Soil Quality & Fertility

Organic and Mineral Input Management to Enhance Crop Productivity in Central Kenya

P. Chivenge,* B. Vanlauwe, R. Gentile, H. Wangechi, D. Mugendi, C. van Kessel, and J. Six

ABSTRACT

Organic resources (ORs) are important nutrient inputs in tropical agriculture. Combined with mineral fertilizers, they form the backbone of integrated soil fertility management. This study was conducted to determine the medium- to long-term influence of OR quality and quantity on maize productivity and to evaluate the occurrence of additive benefits in terms of extra grain yield produced by the combined application of ORs and N fertilizers. Farmyard manure, high quality Mexican sunflower [*Tithonia diversifolia* (Hemsl.) A. Gray], intermediate quality calliandra (*Calliandra calothyrsus* Meisn.) and maize (*Zea mays* L.), and low quality silky-oak (*Grevillea robusta* A. Cunn. ex R. Br.) sawdust were incorporated into the soil at equivalent rates of 1.2 and 4 Mg C ha^{-1} yr^{-1} in Embu (clayey) and Machanga (sandy soil), together with a control to which no OR was added. All plots were split, with one half receiving 120 kg N ha^{-1} season^{-1} as $CaNH_4NO_3$. The ORs, except sawdust and maize, improved maize grain yields compared with the control at both sites. Greatest mean maize yields (i.e., 4.9 and 2.3 Mg ha^{-1} season^{-1}, in Embu and Machanga, respectively) over 10 seasons were observed with the high rate of Mexican sunflower, but was not significantly different from calliandra and manure. Generally, maize yields were greater with higher than lower OR rates, except for maize and sawdust. Although N fertilizer additions to the ORs improved grain yields in Embu, the increase was marginal; resulting in negative interactive effects of applying ORs with N fertilizers, especially with high-N ORs. Thus high-N ORs should not be applied in combination with N fertilizers, especially at such high fertilizer N rates.

Depletion of soil fertility is recognized as the major cause of low food crop production in sub-Saharan Africa (Sanchez, 2002). Hence, nutrient management is a key entry point for sustainable agricultural productivity and poverty alleviation in the region. Smallholder farmers commonly use ORs such as farmyard manure, crop residues, and composts for short-term supply of nutrients and long-term build-up of soil organic matter (SOM). Because of population pressure the quantities available of these resources have dwindled. Furthermore, the quality of the ORs available to farmers is usually low (Table 1) and therefore the effectiveness to supply nutrients to the crop is limited (Mugwira and Murwira, 1997; Vanlauwe et al., 2005a). Moreover, low-quality resources (Table 1) tend to have a period of nutrient immobilization and the subsequent release of nutrients does not match crop demand (Palm et al., 1997; Vanlauwe et al., 2005b). Consequently, the supply of nutrients by the ORs is often insufficient to meet crop demands (Palm et al., 1997).

The use of mineral fertilizers in sub-Saharan Africa is limited by the lack of purchasing power and scarcity of the product in the smallholder sectors while their continuous use can also lead to a decline in SOM by enhancing its decomposition (Nardi et al., 2004), making ORs a critical nutrient source. Consequently, there is a need to explore the efficient utilization of the available nutrient resources that lead to improved crop yields. The use of ORs in combination with mineral fertilizers offers potential for improving soil fertility and crop yields, and forms an integral part of integrated soil fertility management (Vanlauwe et al., 2002b). The release of nutrients and the efficiency of nutrient availability to the plant can be manipulated by controlling the quality and quantity of ORs, which can facilitate the retention of added mineral fertilizers and the timing of their availability (Myers et al., 1994). Research has shown that combinations of ORs and mineral fertilizers result in greater crop yields compared with sole ORs or sole mineral fertilizers (Mtambanengwe et al., 2006; Murwira and Kirchmann, 1993; Nyamangara et al., 2003) with grain yield increases of up to 400% over the control in cases where the control yields are low (Vanlauwe et al., 2001b). This increase in grain yield has been attributed to improved N synchrony with combined inputs through direct interactions of the ORs and N fertilizers (Vanlauwe et al., 2002b). The ORs temporarily immobilize nutrients from mineral fertilizers and may release them in synchrony with crop nutrient uptake. Nutrient losses through leaching have been shown to decrease (Nyamangara, 2001; Vanlauwe et al., 2002a) while N mineralization of ORs is improved with the combined application of ORs and N

P. Chivenge, R. Gentile, C. van Kessel, and J. Six, Dep. of Plant Sciences, Univ. of California, One Shields Ave., Davis, CA 95616; B. Vanlauwe and H. Wangechi, TSBF-CIAT, ICRAF Campus, United Nations Ave., P.O. Box 30677, Nairobi, Kenya; D. Mugendi, Kenyatta Univ., School of Environmental Studies and Human Sciences, P.O. Box 43844, Nairobi, Kenya. Received 14 Nov. 2008. *Corresponding author (ppnhamo@ucdavis.edu).

Published in Agron. J. 101:1266–1275 (2009).
doi:10.2134/agronj2008.0188x

Abbreviations: DSS, decision support system; LR, long rainy season (March–June); OR, organic resource; SOM, soil organic matter; SR, short rainy season (October–December).

fertilizers (Sakala et al., 2000). Indirect interactions may also enhance crop growth by improving the soil environment for root growth through increased SOM, increasing the N demand which can be met by N fertilizers (Vanlauwe et al., 2002b).

Soil texture determines the inherent fertility status and the ability to protect added nutrients from losses such as leaching, and thus influences crop yield and its responses to the application of nutrients. Heavy-textured soils often have greater nutrient stocks, whereas most sandy soils are inherently infertile (Bationo et al., 2007; Grant, 1981) and thus the addition of nutrients may result in greater yield increases in coarse than fine-textured soils (Fofana et al., 2005). For example, Mtambanengwe et al. (2006) observed 1.3 and 3.2 Mg ha^{-1} increases in yield following the application of N fertilizers and sunn-hemp (*Crotalaria juncea* L.) compared with the control in a sandy soil, respectively. In a finer-textured soil, however, they observed yield increases above the control of 0.6 and 1.1 Mg ha^{-1} following the application of N fertilizers and sunn-hemp, respectively. In addition, there were no yield differences when N fertilizers were added with sunn-hemp compared with sunn-hemp alone in the finer textured soil. Similarly, Vanlauwe et al. (2001b) observed positive interactive effects in a less-fertile soil compared with negative interactive effects in a more-fertile soil.

A conceptual decision support system (DSS) for organic N management was developed based on the N, lignin, and polyphenol contents of the ORs (Palm et al., 1997; 2001). The DSS separates ORs into four quality classes (I–IV). Class I ORs have >2.5% N, <15% lignin, and <4% polyphenol contents. These ORs which result in a fast release of nutrients are considered to be high quality and are recommended to be directly applied to the soil (Table 1). Class II ORs have >2.5% N, and either >4% polyphenol or >15% ligin contents, while Class III ORs have <2.5% N, <4% polyphenol, and <15% lignin contents (Table 1). These two quality classes are considered to be intermediate quality with slower nutrient release due to biochemical recalcitrance for Class II ORs and low N content for Class III ORs. The DSS recommends applying intermediate quality ORs with N fertilizers. Organic resources with <2.5% N and >15% lignin are in Class IV and are considered to be low quality (Table 1). Class IV ORs induce extended periods of immobilization and the DSS proposes to surface apply as a mulch for erosion and water control. In support of the DSS, Vanlauwe et al. (2001b, 2002b) showed positive interactive effects of combining N fertilizers with maize leaves (Class III) with improved crop yields and reduced N losses, whereas the use of high quality residues of velvet-bean [*Mucuna pruriens* (L.) DC.] (Class I) in combination with N fertilizer did not significantly improve crop yields when compared with sole velvet-bean residues, but enhanced N leaching.

