)	C min (7 days)	MBC	O250-C	O250-N	O53
N	NS	0.84*	-0.85*	NS	NS	NS	NS
Lignin	NS	NS	NS	0.89**	NS	NS	NS
Lignin/N	0.89**	NS	0.82*	0.82*	NS	NS	NS
Lignin+ PP/N	NS	NS	0.84*	0.82*	NS	NS	NS
PP	NS	NS	NS	NS	0.86*	0.88**	0.83*
PP/N	NS	NS	NS	NS	NS	NS	0.84*

* $P < 0.05$, ** $P < 0.01$

^aFor each plant residue, the average value from the five seasons was used for the correlation and only the soil parameters showing a significant relationship are presented

the differences in inorganic N status. Leaching was not measured in this study. However, slower N release is expected in organic residues than in fertilizers, that could lead to a gradual increase in soil inorganic N, whereas immediate N release from fertilizers can lead to important N losses. Although soil inorganic N differed among the residues, soil inorganic N did not correlate with any of the studied residue quality parameters.

MBC and MBN

MBC has been referred to as an early indicator of changes in soil organic matter due to changes in soil management practices (Powlson et al. 1987; Goyal et al. 1999). *Croton*, *Lantana* and *Senna* treatments resulted in significantly higher MBC compared to the control. MBC in *Tithonia* and *Calliandra* treatments did not statistically differ from that in the control treatment. Among residues, the *Sesbania* treatment resulted in much lower MBC compared to that in other organic residues. In addition, MBC in *Tithonia* and *Calliandra* was lower than that in *Lantana* treatments. Fertilizer treatments did not affect MBC compared to the control except for lower values measured in the 120N 0P treatment.

Only few significant differences were observed in MBN, with only the *Croton* treatment increasing MBN above that of the control.

Differences in MBC and MBN among cropping systems (crop rotations, organic residue applications) have been attributed to differences in substrate composition (Goyal et al. 1999; Kaur et al. 2000). In our study, MBC correlated positively and significantly with the lignin content of residues and its ratio with N [lignin/N, (lignin+PP)/N] (Table 3). However, the extremely low lignin and low MBC values in *Sesbania* compared to other residues might have favoured the correlation. A positive correlation implies that the higher the lignin content in a residue, the higher the MBC. However, since lignin is known to retard decomposition, a negative correlation would be expected. Most of the residues used in this study decomposed relatively quickly with a half-life ranging from 1.1 to 8.2 weeks (Kwabiah 1997). Soil samples were collected at maize harvest (about 19 weeks after incorporation of residues) which would explain the influence of organic residues with relatively high lignin contents on soil microbial biomass. On the other hand, the presence of lignin would favour the development of fungi. However, whether a positive correlation between MBC and lignin occurs would depend on the contribution of fungi to the measured MBC. In this study, however, we did not look at the microbial composition and we, therefore, cannot draw any conclusion on the determining process. Higher MBC and MBN indicate greater potential of a soil to supply nutrients through decomposition and mineralization which are regarded as important processes in low-input systems (Kaur et al. 2000).

N and C mineralization

Mineralizable N was larger in organic treatments than in the control and fertilizer treatments (Table 4). Among the fertilizer treatments, only the addition of 150 kg P ha⁻¹ increased mineralizable N over that in the control treatment. Among the organic residue treatments, *Lantana* resulted in higher mineralizable N than *Sesbania* and *Calliandra*.

C mineralization was measured on day 1 and day 7 of pre-incubation and the ranking of organic residues for the amount of C mineralized changed depending on the time of CO₂ determination. The soil was re-wetted prior to pre-incubation and the resulting flush of microbes would have affected the CO₂ released in the first day. It becomes, therefore, difficult to distinguish between the treatment and the rewetting effects. Nevertheless, it appears from the results that the presence of a C substrate was already discernible (Table 4). After 7 days of pre-incubation, the highest C mineralized values were obtained in *Lantana* and *Croton* treatments, and were significantly higher than the values obtained in the control, 120N 10P and 120N 50P treatments (Table 4). *Senna*, *Lantana* and *Croton* treatments resulted in larger amounts of C mineralized than those measured in the 120N 10P and 120N 50P treatments. The only significant difference among organic residues was the higher mineralized C in the *Lantana* treatment than in *Sesbania* treatment in 7 days. Addition of fertilizers did not change significantly the C mineralized in the control treatment.

