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Effect of Organic Inputs and Mineral Fertilizer on Maize Yield in a Ferralsol and a Nitisol Soil in Central Kenya

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Abstract Declining land productivity is a major problem facing smallholder farmers in Kenya today. This decline primarily results from a reduction in soil fertility caused by continuous cultivation without adequate addition of external nutrient inputs. Improved fertility management combining organic and mineral fertilizer inputs can enable efficient use of the inputs applied and increase overall system's productivity. Field trials were established at three sites in distinct agro-ecological zones of central Kenya (one site at Machang'a and two sites at Mucwa with different soil fertility status) aiming to determine the effects of various organic sources (tithonia, lantana, mucuna, calliandra and manure) and combinations with mineral N fertilizer on maize grain yield during four consecutive seasons. In Machang'a site, sole manure recorded the highest maize grain yield across the four seasons. In Mucwa poor site, sole tithonia gave the highest maize grain yield during the four seasons, while in Mucwa good site, sole calliandra gave the highest maize grain yields. Generally, the maize grain yields were lower in the treatments with fertilizer alone compared to the treatments with organics across the three sites in the four seasons due to the poorly distributed rainfall. In Machang'a during the SR 2004 and SR 2005 seasons, the treatments with integration of organic and mineral fertilizer inputs were significantly higher than treatment with the sole organics; however, in Mucwa good and poor sites, generally the treatments with sole organics did better than the ones with integration of mineral N fertilizer and organics with the exception of the mucuna treatment which did significantly better in the integration compared to the sole application.

Keywords Manure · Tithonia · Lantana · Mineral fertilizer · Maize grain yields

Introduction

The central highlands of Kenya cover both areas with high potential for crop production on inherently fertile Nitisols and drier areas with lower potential on lighter, fragile soils, prone to quick degradation. The high potential areas of the central highlands (e.g. Meru South) are among the most densely populated regions in the country with an average of more than 700 person km^{-2}, leading to land fragmentations. This has eventually led to small farm sizes of about 0.5–1 ha per household.

The population pressure in the high potential areas of the central highlands has resulted in spill over of the population to the low potential areas of the highlands (e.g. Mbeere district). Mbeere district is characterized by frequent droughts due to low and erratic rainfall (Jaetzold and Schmidt, 1983). The soils are generally sandy loam, shallow and are low in organic matter (Warren, 1998); they are also characterized by physical soil loss from erosion, aluminium and iron toxicity, crusting and moisture stress (Place et al., 2003). These soils are also deficient in major plant nutrients such as nitrogen and phosphorus, a situation significantly influencing crop productivity (Warren, 1998).

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The soil fertility in the central highlands has declined over time, with an annual net nutrient depletion exceeding 30 kg N (Smaling, 1993) as a result of continuous cropping with inadequate nutrient replenishment (Mwangi et al., 1996). In most smallholder farms, these deficiencies could be replenished through the use of mineral fertilizers and cattle manure. However, few farmers can afford the mineral fertilizers and the ones using them hardly use the recommended rates (60 kg N ha^{-1}) in the area, with most of them applying less than 20 kg N ha^{-1} (Adiel, 2004); on the other hand, the use of manure is also limited by its low quality (Ikombo, 1984; Kihanda, 1998). As a result, soil fertility has continued to decline as has the productivity of the land (Kapkiyai et al., 1998; Adiel, 2004). The situation in Mbeere district is further aggravated as the immigrants in these areas continue growing crops, which they used to grow in the high potential areas, consequently leading to environmental degradation and occasional crop failures.

Locally available organic inputs could be used to curb this problem. For instance, Kimani et al. (2004) reported a 92% increase in maize grain yields after applying manure compared to the control. Jama et al. (1999), Nziguheba and Mutuo (2000) and Mucheru-Muna et al. (2007) reported more than 50% increase in maize grain yields as a result of applying *Tithonia diversifolia* in the soil compared to the control. Mugendi et al. (1999) reported that application of *Calliandra calothyrsus* green biomass increased maize grain yield by 32%, while Kimetu et al. (2004) reported an increase of 48% compared to the control. Incorporating *Mucuna pruriens* biomass into the soil has been found to increase maize grain yields by 46% above farmer practice in the central highlands of Kenya (Gitari et al., 1998), while Gachene et al. (1999) reported maize yield of 88% higher than the control after incorporating mucuna.