These observations were made in the short term, but the repeated application of different qualities of ORs needs to be understood both in the short and long term. For example, it is known that the application of low-quality ORs such as maize can depress yields by up to 30% (Palm et al., 1997), but these low-quality ORs may enhance the buildup of SOM in the long term, which can influence long-term nutrient supply to crops. Understanding the influence of OR quality on soil quality in the short and long term and how N fertilizers alter this influence is important for the efficient utilization of available ORs.

Table 1. Organic resource quality classes.

Organic resource	Class I†	Class II	Class III	Class IV
Nitrogen, %	>2.5	>2.5	<2.5	<2.5
Polyphenol, %	<4	>4	<4	>4
Lignin, %	<15	>15	<15	>15
Quality	high	intermediate	intermediate	low

† Organic resource classification according to Palm et al. (2001).

In addition, the optimal rates of application and combinations and the linkage with soil type and climate need to be evaluated. Therefore, the objectives of this field study were (i) to evaluate the influence of OR quality and quantity on maize yield over a period of 5 yr (10 seasons), and (ii) to evaluate the interactions between N fertilizers and ORs of differing quality on maize yield.

MATERIALS AND METHODS

Study Sites

The study was conducted at two sites, located 40 km apart, in the central highlands of Kenya, Embu (0°30′ S, 37°27′ E; 1380 m above sea level) and Machanga (0°47′ S, 37°40′ E; 1022 m above sea level), over a period of 10 cropping seasons between 2002 and 2006. Mean annual rainfall is 1200 mm in Embu and 900 mm in Machanga, received in two distinct raining seasons: the long rainy season (LR) is between March and June, and the short rainy season (SR) is between October and December for both sites (Fig. 1). The long-term average rainfall for the LR is 650 mm and 430 mm in Embu and Machanga, respectively, whereas in the SR it is 450 mm in Embu and 350 mm in Machanga (FAO, 2008). The LR-2004 season was a drought season for both sites, and in Embu SR-2005 was also a drought season (Fig. 1). The mean annual temperature is 20°C for Embu and 26°C for Machanga. Embu is on a red clay soil derived from basic volcanic rocks and is classified as Humic Nitisols, while Machanga is on a sandy soil derived from granitic gneisses and is classified as Ferric Alisols (FAO, 1998). Kaolinite is the dominant clay mineral in the Embu soil, while in Machanga the soil minerals consist of a mixture of micas and kaolin minerals (Table 2). By comparison, the soil at Embu is more fertile with greater organic C and total N contents and higher amounts of exchangeable bases than at Machanga (Table 2).

Experimental Design and Management

The long-term experiments at the two sites were established in March 2002 to determine the influence of repeated annual application of ORs of different quality, at two rates, with versus without N fertilizers on soil organic C dynamics (Gentile et al., 2008). Relative high rates of ORs (1.2 and 4 Mg C ha^{-1}) and N fertilizers (120 kg N ha^{-1}) were thus used to increase the probability of observing treatment differences over a relatively short time period. Additionally, lower rates of N fertilizer (60 kg N ha^{-1}) were applied in initial year, 2002, but the crops showed N deficiencies and thus greater rates were chosen to grow the crops under optimal nutrient conditions. Five ORs, four of which belong to the quality classes of the DSS proposed by Palm et al. (1997), were incorporated in the soil (Table 3). A control where no ORs were applied was also included. The ORs applied were; Class I, Mexican sunflower; Class II, calliandra; Class III, maize

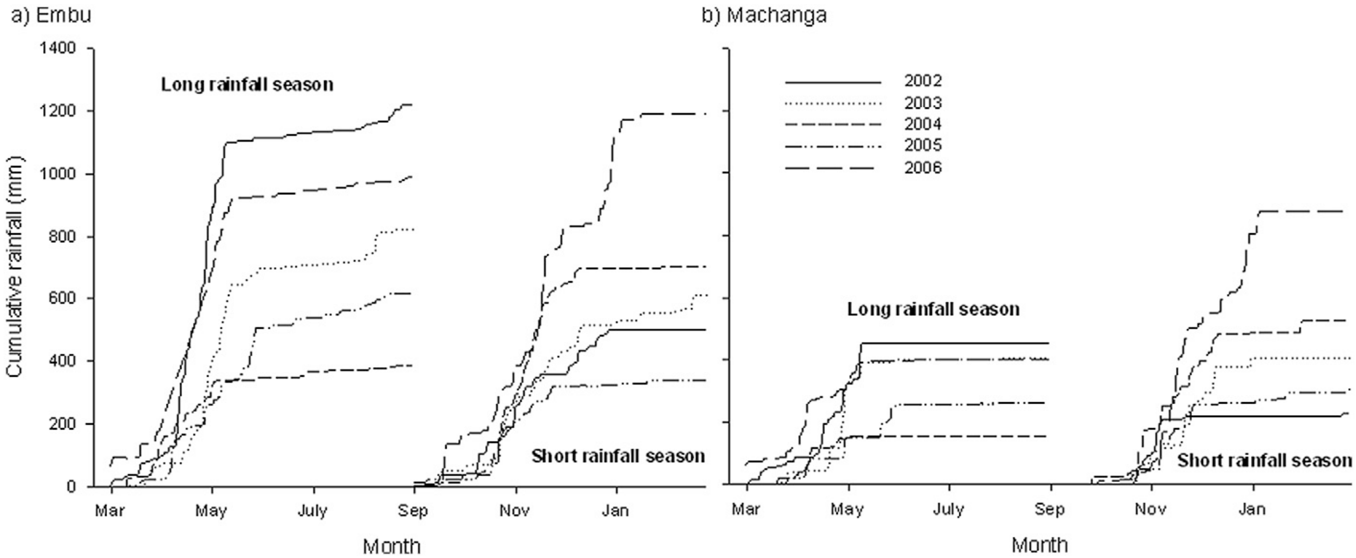

Fig. 1. Cumulative seasonal rainfall at (a) Embu and (b) Machanga between 2002 and 2006.

stover; Class IV, silky-oak sawdust; and farmyard manure, which cannot be classified under a specific OR quality class because its quality is affected by its composition and management over time (Delve et al., 2001; Nzuma and Murwira, 2000).

Table 2. Characteristics of soils (0–15 cm) at Embu and Machanga, Kenya.

Soil Property	Embu	Machanga
Organic C, g kg^{-1}	29.35	3.14
Total N, g kg^{-1}	2.66	0.23
P, g kg^{-1}	0.29	0.26
Exchangeable Ca, cmol$_+$ kg^{-1}	5.45	0.82
Exchangeable Mg, cmol$_+$ kg^{-1}	2.98	0.34
Exchangeable K, cmol$_+$ kg^{-1}	0.82	0.35
Exchangeable Na, cmol$_+$ kg^{-1}	0.07	0.09
CEC, cmol$_+$ kg^{-1}	16.03	2.35
Base saturation, %	58.52	68.38
pH, 1:1 water	5.43	5.27
Texture		
Sand, %	17	66
Silt, %	18	11
Clay, %	65	22
Clay mineralogy	kaolinite (dominant), gibbsite, goethite, hematite	mica, kaolinite, halloysite, gibbsite

At the onset of each year, ORs were analyzed for dry matter, total C, and N (Anderson and Ingram, 1993); and the dry matter and C content were used to determine the amount of ORs to apply. Organic resources were also analyzed for total P, K, Ca, Mg and lignin, and total soluble polyphenols using the Folin-Denis method (Anderson and Ingram, 1993) (Table 3). At every planting for the LR season, ORs were broadcast and hand incorporated to a depth of 15 cm using a hand hoe. The experiment was laid out as a split-plot design with OR (both OR quality and OR rate) as the main plot and N fertilizer application as the subplot, replicated three times. The main plots, with sizes of 12 by 6 m in Machanga and 12 by 5 m in Embu, were split in half where 120 kg N ha^{-1} N fertilizer ($CaNH_4NO_3$) was added every season (i.e., twice a year) to one half of the main plot, while no N fertilizer was added to the other half. One third of the N fertilizer was applied 3 wk after planting, and the remainder of the N fertilizer was applied 8 wk after planting by broadcasting and incorporating into the soil. During the LR-2004 season, a second N application was not performed at both sites, and in Embu the second application during the SR-2005 season did not take place due to extended dry spells. All plots received a blanket basal application of P at 60 kg P ha^{-1} as

Table 3. Average (2002–2006) nutrient concentrations of the organic resources (OR) applied in Embu and Machanga.