C and N mineralization have been referred to as the most sensitive indicators of soil organic matter dynamics and productivity of soils (Biederbeck et al. 1998). The important changes in these parameters between the different treatments, in our study, confirm their sensitivity to crop management. Although there were differences in the amount of mineralizable N in the different residue treatments, miner-

Table 4 Amounts of C and N mineralized, MBC and microbial biomass N (MBN) in a soil amended with organic residues and fertilizers in the highlands of western Kenya^a. For other abbreviations see Tables 2 and 3

Treatment	MBC	MBN	Mineralizable N (mg kg ⁻¹)	C mineralized	
				1 day	7 days
Control	157	34.0	17.1	8.6	31.4
120N 0P	97	48.8	14.4	8.7	36.3
120N 10P	154	23.2	17.0	7.7	25.9
120N 25P	153	16.3	16.5	11.7	37.9
120N 50P	160	33.5	15.6	7.0	31.3
120N 150P	168	29.2	21.1	15.7	39.0
<i>Calliandra</i>	196	35.2	26.0	15.6	36.8
<i>Senna</i>	240	41.0	29.4	16.7	38.4
<i>Croton</i>	233	51.2	28.3	13.4	44.9
<i>Lantana</i>	280	36.7	30.5	13.2	47.0
<i>Sesbania</i>	132	37.5	25.2	15.3	33.0
<i>Tithonia</i>	197	43.9	26.7	15.6	34.6
LSD	56	17.0	3.8	6.2	12.5

^aAnalyses were done after the harvest of crop 5

alizable N did not correlate significantly with any residue quality parameter (data not shown). The amount of C mineralized was affected by both the length of incubation and the quality of organic residues (Tables 3, 4). The similar behaviour of *Croton*- and *Lantana*-treated soils can be attributed to the similar ratio of (lignin+PP)/N in these residues. C mineralized after 7 days could be related to the (lignin+PP)/N and lignin/N ratios while none of these residue quality parameters could describe the amount of C mineralized after 1 day (Table 3). As for MBC, the positive correlation between C mineralized in 7 days and lignin can be attributed to the sampling time (19 weeks after the last application of residues) when the materials with lower lignin contents had already decomposed (Table 3).

Soil organic matter

Size separates

All organic residues increased the amount of particulate organic matter (POM) fractions (POM=O53 and O250) compared to the control (Table 5). The *Calliandra*, *Croton*, *Lantana* and *Senna* treatments resulted in more substantial POM fractions than the fertilizer treatments. Larger increases in POM fractions with organic residues than with fertilizers are consistent with earlier observations (Wander et al. 1994) and confirm the link between POM and organic amendments (Vanlauwe et al. 1998). Among the organic residues, the *Calliandra* treatment resulted in larger O250 fractions than any other residue treatment and in larger O53 fractions than any other residue, except for *Lantana*. Differences in POM between the different residue treatments may originate from the decomposition characteristics of the residues. By definition, POM consisted of less decomposed organic matter and is considered as the most labile fraction of soil organic matter (Woomer et al. 1994; Vanlauwe et al. 1998). The sequence of residues in terms of their decomposition rate is: *Tithonia*>*Sesbania*>*Senna*>*Lantana*>*Croton*>*Calliandra* (Kwabiah 1997). *Calliandra* residues were the slowest to decompose among the organic residues used and resulted in the largest amounts of POM, whereas *Sesbania* and *Tithonia* decomposed fastest. Hassink (1995) found a much bigger light fraction from

chaff amendments than from lucerne (*Medicago sativa* L.) and assumed that organic matter from the faster decomposing residue (lucerne) was transferred rapidly to heavier fractions than that of slowly decomposing residues. In this study, we did not separate organic matter from the mineral fraction in the soil fractions <53 μm . Nevertheless, transfer of organic matter in the heavier fraction would be accompanied by an increase in C in these fractions. No significant difference in C content was observed between the different residue treatments in the soil fractions <53 μm . Whereas the short duration of the experiment (2.5 years) can partly explain the lack of many significant differences in POM between different residues compared to large differences observed after 25 years in Hassink's study (1995), the difference in decomposition characteristics between the residues used in this study was also not as large as that between chaff and lucerne. Among the fertilizer treatments, only the 120N 150P treatment increased the O250 fraction compared to the control. The increase in the O250 fraction with the addition of 150 kg P ha⁻¹ can be attributed to larger organic inputs, mainly root biomass, related to higher yields as reported by Nziguheba et al. (2002). This root biomass decomposed slowly compared to the biomass from the added organic residues, which resulted in increased amounts in the larger POM fractions. Addition of organic residues and fertilizers did not affect the size of fractions <53 μm , most probably because of the large size of the mineral fraction which can be derived from the soil texture.

C, N and C/N ratio in SOM fractions

Despite high concentrations of C and N in POM fractions, with ranges of 29–37% C and 1.0–2.6% N (data not shown), the contribution of these fractions to total soil C and N was very small (Table 6). In the control soil, C and N in the POM fractions (POM-C, POM-N) represented respective values of 3.6 and 1.9% of the total soil C and N (Table 6). These values were increased by the addition of organic residues to 6.1–11.0% for C and to 3.7–8.2% for N. Although the largest proportions of soil C and N were found in the fractions <53 μm , differences between the treatments occurred mainly in the POM fractions, confirming the sensitivity of POM to soil management.