Technologies that combine mineral fertilizers with organic nutrient sources can be considered as better options in increasing fertilizer use efficiency and providing a more balanced supply of nutrients (Donovan and Casey, 1998). Combination of organic and mineral fertilizer nutrient sources has been shown to result in synergistic effects and improved synchronization of nutrient release and uptake by crop (Palm et al., 1997) leading to higher yields, especially when the levels of mineral fertilizers used are relatively low as is the case in most smallholder farms of central Kenya (Kapkiyai et al., 1998). Maize yields were increased with increasing rates of farmyard manure application; however, maize grain yields above 3.5 t ha^{-1} were obtained only when both farmyard manure and NP fertilizers were applied (Kihanda, 1996). Calliandra biomass combined with mineral fertilizer gave higher crop yields as compared to sole use of mineral fertilizer or sole calliandra biomass (Mugendi et al., 1999; Mucheru, 2003). The practice may hold the key to effective soil fertility management in the central highlands.

Trials using organic and mineral fertilizer inputs were established in the main maize-growing areas of the central highlands of Kenya in 2004 with the main objective of addressing the decline in soil fertility. The study aimed to determine the effects of different organic sources and combinations with mineral fertilizer inputs on maize grain yield.

Materials and Methods

The Study Area

The study was conducted in Meru South and Mbeere districts in the central highlands of Kenya. In Meru South, the experiment was conducted in Mucwa (00°18′48.2″S; 37°38′38.8″ E), which is located in upper midland 3 with an altitude of approximately 1373 m above sea level. The soils are Rhodic Nitisols (Jaetzold and Schmidt, 1983), which are deep, well weathered with moderate to high inherent fertility. The study was conducted in two farms: one that had relatively good (fertile) soils and another that had poor (unfertile) soils (Table 1).

Meru South is characterized by rapid population growth and low soil fertility (Government of Kenya, 2001). The main staple food crop is maize (*Zea mays* L.), which is commonly intercropped with beans (*Phaseolus vulgaris* L.). Other food crops include Irish potatoes, bananas, sweet potatoes, vegetables and fruits that are mainly grown for subsistence consumption. Livestock production is a major enterprise, especially dairy cattle of improved breeds. Other livestock in the area include sheep, goats and poultry. The main cash crops include coffee, tobacco and tea in that order. The rainfall is bimodal, falling in two seasons: the long rains (LR) lasting from March to June and

Table 1 Soil characterization in Mucwa good and poor sites, Meru South district, Kenya

	Site	
Soil parameters	Mucwa good	Mucwa poor
pH in water	5.0	4.6
Total N (%)	0.25	0.24
Total soil organic carbon (%)	2.1	1.8
Exchangeable P (ppm)	33.8	20.4
Exchangeable K (cmol kg^{-1})	0.36	0.21
Exchangeable Ca (cmol kg^{-1})	1.13	0.9
Exchangeable Mg (cmol kg^{-1})	0.20	0.20
Clay (%)	40	40
Sand (%)	32	32
Silt (%)	28	28

short rains (SR) lasting from October to December. The area receives an annual mean rainfall of 1400 mm. Rainfall for the four seasons in which the experiment was conducted is presented in Fig. 1.

In Mbeere district, the experiment was conducted in Machang'a (00°47′26.8″S; 37°39′45.3″E) with an altitude of approximately 1028 m above sea level and annual mean temperature of about 23°C. The soils are sandy clay loam, blackish grey or reddish brown, classified as the Nitro-rhodic Ferralsols (Jaetzold and Schmidt, 1983). The soils are shallow (about 1 m deep) and lose their organic matter, including nutrient-rich aggregates within 3–4 years of cultivation without adequate external organic material inputs and soil protection from water erosion (Jaetzold and Schmidt, 1983; Warren et al., 1998; Micheni et al., 2004). Table 2 shows the soil characteristics of the soils in Machang'a.

The major cropping enterprises include maize (*Z. mays* L.) and beans (*P. vulgaris* L.). Other food crops include cowpea, millet, sorghum, green grams and fruits (pawpaws and mangoes). Livestock (cows, goats, sheep and poultry) production is a major enterprise, and the farmers mainly keep the local breeds. Bee keeping is also a major enterprise in the area. Farmers plant food crops and keep livestock with a high staple and economic value as they do not grow any "cash crop"; therefore the crops they grow double as food crops and cash crops.