	Mexican sunflower	calliandra	Maize		Sawdust	Farmyard manure
			Embu	Machanga		
Total C %	38.1 ± 1.6b†	44.3 ± 0.9a	40.4 ± 1.5ab	40.0 ± 1.5ab	44.3 ± 0.8a	28.4 ± 6.8c
Lignin %	10.7 ± 2.9b	12.4 ± 4.5ab	4.4 ± 2.0c	4.5 ± 1.7c	18.4 ± 0.9a	14.0 ± 3.0ab
Polyphenol %	1.5 ± 1.0b	10.7 ± 2.8a	1.2 ± 0.2b	1.1 ± 0.2b	0.5 ± 0.2b	0.9 ± 0.9b
Total N %	3.1 ± 0.8ab	3.4 ± 0.2a	0.7 ± 0.2c	0.7 ± 0.2c	0.2 ± 0.0c	2.4 ± 0.6b
Total P %	0.2 ± 0.1b	0.1 ± 0.0bc	0.03 ± 0.0d	0.1 ± 0.0cd	0.01 ± 0.0d	0.4 ± 0.1a
Total K %	3.6 ± 0.7a	1.0 ± 0.5b	1.0 ± 0.7b	1.5 ± 0.9b	0.2 ± 0.1b	3.6 ± 0.1a
C/N ratio	13.1 ± 3.4c	13.3 ± 0.8c	59.0 ± 15.7b	60.2 ± 15.8b	208.4 ± 14.0a	12.1 ± 0.9c
Soluble C mg g^{-1} C	1.7 ± 0.5ab	2.2 ± 0.2a	1.5 ± 0.5bc	1.3 ± 0.3bc	0.8 ± 0.0c	0.2 ± 0.1d
OR class‡	I	II	III	III	IV	III
Mean OR N, kg N ha^{-1} yr^{-1}§	104	101	27	24	6	101
Mean OR N, kg N ha^{-1} yr^{-1}¶	347	337	88	81	20	337

† n = 5; mean ± standard deviation. Values followed by different letters (a–d) in the same row are significantly different ($p < 0.05$).

‡ Organic resource classification according to Palm et al. (2001).

§ Represents ORs applied at the rate of 1.2 Mg C ha^{-1}.

¶ Represents ORs applied at 4 Mg C ha^{-1}.

triplesuperphosphate and K at 60 kg K ha^{-1} as muriate of potash at planting by broadcasting followed by incorporation into the soil.

At Embu, hybrid 513 maize (100 d to maturity) was planted as the test crop both in the LR and SR seasons with a between row spacing of 0.75 m and a within row spacing of 0.5 m. At Machanga, Katumani hybrid maize variety (75 d to maturity) was planted with a between-row spacing of 0.9 m and a within-row spacing of 0.6 m. Three seeds were planted per hill and thinned to 2 plants after emergence. The target population was about 53,000 and 37,000 plants ha^{-1} for Embu and Machanga, respectively. The plots were kept weed-free by hand weeding twice during each season. Maize stalk borer [*Busseola fusca* (Fuller)] was controlled every season by a one-time application of a pinch of Dipterex (1% Thiodan) or Buldock (0.05–2.5% Beta cyfluthrin) in the maize funnel at 4 wk after crop emergence, depending on availability of the insecticides.

At maturity, grain yield and total biomass measurements were taken from a net plot of 20.9 m^2 in Machanga and 16.4 m^2 in Embu. The net plot is the area that was sampled, avoiding treatment mixing at the edges of the plot. Subsamples of the grain harvested were dried in the oven at 60°C until constant weight. Grain yield was calculated at 12.5% moisture content.

Calculations

The interactive effects of combining ORs with N fertilizer in terms of maize biomass and total N uptake was calculated following Vanlauwe et al. (2001a):

$$\text{Interactive effects} = Y_{\text{comb}} - Y_{\text{con}} - (Y_{\text{OR}} - Y_{\text{con}}) - (Y_{\text{N fert}} - Y_{\text{con}})$$

where Y_{con}, $Y_{\text{N fert}}$, Y_{OR}, and Y_{comb} are mean grain yield in control treatment, sole N fertilizer, sole OR, and the combined OR and N fertilizer treatment, respectively. Interactive effects represent the extra yield obtained following the combined application of ORs and N fertilizers compared with the sum of the two when added separately (Vanlauwe et al., 2001a).

Statistical Analysis

Maize grain yield data were analyzed using a split-split-plot design using the repeated measure analysis in SAS 9.1 (SAS Institute, 2003) statistical package. A mixed model was used, with season as main plot factor, OR (5 OR types, 2 OR rate and control) as the subplot factor, and N fertilizer addition as the sub-subplot factor. Season, OR (5 OR types, 2 OR rates, and control) and N fertilizer and their interactions were considered as fixed effects, while block and block × OR (5 OR types, 2 OR rates, and control) were considered as random effects. Significant differences between means were separated with the PDIFF option of the LSMEANS statement at $p < 0.05$, unless stated differently.

RESULTS

Impact of Organic Resources and Fertilizer on Maize Yields: Ten-Season Average

The addition of ORs alone significantly increased mean maize grain yields over 10 growing seasons in Embu compared with the control with no N inputs, except when maize stover was applied at 1.2 Mg C ha^{-1} and sawdust applied at 4 Mg C ha^{-1} (Fig. 2a and b). In contrast, on a sandy soil in Machanga, there were no significant differences in grain yield