Table 5 Amount of particle size fractions at the harvest of maize after five seasonal additions of organic residues and fertilizers to a soil in a maize-based cropping system in western Kenya. For abbreviations see Tables 2 and 3

Fraction	Control (g kg ⁻¹)	120N 10P (g kg ⁻¹)	120N 150P (g kg ⁻¹)	<i>Calliandra</i> (g kg ⁻¹)	<i>Senna</i> (g kg ⁻¹)	<i>Croton</i> (g kg ⁻¹)	<i>Lantana</i> (g kg ⁻¹)	<i>Sesbania</i> (g kg ⁻¹)	<i>Tithonia</i> (g kg ⁻¹)	LSD
O250	0.8	1.2	1.5	3.1	2.2	2.2	2.1	1.6	1.7	0.6
O53	1.5	1.8	1.3	3.1	2.2	2.8	2.3	2.0	2.1	0.4
5–53 ^a	146	155	158	147	155	148	146	153	152	NS ^c
0–5 ^b	467	461	458	459	454	488	483	475	464	NS

^aLSD=12 in the 5- to 53- μm fraction-

^bLSD=37 in the 0- to 5- μm fraction

^cNo significant differences were detected in these fractions

Table 6 Distribution of C and N in soil fractions of a soil amended with organic residues and fertilizers in a maize-based cropping system in western Kenya. For abbreviations see Table 2

	Fraction	Control (mg kg ⁻¹ soil)	120N 10P (mg kg ⁻¹ soil)	120N 150P (mg kg ⁻¹ soil)	<i>Calliandra</i> (mg kg ⁻¹ soil)	<i>Senna</i> (mg kg ⁻¹ soil)	<i>Croton</i> (mg kg ⁻¹ soil)	<i>Lantana</i> (mg kg ⁻¹ soil)	<i>Sesbania</i> (mg kg ⁻¹ soil)	<i>Tithonia</i> (mg kg ⁻¹ soil)	LSD
C	O250	234	379	491	1,166	677	660	728	493	511	228
	O53	408	510	468	1,072	747	1,026	832	648	646	166
	5–53	4,240	4,409	4,507	4,767	4,931	4,640	4,727	4,606	4,638	568
	0–5	12,423	12,105	12,358	12,776	12,319	13,572	13,411	12,283	12,475	1,179
N	O250	8	14	22	70	29	29	33	24	22	17
	O53	22	29	24	82	50	63	60	40	42	14
	5–53	275	323	321	340	391	344	361	335	354	52
	0–5	1,255	1,239	1,252	1,304	1,291	1,386	1,367	1,302	1,267	134
C/N ratio	O250	28	27	22	17	23	22	22	21	24	8
	O53	19	17	19	13	15	16	14	16	15	2
	5–53	15	14	14	14	13	13	13	14	13	1
	0–5	10	10	10	10	9	10	10	9	10	0

Addition of organic residues significantly increased POM-C and POM-N, except for the *Sesbania* and *Tithonia* treatments for O250-N. The only significant increase from fertilizers was observed in the POM-C for the 120N 150P treatment. Significant differences in POM-C and POM-N between organic residues occurred mainly in the O53 fraction where the amounts of C and N obtained with *Lantana*, *Calliandra* and *Croton* amendments were larger than the values from *Tithonia* and *Sesbania* amendments. In the O250 fraction, C and N contents in *Calliandra* treatments were significantly larger than those in other residue treatments. The amounts of C and N in fractions <53 μm were not significantly affected by the treatments.

The C/N ratios of the POM fractions in the unfertilized plots were 28 and 19, respectively, in the O250 and O53 fractions (Table 6). Addition of organic residues decreased the ratio in the O53 but not in the O250 except for *Calliandra*. No significant reduction in the C/N ratio was observed in fertilizer treatments. The differences in the C/N ratio between treatments narrowed in the 5- to 53- μm fractions and became relatively constant in the 0- to 5- μm fractions for all treatments.

Wider C/N ratios in POM, particularly in the O53 fractions in the fertilizer treatments than in organic residue treatments, suggest differences in the quality of soil organic matter resulting from the two types of amendments. This confirms our earlier assumption that POM in fertilizer treatments was mainly maize-root derived and was of low quality (N content of about 6.4 g kg⁻¹) compared to that in organic residue treatments. Because of this, the release of POM-N would be slower in fertilizer-treated soil than in organic residue treatments (Bending and Turner 1999). The narrow C/N ratio in the *Calliandra* treatment would suggest a more rapid N mineralization in this treatment than in other organic residue treatments. However, this was not confirmed by the N mineralization data. The large PP concentrations in the *Calliandra* residue can bind N, thus constraining its mineralization (Handayanto et al. 1997).