Machang'a lies at the transition between the marginal cotton (LM4) and main cotton (LM3) agro-ecological zones (Jaetzold and Schmidt, 1983). The rainfall is bimodal, falling in two seasons: the long rains (LR) lasting from March to June and short rains (SR) from October to December. The total rainfall is however unreliable, with a mean annual rainfall of 900 mm (Government of Kenya, 1997). Total rainfall per season during the study period ranged between 209 and 731 mm. Rainfall for the four seasons in which the experiment was conducted is presented in Fig. 2.

Experimental Layout

The experiments were established in Meru South and Mbeere districts, and were laid out as randomized complete block design replicated thrice with the plots measuring 6 m × 4.5 m. In Meru South district, the test crop was maize (*Z. mays* L, var. H513) planted at a spacing of 0.75 and 0.5 m inter- and intra-row, respectively, while in Mbeere district, the test crop was maize (*Z. mays* L, var. Katumani) planted at a spacing of 0.90 and 0.6 m inter- and intra-row, respectively. Three (3) seeds were sown per hole and thinned 4 weeks later to two plants. External nutrient replenishment inputs were applied to give an equivalent amount of 60 kg N ha^{-1} (this is the recommended rate of N to meet maize nutrient requirement for an optimum crop production in the area; FURP, 1987) with the exception of the herbaceous legume treatment whereby the amount of N was determined by the biomass harvested and incorporated in the respective treatments. The treatments included (1) manure, (2) manure + 30 kg N ha^{-1}, (3) tithonia, (4) calliandra/lantana, (5) tithonia + 30 kg N ha^{-1}, (7) calliandra/lantana + 30 kg N ha^{-1}, (8) mucuna, (9) mucuna+ 30 kg N ha^{-1}, (10) fertilizer (60 kg N ha^{-1}) and (11) control.

Trial Management

The organic materials were harvested from nearby plots established for that purpose. A sample of each organic input was taken and N content determined, and then the amount of organic to be applied, equivalent to 30 or 60 kg N, was determined (for the treatments with sole organic and integration, an equivalent of 60 and 30 kg N ha^{-1}, respectively, was applied). The weight of mucuna biomass applied during the second, third and fourth seasons is presented in Table 3.

All organic inputs were harvested, weighed, chopped and incorporated into the soil to a depth of