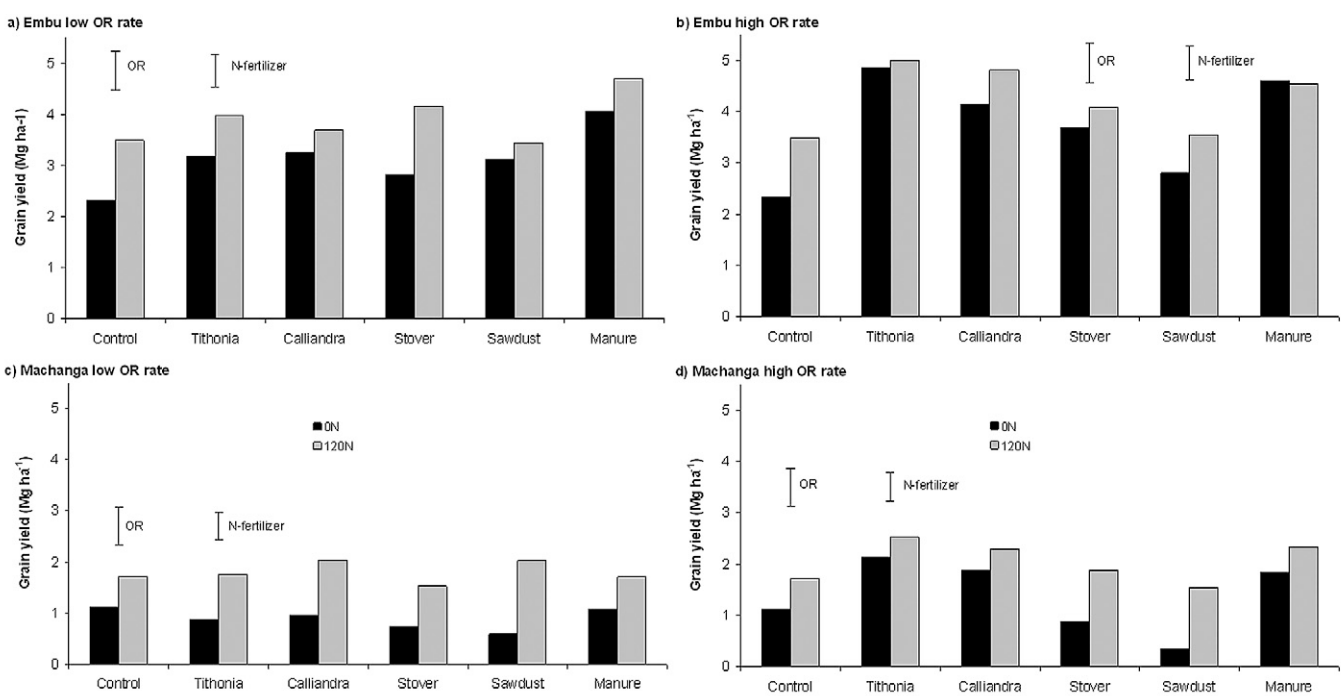

Fig. 2. Mean maize grain yields obtained with different quality organic resources (OR) applied annually with (120 N) or without (0 N) 120 kg N ha^{-1} season^{-1} as $CaNH_4NO_3$ fertilizer over 10 seasons [i.e., Long rainfall season in 2002 (LR 2002) to the short rainfall season in 2006 (SR 2006)]. (a) Embu, OR applied at 1.2 Mg C ha^{-1} yr^{-1} (low rate), (b) Embu OR applied at 4 Mg C ha^{-1} yr^{-1} (high rate), (c) Machanga OR applied at 1.2 Mg C ha^{-1} yr^{-1} (low rate), and (d) Machanga OR applied at 4 Mg C ha^{-1} yr^{-1} (high rate). Error bars are standard error of the difference between two means; the error bar labeled OR is for comparisons among different OR within the same N fertilizer, whereas the error bar labeled N fertilizer is for comparisons between with and without N fertilizer within the same OR.

Table 4. Statistical significance of five organic resources (ORs) applied at two equivalent C rates of 1.2 and 4 t C ha^{-1} with or without 120 kg mineral N fertilizer ha^{-1} (N fertilizer) on maize grain yield. The studies were carried out at two sites, Embu (clayey) and Machanga (sandy soil) in central Kenya over 10 seasons between 2002 and 2006.

Source of variation	Statistical significance	
	Embu	Machanga
OR†	***	***
N fertilizer (2 levels)	***	***
OR × N fertilizer	***	***
Season (10 seasons)	***	***
OR × Season	***	***
N fertilizer × Season	***	***
OR × N fertilizer × Season	ns‡	ns

*** $p < 0.001$.

† OR represents the five organic resource types, 2 OR rates, and control.

‡ ns = not significant at $p < 0.05$.

between ORs applied alone at the low rate and the control, but there was a general decline in maize yield compared with the control (Fig. 2c). At this site, the high rate of Mexican sunflower and calliandra resulted in greater maize yields than the control, while sawdust reduced maize yields by 47 and 69% compared with the control for the low and high OR rates, respectively (Fig. 2d). In Embu, sole applications of Mexican sunflower and manure at the high OR rate resulted in yields that were 40 and 32% greater than sole N fertilizer application, while sawdust resulted in yields that were 20% less than sole N fertilizer application (Fig. 2b). In Machanga, on the other hand, sole N fertilizer resulted in mean maize yields that were not significantly different from the high rate of sole applied Mexican sunflower, calliandra, and manure (Fig. 2d). The high rate of Mexican sunflower alone had the greatest mean maize yields of 4.9 Mg ha^{-1} season^{-1} and 2.3 Mg ha^{-1} season^{-1}, in Embu and Machanga, respectively (Fig. 2).

Impact of Organic Resources and Fertilizer on Maize Yields: Seasonal Differences

Season, addition of ORs, and addition of N fertilizers influenced crop yields (Table 4). There were interactions among the factors, but there was no three-way interaction {[OR (5OR + 2 rates + control) × fertilizer × season]; Table 4}. The general response of maize yield to OR additions over the 10 growing seasons, within an application rate in Embu, followed the order: Mexican sunflower = farmyard manure = calliandra ≥ maize stover ≥ sawdust ≥ control (Fig. 2; see also Appendix Table 1). In contrast, in Machanga, the addition of maize stover and sawdust resulted in yields less than or equal to the control in most seasons with the general order for the high rate of OR application of Mexican sunflower = farmyard manure = calliandra > control ≥ maize stover ≥ sawdust (Fig. 2; see also Appendix Table 2).

In general, adding N fertilizers increased grain yield compared with the control (Fig. 3). However, the greater differences between treatments with and those without N fertilizers were observed in wetter seasons with the wettest season (SR-2006) having the greatest differences both in Embu and Machanga (Fig. 3). In drier seasons, on the other hand, lower yields were generally observed and there were no yield responses to the addition of N fertilizers in LR-2004 both in Embu and Machanga (Fig. 3). However, the lowest yields in Embu were observed during SR-2005, in which only 300 mm were received; there were negative yield responses to the addition of N fertilizers: treatments with N fertilizers had 35% lower yields than treatments without N fertilizers (Fig. 3). Although greater yields across seasons were observed in Embu than in Machanga, greater yield increases in maize yields due the addition of N fertilizers were observed in Machanga (0.81 Mg ha^{-1}) than in Embu (0.61 Mg ha^{-1}; Fig. 3).

Interactive Effects between Organic Resources and Nitrogen Fertilizers

Organic resource (both OR quality and OR rate) and season influenced the interactive effects of combining ORs and N fertilizers at both sites ($p < 0.001$; for data shown on Fig. 4a), but there were no interactions between the two factors. Seasonally, there were negative interactive effects when averaged across treatments in Embu, except during the SR-2006 season, which had a positive interactive effect of about 0.9 Mg ha^{-1} (Fig. 4a). In Machanga, on the other hand, there were positive interactive effects in most of the seasons, with the greatest interactive effect of 1.3 Mg ha^{-1} in the SR-2003 season (Fig. 4a). When comparing mean treatment interactive effects across seasons, all treatments resulted in negative interactive effects in Embu, except for the low rate of maize stover and Mexican sunflower, and the high rate of sawdust (Fig. 4b). In contrast, there was a general trend of positive interactive effects for the OR applied at the low rate and the high rate of the low quality in Machanga (Fig. 4b). In addition, in Machanga, there was a significant positive interactive effect for both the low and high rates of the sawdust (Fig. 4b).

DISCUSSION

The high amounts of N added as ORs (Table 3) and N fertilizers in this study were likely beyond the linear phase of the maize response curve, thereby masking the possible positive interactive effects of the combined application of the two resources. The positive interactive effects observed in Machanga versus the negative in Embu were likely due to differences in soil texture, but also climate (Fig. 4). Soil moisture availability may be improved by the addition of ORs (Bauer and Black, 1992; Vanlauwe et al., 2002b) and more so in Machanga than in Embu because of the combination of a sandy soil and a low rainfall at Machanga. Thus, the indirect improvement of the soil condition could have improved the responses to the addition of N fertilizers in Machanga, resulting in the positive interactive effects (Fig. 4). However, across the seasons, the influence of total rainfall amount was not clear. For example, 360, 497, and 237 mm of rainfall were received in LR 2003, SR 2004, and LR 2005, respectively, but the interactive effects in these seasons were similar (~0.5 Mg ha^{-1}; Fig. 4). Thus, the interactive effects may be due to other factors such as seasonal rainfall distribution and/or soil fertility status.