The wider C/N ratio in POM compared to fractions <53 μm is in line with the findings of Hassink (1995) and Vanlauwe et al. (1998) who concluded that POM consisted mainly of less decomposed plant residues while organic matter in smaller fractions is more stable.

Relationships between studied soil parameters

Correlations between the C and N concentrations in POM and other measured soil properties were found to be more significant in the O53 fraction as compared to the O250 fraction (Table 7). C and N concentrations of the O53 frac-

Table 7 Correlation coefficients (*r*) between different biochemical properties of a soil amended with plant residues and inorganic fertilizers in western Kenya (*n*=13)^a. N min N mineralized; for other abbreviations see Tables 2 and 3

	SOC	Total N	C min (1 day)	C min (7 days)	N min	MBC
O250-C	0.65	0.52	0.35	0.31	0.24	0.20
O250-N	0.62	0.46	0.53	0.31	0.38	0.15
O250-C/N	-0.67*	-0.53	-0.75*	-0.44	-0.59	-0.20
O53-C	0.63	0.84*	0.70*	0.88**	0.75*	0.64
O53-N	0.82**	0.64	0.63	0.75*	0.89**	0.75*
O53-C/N	-0.75*	-0.29	-0.43	-0.39	-0.77*	-0.59
SOC		0.54	0.63*	0.60*	0.53	0.39
Total N			0.83***	0.65*	0.75**	0.62*
C min (1 day)				0.59*	0.75**	0.48
C min (7 days)					0.58*	0.64*
N min						0.83***

P*<0.05, *P*<0.01, ****P*<0.001

^aOnly parameters showing some significant correlations are presented

tion correlated significantly with the amounts of C and N mineralized in the whole soil. The C/N ratio in all POM fractions correlated negatively with SOC. In addition, the C/N ratio in O250 correlated negatively with C mineralized after 1 day of incubation whereas the C/N ratio in O53 was negatively correlated with N mineralized.

C and N mineralization have been referred to as the best indicators of biologically active organic matter (Biederbeck et al. 1998). The significant correlations between C and N mineralized and the C and N content of the O53 fractions, in our study, suggest that the microbiological activity was mainly localized in this fraction. The lower microbiological activity in O250 compared to O53 can be attributed to the long time elapsed between the application of residues and the analyses. Easily decomposed materials would have been processed by then and only recalcitrant materials subject to slow change would remain. MBC correlated with total soil N, C and N mineralization at 7 days, N in O53 in POM but not with soil organic C. Often poor correlations between MBC and other soil properties have been reported (Hassink et al. 1993; Hassink 1995; Wang et al. 2003). Wang et al. (2003) attributed the poor relationship with soil organic C to the non-availability of most of the organic C to microbes due to chemical recalcitrance or physical protection. Such physical protection would be more pronounced in clayey soil, as used in our study, than in coarse-textured soils. Correlations between MBC and C mineralization have generated different conclusions. Poor correlations between the two parameters have been attributed to the non-reliability of MBC as an indicator of microbial activity. However, some studies have shown an influence of the time of CO₂ determination on the resultant correlations. Wang et al. (2003) reported good correlations when CO₂ was determined during 7 days of pre-incubation of re-wetted air-dried soil, whereas poor correlations were observed when CO₂ was determined during the incubation of soil which had already been subject to pre-incubation. Hassink et al. (1993) and Hassink (1995) attributed the lack of correlation between POM and MBC to the presence of the largest proportion of microbial biomass in the clay fractions.

Conclusions

The often advocated advantage of organic inputs over fertilizers when applied to soil is the improvement of many soil physical and biochemical properties controlling nutrient cycling and hence crop production. In this study, MBC, C and N mineralization, and POM were the properties most increased by organic residue amendments. Changes in these properties by the addition of fertilizers depended on their rate of application. While it was true that most of the organic residues used in this study improved more than one soil parameter, in only a few cases, mainly in N mineralization and POM, was the effect larger than that of mineral fertilizers. Perhaps the short duration of the experiment (2.5 years) was the reason for the lack of a clear effect of the organic versus fertilizer treatments. The quality of the organic residue affects the magnitude of changes in a given soil

parameter. The decomposition characteristics of organic residues expressed in terms of lignin/N or (lignin+PP)/N ratios influenced the MBC, C mineralization, and C and N in POM fractions. Among the POM fractions, the 53- to 250- μ m fraction was found to be the most biologically active, correlating with most of the studied soil properties.

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