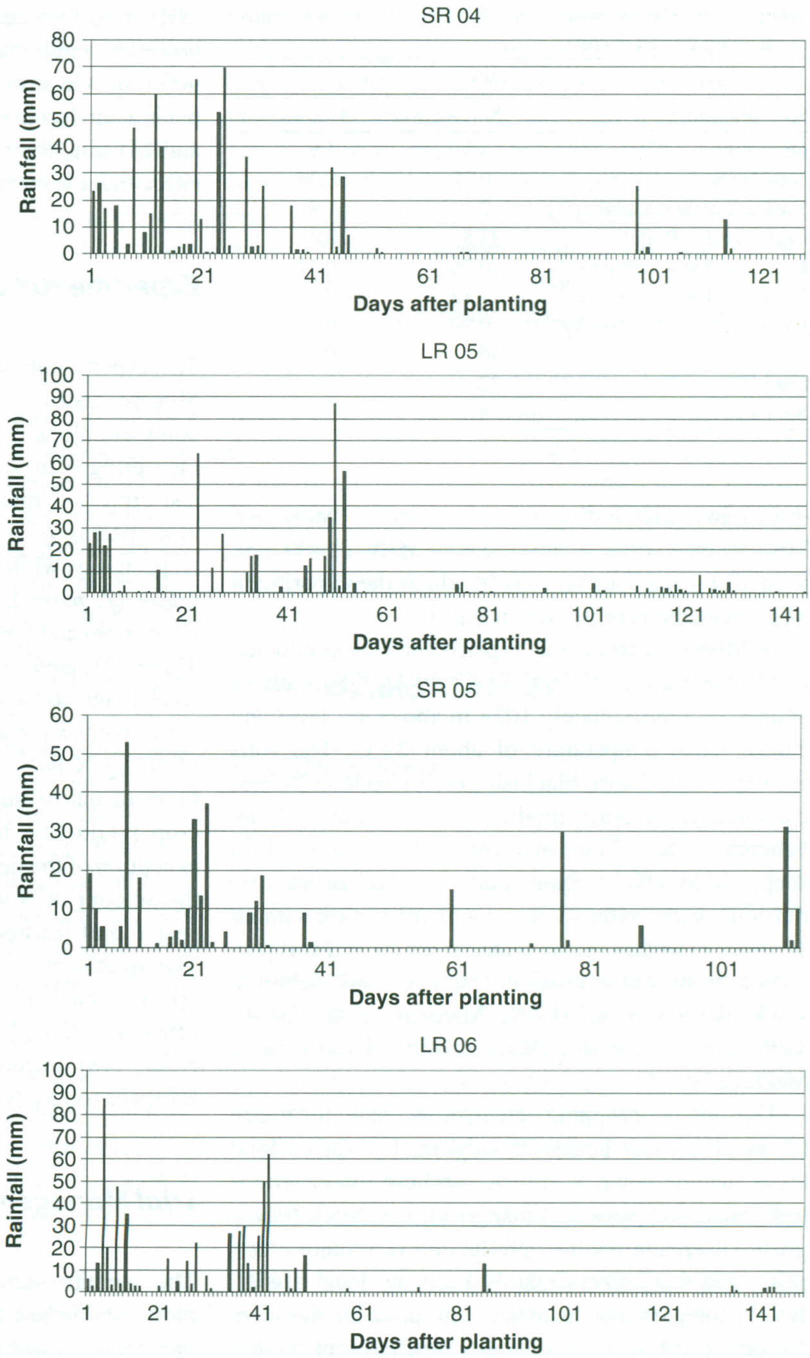


Fig. 1 Rainfall distribution from 2004 to 2006 in Mucwa site, Meru South district, Kenya

15 cm during land preparation. CAN was the source of mineral N and at all application rates, one-third was applied 4 weeks after planting and two-thirds 6 weeks after planting. Since organic inputs were being applied in this experiment and they (organic inputs) are often limited in their ability to increase P availability due to their low P content (Palm et al., 1997), P was applied in all plots at the recommended rate (60 kg P ha^{-1}) as triple super phosphate (TSP) to minimize the possibility of its confounding effects. This way it was assumed that nitrogen was the only macronutrient limiting maize yields. Other agronomic procedures

Table 2 Soil characterization in Machang'a site, Mbeere district, Kenya

Soil parameters	
pH in water	6.4
Total N (%)	0.09
Total soil organic carbon (%)	1.05
Exchangeable P (ppm)	12.9
Exchangeable K (cmol kg^{-1})	0.35
Exchangeable Ca (cmol kg^{-1})	1.0
Exchangeable Mg (cmol kg^{-1})	0.14
Clay (%)	22
Sand (%)	67
Silt (%)	11

for maize production were appropriately followed after planting.

Maize Harvesting

Maize grain and stover were harvested at maturity from a net area of 21.0 m^2 (out of the total area of 27 m^2) after leaving out one row on each side of the plot and the first and last maize plants on each row to minimize the edge effect. Cobs in each plot were separated from the stovers and their fresh weight was determined. At maturity, the maize and legumes were harvested and the fresh weight of both grain and stover was taken. Maize grains were dried and expressed in terms of dry matter content. Maize stovers were cut at ground level and the total fresh weight was determined. After harvesting, all the maize stovers were removed from the experimental plots to ensure that no nutrients were returned to the plots from the stovers that may confound the effects of adding a material of different quality into the experimental plots. Stover samples were oven dried at 70°C for 72 h to determine moisture contents, which were used to correct stover yields measured in the field to dry matter produced.

Statistical Analysis

Data were subjected to analysis of variance using GENSTAT programme, and the means were separated using Tukey's test at $p < 0.05$.

Results and Discussions

Results

There was a significant ($p < 0.001$) effect of seasons on maize grain yield in Mucwa good site. The mean maize grain yields were highest during the LR 05 season followed by SR 05, LR 06 and SR 04 seasons with 5.6, 3.1, 2.2 and 1.6 t ha^{-1}, respectively (Table 4). During the LR 05 season, the maize grain yield ranged between 3.3 and 6.5 t ha^{-1}, while during the SR 04 season, the maize grain yield ranged between 0.6 and 3.4 t ha^{-1} (Table 4).