The negative interactive effects for OR classes I and II at Machanga reflect the importance of OR quality. For these two OR classes, there was only a small increase in grain yields with the addition of N fertilizers to them (Fig. 2; see also Appendix Table 2). As a result, the combined application of ORs and N fertilizers was not large enough to surpass the yield increase brought about by the sum of the separate addition of the two

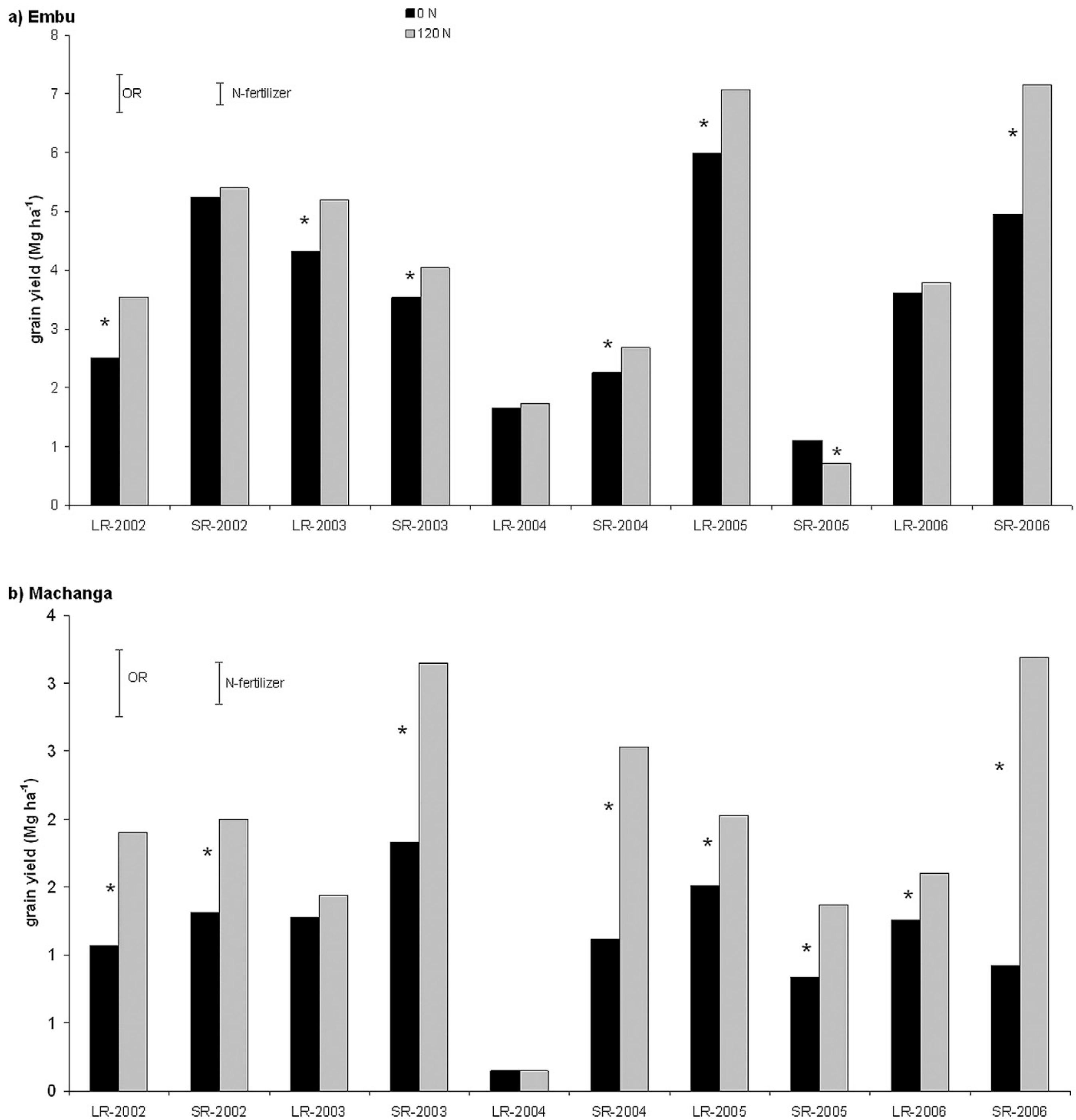

Fig. 3. Mean seasonal grain yields averaged across different organic resources (ORs) applied annually with (120 N) or without (0N) 120 kg N ha^{-1} season^{-1} as $CaNH_4NO_3$ fertilizer in (a) Embu and (b) Machanga. Organic resources: Mexican sunflower, calliandra, Maize stover, sawdust, and farmyard manure, were applied at equivalent rates of either 1.2 Mg C ha^{-1} yr^{-1} (low rate) or 4 Mg C ha^{-1} yr^{-1}(high rate). Error bars represent standard error of the difference between two means; the error bar labeled OR is for comparisons across seasons within the same N fertilizer, whereas the error bar labeled N fertilizer is for comparisons with the same season between with and without N fertilizer.

resources. These results are in accordance with other studies. For example, Mucheru-Muna et al. (2007), Mafongoya and Dzowela (1999), and Vanlauwe et al. (2001a) observed negative interactive effects when Class I ORs, Mexican sunflower, *Sesbania* spp., and velvet-bean, respectively, were applied in combination with N fertilizers. In contrast, in the same studies, there were positive interactive effects of the addition of Class III ORs with N fertilizers. Similarly, Mtambanengwe et al. (2006) observed only a 13% yield increase due to the addition of N fertilizer with sunn-hemp compared with sole sunn-hemp (Class I), which resulted in negative interactive effects. In contrast, the yield increase was 325% when maize (Class III) was applied with N fertilizer compared with sole maize and was associated with positive interactive effects. However, while the overall interactive effects may generally be negative, the addition of Class I ORs with N fertilizer has been shown to increase crop yields and, in some instances, resulting in positive interactive effects (Kimetu et al., 2004; Nhamo, 2002).