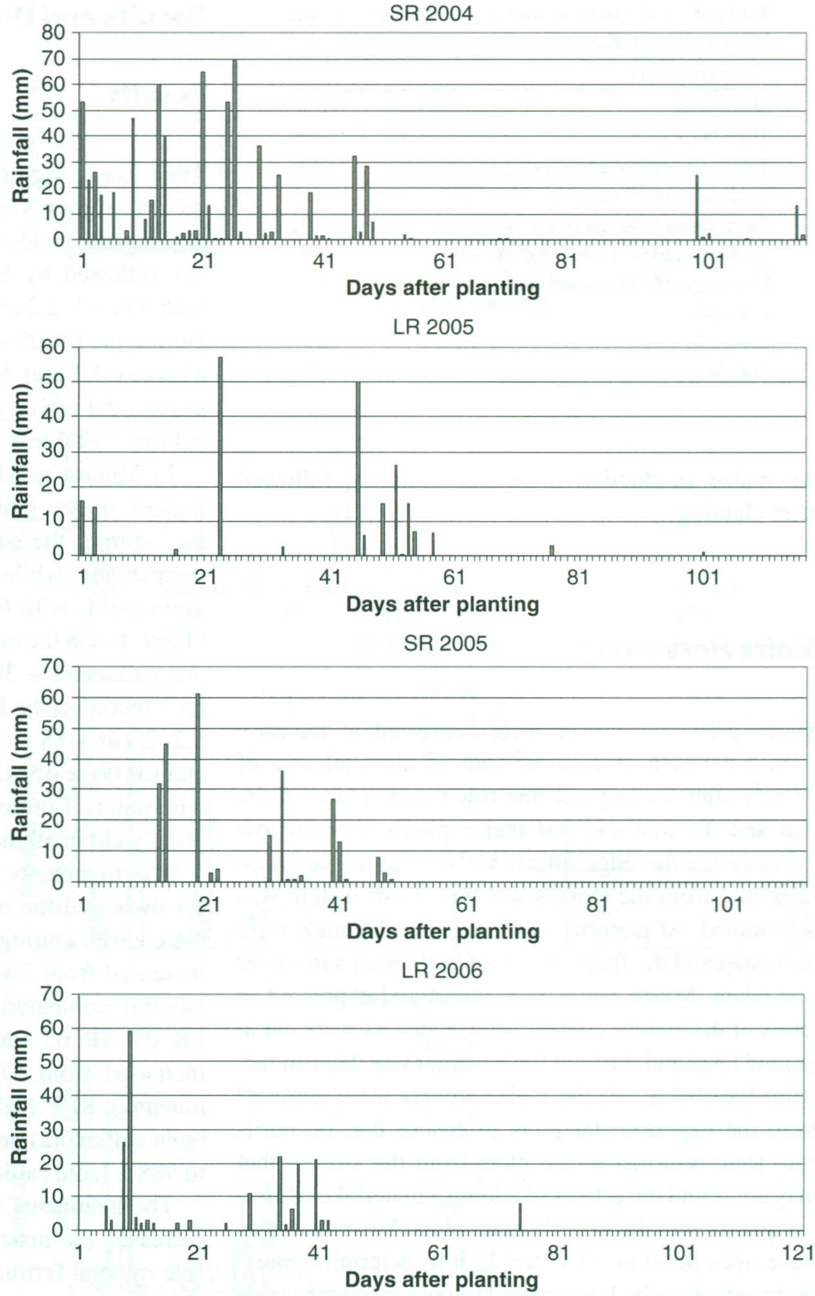
In Mucwa good site, sole calliandra recorded the highest maize grain yields with 3.4, 4.8 and 3.7 t ha^{-1} during the SR 04, SR 05 and LR 06 seasons, respectively, while sole mucuna recorded the highest grain yields with 6.5 t ha^{-1} during the LR 05 season (Table 4). On the other hand, sole mucuna, sole calliandra, calliandra + 30 kg N ha^{-1} and manure + 30 kg N ha^{-1} recorded the lowest maize grain yields with 0.7, 5.2, 2.9 and 0.8 t ha^{-1} during the SR 04, LR 05, SR 05 and LR 06 seasons, respectively, among the treatments with inputs. Control recorded the overall lowest maize grain yield in all the four seasons.

The treatments with organic and mineral fertilizers increased the maize grain yield in comparison to the control. During the SR 04 season, the grain yields increased from 3% (sole mucuna) to 430% (sole calliandra) compared to the control, while during the LR 05, SR 05 and LR 06 seasons, the grain yields increased from 57% (sole calliandra) to 95% (sole mucuna), 81% (calliandra + 30 kg N ha^{-1}) to 193% (sole calliandra) and 132% (manure + 30 kg N ha^{-1}) to 988% (sole calliandra).

The treatments with organic and mineral fertilizers increased the maize grain yield in comparison to the sole mineral fertilizer (60 kg N ha^{-1}) in Mucwa good site. For instance, during the SR 04 season, the grain yields increased from 37% (tithonia + 30 kg N ha^{-1}) to 151% (sole calliandra) compared to the sole mineral fertilizer, while during the LR 05, SR 05 and LR 06 seasons the maize grain yields increased from 1% (manure + 30 kg N ha^{-1}) to 11% (sole mucuna), 1% (manure + 30 kg N ha^{-1}) to 57% (sole calliandra) and 32% (sole mucuna) to 119% (sole calliandra).

Generally, in Mucwa good site, treatments with sole organics performed significantly better than did the

Fig. 2 Rainfall distribution from 2004 to 2006 in Machang'a site, Mbeere district, Kenya



ones with integration of organic and mineral fertilizer across the four seasons. For instance, during the SR 2004 season, treatments with sole organics recorded significantly higher maize grain yields compared to the integration of organic and mineral fertilizer with the exception of mucuna treatment where the integration was significantly higher than the sole application at $p < 0.001$.

In Mucwa poor site, there was a significant ($p < 0.001$) effect of seasons on maize grain yield. The mean maize grain yields were highest during the LR 05 season followed by SR 05, LR 06 and SR 04 seasons

Table 3 Mucuna incorporated in the 2005 long rain, 2005 short rain and 2006 long rain seasons in Mucwa good, Mucwa poor site and Machang'a

Treatment	2005 LR season Biomass incorp. ($t\ ha^{-1}$)	2005 LR season N equivalence ($kg\ ha^{-1}$)	2005 SR season Biomass incorp. ($t\ ha^{-1}$)	2005 SR season N equivalence ($kg\ ha^{-1}$)	2006 LR season Biomass incorp. ($t\ ha^{-1}$)	2006 LR season N equivalence ($kg\ ha^{-1}$)
Mucwa good						
Mucuna	12.5	30	32.8	83	16.6	45.2
Mucuna + 30 kg N ha^{-1}	12.7	29.2	38.6	108.9	16.8	50
Mucwa poor						
Mucuna	9.2	23	32.3	111.4	13.2	37
Mucuna + 30 kg N ha^{-1}	6.3	16.4	34.4	115.9	16.2	45.5
Machang'a						
Mucuna	12.6	18.9	26.9	48.2	18.6	38.5
Mucuna + 30 kg N ha^{-1}	13	18.9	27.3	43.4	18.1	28.6

Table 4 Maize grain yields ($t\ ha^{-1}$) under different treatments during the 2004 short rain, 2005 long rain, 2005 short rain and 2006 long rain seasons at Mucwa good site

Treatment	SR 2004 season –N	SR 2004 season +N Fertilizer	LR 2005 season –N	LR 2005 season +N Fertilizer	SR 2005 season –N	SR 2005 season +N Fertilizer	LR 2006 season –N Fertilizer	LR 2006 season +N
Organic residue application								
Calliandra	3.39	2.01	5.21	5.39	4.75	2.93	3.70	2.60
Mucuna	0.66	0.82	6.47	6.09	3.04	3.00	2.23	2.67
Tithonia	2.97	1.85	6.04	6.05	3.07	3.51	2.86	2.75
Manure	1.35	1.01	5.45	5.89	3.51	2.97	2.28	0.79
Fertilizer (60 kg N ha^{-1})								
Control	0.64		3.32		1.62		0.34	
SED (N_{level})			0.28*		ns			
SED (treatment)			ns		ns			
SED (N_{level} × treatment)	0.16***		ns		ns		0.39*	

*, ** and *** significant at $p < 0.05$, $p < 0.01$ and $p < 0.001$, respectively
ns, not significant
SED, standard error of differences between means

with 5.0 2.0, 1.6 and 1.4 t ha^{-1}, respectively (Table 5). During the LR 05 season, the maize grain yield ranged between 2.4 and 6.7 t ha^{-1}, while during the SR 04 season the maize grain yield ranged between 0.3 and 2.9 t ha^{-1} (Table 5).