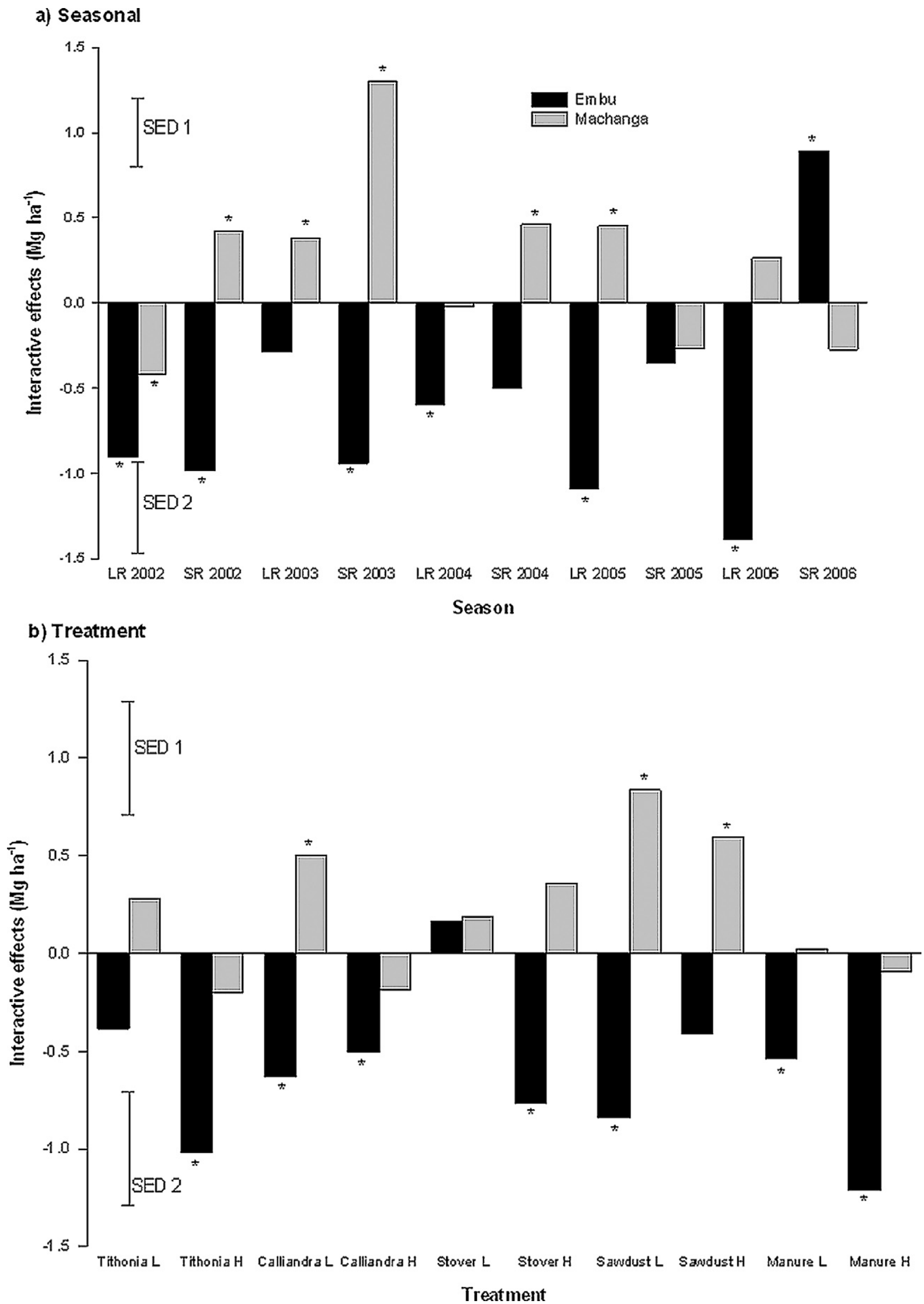

Fig. 4. Mean interactive effects of combining organic and mineral nutrient sources on grain yields in Embu and Machanga (a) seasonal means averaged across treatments, (b) treatment means over 10 seasons, low = low organic resource (OR) rate (1.2 Mg C ha^{-1} yr^{-1}), high = high OR rate (4 Mg C ha^{-1} yr^{-1}), *Denotes significant interactive effect ($p < 0.05$). Standard error of the difference for Machanga and Embu are shown as SED 1 and SED 2, respectively.

Kimetu et al. (2004) observed a general yield increase in crop yields following the combined application of Mexican sunflower with N fertilizers compared with sole Mexican sunflower, but positive interactive effects were only observed in the first year of OR application. These positive interactive effects observed following the application of Mexican sunflower with N fertilizers have been attributed to the high amount of P and K which may have indirectly influenced yield responses to the added N (Sanchez and Jama, 2002). In the current study, both P and K were added to all treatments, and thus responses to these were probably eliminated.

High N ORs (i.e., Mexican sunflower, calliandra, and manure) generally resulted in greater maize yields compared with the control, N fertilizer, maize stover, and sawdust (Fig. 2; see also Appendix Tables 1 and 2). Foremost, because more N was added by these high-quality ORs (Table 3), but probably also because a high proportion of the N was readily available for plant uptake. Additionally, the high C/N ratios observed with maize stover and sawdust may have induced N limiting conditions, resulting in lower maize yields. However, there were no differences in maize yields following the addition of Mexican sunflower versus calliandra despite the differences in polyphenol contents. Contrary to our observations, high polyphenol content has been observed to strongly reduce crop yields (Cadisch et al., 1998; Mtambanengwe and Mapfumo, 2006; Mtambanengwe et al., 2006). Organic resources with >4% polyphenol content, such as calliandra, have slower N mineralization due to N binding by the polyphenols (Mafongoya et al., 1998; Oglesby and Fownes, 1992; Palm and Sanchez, 1991), resulting in lower crop yields than those with less polyphenol content (Baijukya et al., 2006; Palm et al., 2001). Greater crop yields have been observed following the combined application of Class II ORs with N fertilizers compared with sole ORs (Mucheru-Muna et al., 2007). However, Vanlauwe et al. (2002a) noted that high rainfall, similar to that observed at our sites, may leach out soluble polyphenols, removing their effects on crop yields. In addition, only leaves were added with calliandra, whereas with Mexican sunflower the whole plant was used, including stems which had a lower quality (Table 3). Nevertheless, Teklay and Malmer (2004) observed higher N and P mineralization with pampena [*Albizia gummifera* (J.F. Gmel.) C.A. Sm.], which had initial polyphenol contents of 4.6% and greater concentrations of condensed tannins compared with Cordia Africana Lam., whose polyphenol content was 2.9%. Albizia had, however, higher initial N content. More recently, Parton et al. (2007) also observed in a study conducted over 10 yr across 21 sites that N release from ORs is driven primarily by initial N content of the ORs. Vanlauwe et al. (2005c) also observed that 76% of N mineralization was explained by initial OR N content. Based on these and our results, total N added seems to be the most important indicator of N availability and resulting plant growth. As indicated in Table 3, similar amounts of N were added by Mexican sunflower, calliandra, and manure, and subsequently, similar maize yields were observed with these ORs (Fig. 2).

The OR rate of application influenced maize yield for the high quality ORs because of the differences in amount of nutrients added at the two rates, especially N (Table 3). Thus, similar to the differences observed among OR quality, greater amounts of N added with the high OR rate seem to influence maize yields. Similarly, Mtambanengwe et al. (2006) showed that maize yields were greater when ORs were applied at an equivalent rate of 7.5 Mg C ha^{-1} compared with 2.5 Mg C ha^{-1}. For the low quality ORs (i.e., sawdust), the addition of greater quantities resulted in a decline in maize yield, although this was not significant, probably because greater immobilization was induced due to the wider C/N ratios, resulting in more nutrient limitations. Similarly, Murwira et al. (1998) did not find significant differences between low quality manure (0.5% N) applied at four and eight Mg ha^{-1} on coarse textured soils. Contrary to our results, however, Kimani et al. (2007) observed almost a two-fold increase in maize yield following the doubling of the manure application rate (from five to 10 Mg ha^{-1}) at the sites where water shortages occurred, whereas there were only marginal increases in yield at sites where water was less limited. They attributed the increase at the sites with water shortage to increased water holding capacity by addition of manure. This increase was also expected at Machanga where rainfall was low in most seasons (Fig. 1), but was not observed.

CONCLUSIONS

Organic resource qualities, and the total amounts of nutrients, especially N, were important factors controlling crop yields, but polyphenol content did not seem to greatly influence nutrient supply capacity of ORs under our field conditions. Therefore, in contrast to the proposed four DSS quality classes, we observed only three quality classes based on their N content differences: high-quality, intermediate-quality, and low-quality ORs. High-quality ORs improved crop yields compared with the absolute control and, in fact, resulted sometimes in yields comparable or better than sole N fertilizer. However, the yield response to OR addition was not only dependent on the quality (i.e., initial N content) of the ORs, but the yield responses were greater in the finer-textured, more fertile soil on a wetter site at Embu than in the coarse-textured and less-fertile soil of Machanga which was also drier. There were negative interactive effects derived from adding high-quality ORs in combination with N fertilizers. However, under rain-fed agriculture, ORs with high N content can be used directly to improve crop yields in maize-based systems. In coarse-textured infertile soil, low-quality ORs depressed maize yield; there were, however, positive interactive effects when intermediate and low quality ORs were added in combination with N fertilizers. Thus, there is no benefit derived from applying high-quality ORs in combination with N fertilizer, but the combinations are essential for intermediate- and low-quality ORs. In the smallholder farms, intermediate- and low-quality ORs are found in larger quantities than high-quality ORs, and thus it would be beneficial to combine their application to crops with N fertilizers, especially in coarse-textured, low-fertility soils.

APPENDIX

Appendix Table 1. Maize grain yield following the application of five organic resources (OR) applied at two equivalent C rates; 1.2 (L) and 4 t C ha^{-1} (H) at Embu in central Kenya over 10 cropping seasons between 2002 and 2006.