Sole tithonia gave the highest maize grain yield during the SR 2004, LR 2005, SR 2005 and LR 2006 seasons with 2.9, 6.6, 2.8 and 3.1 t ha^{-1}, respectively (Table 5) in Mucwa poor site. Sole mucuna gave the lowest maize grain yield during the LR 2005 and the SR 2006 seasons, while mucuna + 30 kg N ha^{-1} and manure + 30 kg N ha^{-1} gave the lowest maize grain yield during the SR 2004 and LR 2006 seasons with 0.2, 4.9, 1.4 and 0.7 t ha^{-1}, respectively, in the treatments that received inputs. Overall, control gave the lowest maize grain yields during the LR 2005, SR 2005 and LR 2006 seasons with 2.4, 0.8 and 0.5 t ha^{-1}, respectively.

The treatments with organic and mineral fertilizers increased the maize grain yield in comparison to the control during all the seasons. During the SR 04 season, the maize grain yields increased from 58% (manure + 30 kg N ha^{-1}) to 282% (sole tithonia), while during the LR 05, SR 05 and LR 06 seasons the maize grain yields increased from 104% (sole mucuna, calliandra + 30 kg N ha^{-1} and manure + 30 kg N ha^{-1}) to 185% (sole tithonia), 84% (sole mucuna) to 268% (sole tithonia and manure) and 30% (manure + 30 kg N ha^{-1}) to 474% (sole tithonia), respectively, compared to the control.

Table 5 Maize grain yields (t ha^{-1}) under different treatments during the 2004 short rain, 2005 long rain, 2005 short rain and 2006 long rain seasons at Mucwa poor site

	SR 2004 season		LR 2005 season		SR 2005 season		LR 2006 season	
Treatment	–N	+N Fertilizer	–N	+N Fertilizer	–N	+N Fertilizer	–N	+N Fertilizer
Organic residue application								
Calliandra	2.10	2.82	5.57	4.80	2.60	1.74	2.91	1.08
Mucuna	0.28	0.21	4.79	5.88	1.44	2.65	1.05	2.74
Tithonia	2.88	2.34	6.65	5.00	2.80	2.18	3.06	1.78
Manure	0.73	1.17	5.85	4.79	2.76	1.70	1.80	0.73
Fertilizer (60 kg N ha^{-1})								
Control	0.76		2.35		0.76		0.54	
SED (N_{level})								
SED (treatment)								
SED (N_{level} × treatment)	0.62*		0.46*		0.46*		0.55**	

* and ** significant at $p < 0.05$ and $p < 0.01$, respectively
ns, not significant
SED, standard error of differences between means

The treatments with sole organics and organics integrated with mineral fertilizers increased the maize grain yield in comparison to the sole mineral fertilizer (60 kg N ha^{-1}). During the SR 04 season, the grain yields increased from 58% (manure + 30 kg N ha^{-1}) to 282% (sole tithonia), while during the LR 05, SR 05 and LR 06 seasons, the grain yields increased from 12% (sole mucuna, calliandra + 30 kg N ha^{-1} and manure + 30 kg N ha^{-1}) to 57% (sole tithonia), 1% (calliandra + 30 kg N ha^{-1} and manure + 30 kg N ha^{-1}) to 67% (sole tithonia and manure) and 35% (manure + 30 kg N ha^{-1}) to 496% (sole tithonia), respectively, compared to the sole mineral fertilizer.