Treatment	LR-2002†	SR-2002	LR-2003	SR-2003	LR-2004	SR-2004	LR-2005	SR-2005	LR-2006	SR-2006
	Grain yield, Mg ha^{-1}									
Control	2.07d‡	4.16b	3.57c	2.98b	0.82d	1.74b	5.80c	0.46b	1.63d	5.82c
Mexican sunflower L	2.33cd	5.48a	5.26b	3.31b	1.55cd	2.26b	6.28bc	0.77ab	2.88c	5.44cd
Mexican sunflower H	4.28a	5.91a	6.64a	4.02a	3.28a	3.45a	7.73a	1.68a	5.35a	6.94ab
calliandra L	2.44cd	5.34a	4.59bc	3.56ab	1.49cd	2.07b	6.35b	0.60b	2.77c	5.00cd
calliandra H	3.83ab	5.73a	5.39b	4.18a	2.65ab	2.60ab	6.97ab	1.18ab	5.23a	7.03ab
Maize L	2.99bc	5.16ab	4.46bc	3.69ab	1.09cd	2.16b	5.87c	0.78ab	2.96c	5.65cd
Maize H	2.93bc	5.40a	4.66b	4.14a	1.48cd	2.88a	6.44bc	0.85ab	4.01b	6.06bc
Sawdust L	1.97d	5.02ab	3.58c	3.64ab	0.79d	2.42ab	6.55bc	0.66b	2.64c	5.41cd
Sawdust H	2.70cd	4.70ab	3.87c	3.57ab	0.86d	2.03b	5.49c	0.64b	3.01c	4.91d
Manure L	3.28bc	5.68a	5.11b	4.54a	2.03bc	2.84a	6.98ab	1.28ab	4.86ab	7.13a
Manure H	4.43a	5.95a	5.21b	4.02ab	2.51ab	2.69ab	7.38a	1.09ab	5.29a	7.15a

† LR, long rainy season (March–June); SR, short rainy season (October–December).

‡ Grain yield (n = 6) values followed by different letters (a–d) in the same column are significantly different (p < 0.05). The standard error of the difference for treatment and season is 0.53 and 0.52 Mg ha^{-1}, respectively.

Appendix Table 2. Maize grain yield following the application of five organic resources (OR) applied at two equivalent C rates; 1.2 (L) and 4 t C ha^{-1} (H) at Machanga in central Kenya over 10 cropping seasons between 2002 and 2006.

	LR-2002†	SR-2002	LR-2003	SR-2003	LR-2004	SR-2004	LR-2005	SR-2005	LR-2006	SR-2006
	Grain yield, Mg ha^{-1}									
Control	1.07b‡	1.27b	0.97bc	2.55bc	0.10a	1.81bc	2.02abc	1.12a	1.31cd	1.99bc
Mexican sunflower L	1.50ab	1.68ab	1.44b	2.36c	0.13a	1.62bc	1.12cd	0.79a	1.01cd	1.51c
Mexican sunflower H	2.16a	2.59a	2.67a	3.03ab	0.18a	2.87a	2.18ab	1.65a	2.79a	3.13a
calliandra L	1.49ab	1.42b	1.42b	2.44c	0.08a	1.99ab	1.51cd	1.04a	1.43c	2.06b
calliandra H	2.10a	2.46a	2.53a	3.45a	0.25a	2.26ab	2.55ab	1.44a	1.87bc	1.94bc
Maize L	1.26b	1.17b	0.57c	2.23cd	0.18a	1.27c	1.32cd	0.84a	1.01cd	1.46c
Maize H	0.87b	1.33b	0.86c	2.21cd	0.20a	1.71bc	1.74bcd	1.01a	1.11cd	2.58ab
Sawdust L	1.59ab	1.46b	0.79c	2.24cd	0.14a	1.58bc	1.65cd	1.04a	0.72d	1.87bc
Sawdust H	1.30b	1.25b	0.47c	1.51d	0.09a	1.11c	0.99d	0.68a	0.38d	1.62c
Manure L	1.41b	1.57b	1.23bc	1.99cd	0.09a	1.42bc	1.66bcd	0.87a	1.50c	2.15b
Manure H	1.57ab	2.03ab	1.97ab	3.34ab	0.22a	2.43ab	2.70a	1.66a	2.62ab	2.34ab

† LR, long rainy season (March–June); SR, short rainy season (October–December).

‡ Grain yield (n = 6) values followed by different letters (a–d) in the same column are significantly different (p < 0.05). The standard error of the difference for treatment and season is 0.45 and 0.39 Mg ha^{-1}, respectively.

ACKNOWLEDGMENTS

This study was funded by the National Science Foundation, Ecosystem Cluster (DEB: 0344971) and the Flemish Inter-University Council (VLIR), Belgium, through the project on "Integrated Soil Fertility Management Strategies to Enhance Food Security in the Central Highlands of Kenya." We are also grateful to Wilson Ngului and technical staff at TSBF-CIAT Nairobi for laboratory analyses and field technicians Kiragu and Mureithi for monitoring the field experiments.

REFERENCES

Anderson, J.M., and J.S.I. Ingram. 1993. Tropical soil biology and fertility: A Handbook of methods. CABI Publ., Oxfordshire, UK.

Baijukya, F.P., N. de Ridder, and K.E. Giller. 2006. Nitrogen release from decomposing residues of leguminous cover crops and their effect on maize yield on depleted soils of Bukoba District, Tanzania. Plant Soil 279:77–93.

Bationo, A., J. Kihara, B. Vanlauwe, B. Waswa, and J. Kimetu. 2007. Soil organic carbon dynamics, functions and management in West African agro-ecosystems. Agric. Syst. 94:13–25.

Bauer, A., and A.L. Black. 1992. Organic carbon effects on available water capacity of three soil textural groups. Soil Sci. Soc. Am. J. 56:248–254.

Cadisch, G., E. Handayanto, C. Malama, F. Seyni, and K.E. Giller. 1998. N recovery from N prunnings and priming effects are governed by the residue quality. Plant Soil 205:125–134.

Delve, R.J., G. Cadisch, J.C. Tanner, W. Thorpe, P.J. Thorne, and K.E. Giller. 2001. Implications of livestock feeding management on soil fertility in the smallholder farming systems of sub-Saharan Africa. Agric. Ecosyst. Environ. 84:227–243.

FAO. 1998. World reference base for soil resources. FAO, Rome.

FAO. 2008. Aquastat, Climate information tool. Available at http://www.fao.org/nr/water/aquastat/data/query/results.html [accessed 21 Dec 2008; verified 16 July 2009]. FAO, Rome.

Fofana, B., A. Tamelokpo, M.C.S. Wopereis, H. Breman, K. Dzotsi, and R.J. Carsky. 2005. Nitrogen use efficiency by maize as affected by a mucuna short fallow and P application in the coastal savanna of West Africa. Nutr. Cycling Agroecosyst. 71:227–237.

Gentile, R., B. Vanlauwe, P. Chivenge, and J. Six. 2008. Residue quality and N fertilizer do not influence aggregate stabilization of C and N in two Kenyan soils. Nutr. Cycling Agroecosyst. doi:10.1007/s10705-008-9216-9.

Grant, P. 1981. The fertility of sandy soils in peasant agriculture. Zimbabwe Agric. J. 78:168–175.

Kimani, S.K., A.O. Esilaba, M.M. Odera, L. Kimenye, B. Vanlauwe, and A. Bationo. 2007. Effects of organic and mineral sources of nutrients on maize yields in three districts of central Kenya. p. 353–357. *In* A. Bationo, B. Waswa, J. Kihara, and J. Kimetu (ed.) Advances in integrated soil fertility research in sub-Saharan Africa: Challenges and opportunities. Springer, Dordrecht, the Netherlands.

Kimetu, J.M., D.N. Mugendi, C.A. Palm, P.K. Mutuo, C.N. Gachengo, A. Bationo, S. Nandwa, and J.B. Kungu. 2004. Nitrogen fertilizer equivalencies or organics of differing quality and optimum combination with inorganic nitrogen source in Central Kenya. Nutr. Cycling Agroecosyst. 68:127–135.

Mafongoya, P.L., and B.H. Dzowela. 1999. Biomass production of tree fallows and their residual effect on maize in Zimbabwe. Agrofor. Syst. 47:139–151.

Mafongoya, P.L., K.E. Giller, and C.A. Palm. 1998. Decomposition and nitrogen release patterns of tree prunings and litter. Agrofor. Syst. 38:77–97.

Mtambanengwe, F., and P. Mapfumo. 2006. Effects of organic resource quality on soil profile N dynamics and maize yields on sandy soils in Zimbabwe. Plant Soil 281:173–191.

Mtambanengwe, F., P. Mapfumo, and B. Vanlauwe. 2006. Comparative short-term effects of different quality organic resources on maize productivity under two different environments in Zimbabwe. Nutr. Cycling Agroecosyst. 76:271–284.

Mucheru-Muna, M., D. Mugendi, J. Kung'u, J. Mugwe, and A. Bationo. 2007. Effects of organic and mineral fertilizer inputs on maize yield and soil chemical properties in a maize cropping system in Meru South District, Kenya. Agrofor. Syst. 69:189–197.

Mugwira, L.M., and H.K. Murwira. 1997. Use of Cattle manure to improve soil fertility in Zimbabwe: Past and current research and future research needs. Soil Fertility Network Research Results Working Paper No. 2. CIMMYT, Zimbabwe.

Murwira, H.K., and H. Kirchmann. 1993. Nitrogen dynamics and maize growth in a Zimbabwean sandy soil under manure fertilisation. Commun. Soil Sci. Plant Anal. 24:2343–2359.

Murwira, H.K., F. Tagwira, R. Chikowo, and S.R. Waddington. 1998. An evaluation of the agronomic effectiveness of low rates of cattle manure and combinations of inorganic N in Zimbabwe. p. 179–182. *In* S.R. Waddington, H.K. Murwira, J.D.T. Kumwenda, D. Hikwa, and F. Tagwira (ed.) Soil Fertility Research for Maize-based Systems in Malawi and Zimbabwe. Proceedings of the Soil Fertility Network, Results and Planning, 7–11 July 1997, Mutare, Harare.

Myers, R.J.K., C.A. Palm, E. Cuevas, I.U.N. Gunatilleke, and M. Brossard. 1994. The synchronization of nutrient mineralisation and plant nutrient demand. *In* P.L. Woomer and M.J. Swift (ed.) The Biological Management of Tropical Soil Fertility. John Wiley & Sons, Chichester, UK.

Nardi, S., F. Morari, A. Berti, M. Tosoni, and L. Giardini. 2004. Soil organic matter properties after 40 years of different use of organic and mineral fertilisers. Eur. J. Agron. 21:357–367.

Nhamo, N. 2002. An evaluation of the efficacy of organic and inorganic fertilizer combinations in supplying nitrogen to crops. Master of philosophy thesis, Univ. of Zimbabwe., Harare.

Nyamangara, J. 2001. Nitrogen leaching and recovery studies in a sandy soil amended with cattle manure and inorganic fertilizer N under high rainfall conditions. Ph.D. thesis, Univ. of Zimbabwe, Harare.

Nyamangara, J., M.I. Piha, and K.E. Giller. 2003. Effect of combined cattle manure and mineral nitrogen on maize N uptake and grain yield. African Crop Sci. J. 11:289–300.

Nzuma, J., and H.K. Murwira. 2000. Improving the management of manure in Zimbabwe. p. 20. *In* Managing Africa's Soils No. 15. FAO, Rome.

Oglesby, K.A., and J.H. Fownes. 1992. Effects of chemical composition on nitrogen mineralization from green manures of seven tropical leguminous trees. Plant Soil 143:127–132.

Palm, C.A., C.N. Gachengo, R.J. Delve, G. Cadisch, and K.E. Giller. 2001. Organic inputs for soil fertility management in tropical agroecosystems: Application of an organic resource database. Agric. Ecosyst. Environ. 83:27–42.

Palm, C.A., R.J.K. Myers, and S.M. Nandwa. 1997. Combined use of organic and inorganic nutrient sources for soil fertility maintenance and replenishment. p. 193–217. *In* R.J. Buresh, P.A. Sanchez, and F. Calhoun (ed.) Replenishing soil fertility in Africa. SSSA Spec. Publ. 51. SSSA and ASA, Madison, WI.

Palm, C.A., and P.A. Sanchez. 1991. Nitrogen release from the leaves of some tropical legumes as affected by their lignin and polyphenolic contents. Soil Biol. Biochem. 23:83–88.

Parton, W., W.L. Silver, I.C. Burke, L. Grassens, M.E. Harmon, W.S. Currie, J.Y. King, E.C. Adair, L.A. Brandt, S.C. Hart, and B. Fasth. 2007. Global similarities on nitrogen release patterns during long-term decomposition. Science 315:361–364.

Sakala, W., G. Cadisch, and K.E. Giller. 2000. Interactions between residues of maize and pigeonpea and mineral N fertilizers during decomposition and N mineralization. Soil Biol. Biochem. 32:679–688.

Sanchez, P.A. 2002. Soil fertility and hunger in Africa. Science 295:2019–2020.

Sanchez, P., and B. Jama. 2002. Soil fertility replenishment takes off in east and southern Africa. p. 23–46. *In* B. Vanlauwe, J. Diels, N. Sanginga, and R. Merckx (ed.) Integrated plant nutrient management in sub-Saharan Africa: From concept to practice, CABI, Wallingford, UK.

SAS Institute. 2003. SAS OnlineDOC. v. 9.1. SAS Inst., Cary, NC.

Teklay, T., and A. Malmer. 2004. Decomposition of leaves from two indigenous trees of contrasting qualities under shaded-coffee and agricultural land-uses during the dry season at Wondo Genet, Ethiopia. Soil Biol. Biochem. 36:777–786.

Vanlauwe, B., J.J. Ramisch, and N. Sanginga. 2005a. Integrated soil fertility management in africa: From knowledge to implementation. p. 257–272. *In* N. Uphoff et al. (ed.) Biological approaches to sustainable soil systems. CRC Press, Boca Raton, FL.

Vanlauwe, B., J. Wendt, and J. Diels. 2001a. Combined application of organic matter and fertilizer. p. 247–279. *In* G. Tian, F. Ishida, and J.D.H. Keatinge (ed.) Sustaining Soil Fertility in West Africa. SSSA Spec. Publ. 58. SSSA and ASA, Madison, WI.

Vanlauwe, B., K. Aihou, P. Houngnandam, J. Diels, N. Sanginga, and R. Merckx. 2001b. Nitrogen management in 'adequate' input maize-based agriculture in the derived savanna benchmark zone of the Benin Republic. Plant Soil 228:61–71.

Vanlauwe, B., J. Diels, K. Aihou, E.N.O. Iwuafor, O. Lyasse, N. Sanginga, and R. Merckx. 2002b. Direct interactions between N fertilizer and organic matter: Evidence from trials with 15N-labelled fertilizer. p. 173–184. *In* B. Vanlauwe et al. (ed.) Integrated plant nutrient management in Sub-Saharan Africa. CABI, Wallingford, UK.

Vanlauwe, B., J. Diels, N. Sanginga, and R. Merckx. 2005b. Long-term integrated soil fertility management in South-western Nigeria: Crop performance and impact on soil fertility status. Plant Soil 273:337–354.

Vanlauwe, B., C. Geachengo, K. Shepherd, E. Barrios, G. Cadisch, and C.A. Palm. 2005c. Laboratory validation of a resource quality-based conceptual framework for organic matter management. Soil Sci. Soc. Am. J. 69:1135–1145.

Vanlauwe, B., C.A. Palm, H.K. Murwira, and R. Merckx. 2002a. Organic resource management in Sub-Saharan Africa: Validation of a quality-driven decision support system. Agronomie 22:1–8.