Generally, in Mucwa poor site, treatments with sole organics performed significantly better than did the ones with integration of organic and mineral fertilizer across the four seasons. For instance, during the SR 2004 season, treatments with sole organics recorded significantly higher maize grain yields compared to treatments with integration of organic and mineral fertilizer with the exception of mucuna treatment where the integration was significantly higher than the sole application at $p < 0.001$. There was a significant ($p < 0.001$) effect of seasons on maize grain yield in Machang'a. The mean maize grain yields were highest during the LR 05 season followed by SR 04, LR 06 and SR 05 seasons with 2.5, 2.1, 2.1 and 1.6 t ha^{-1}, respectively (Table 6). During the LR 05 season, the maize grain yield ranged between 1.7 and 3.1 t ha^{-1}, while during the SR 05 season the maize grain yield ranged between 0.9 and 2.9 t ha^{-1} (Table 6).

In Machang'a site, sole manure recorded the highest maize grain yield during the SR 04, LR 05, SR 05 and LR 06 seasons with 3.0, 3.1, 2.9 and 2.7 t ha^{-1}, respectively (Table of 6). Sole mucuna recorded the lowest yield during the SR 04 and LR 05 seasons, whereas sole tithonia and mucuna + 30 kg N ha^{-1} recorded the lowest maize grain yields during the SR 05 and LR 06 seasons with 1.5, 2.3, 1.1 and 1.6 t ha^{-1}, respectively, among the treatments with inputs. Overall, control gave the lowest maize grain yields with 1.3, 1.9, 0.9 and 1.4 t ha^{-1} during the SR 04, LR 05, SR 05 and LR 06 seasons, respectively.

The treatments with sole organics and integrations of organics with mineral fertilizers increased the maize grain yield in comparison to the control. During the SR 04 season, the grain yields increased from 15% (sole mucuna) to 131% (sole manure), while during the LR 05, SR 05 and LR 06 seasons the grain yields increased from 24% (sole mucuna) to 67% (sole manure and tithonia + 30 kg N ha^{-1}), 20% (sole tithonia) to 215% (sole manure) and 11% (mucuna + 30 kg N ha^{-1}) to 88% (sole manure), respectively, compared to the control. The treatments with sole organics and combination of organics and mineral fertilizers increased the maize grain yield in comparison to the sole mineral fertilizer (60 kg N ha^{-1}) in Machang'a. During the SR 04 season, the grain yields increased from 18% (sole lantana) to 97% (sole manure), while during the LR 05, SR 05 and LR 06 seasons the grain yields increased from 36% (sole mucuna) to 83% (sole manure and tithonia + 30 kg N ha^{-1}), 14% (manure

Table 6 Maize grain yields (t ha^{-1}) under different treatments during the 2004 short rain, 2005 long rain, 2005 short rain and 2006 long rain seasons at Machang'a site

	SR 2004 season		LR 2005 season		SR 2005 season		LR 2006 season	
Treatment	–N	+N fertilizer	–N	+N fertilizer	–N	+N fertilizer	–N	+N fertilizer
Organic residue application								
Lantana	1.80	2.43	2.66	2.99	1.49	1.97	2.15	2.47
Mucuna	1.47	2.57	2.32	2.78	1.49	2.03	1.89	1.62
Tithonia	2.21	2.37	2.64	3.09	1.08	1.84	2.34	2.36
Manure	3.04	2.22	3.12	2.55	2.89	1.25	2.73	2.18
Fertilizer (60 kg N ha^{-1})								
Control	1.29		1.86		0.92		1.44	
SED (N_{level})			ns				ns	
SED (treatment)			ns				ns	
SED (N_{level} × treatment)	0.30**		ns		0.38**		ns	

** significant at $p < 0.01$
ns, not significant
SED, standard error of differences between means

+ 30 kg N ha^{-1}) to 154% (sole manure) and 2% (mucuna + 30 kg N ha^{-1}) to 72% (sole manure), respectively, compared to the sole mineral fertilizer.

During the SR 04 and SR 05 seasons in Machang'a, there was a positive interaction between the mineral N fertilizer and organic residues ($p < 0.01$). There was also a significant difference between the treatments with sole organic and the treatments with organics integrated with mineral N fertilizer. For instance, treatments of lantana and sole mucuna with mineral fertilizer N were significantly higher than the treatments with sole lantana and sole mucuna, while sole manure treatment was significantly higher than treatment with manure integrated with mineral N fertilizer during the SR 04 and SR 05 seasons. In addition, during the SR 2005 season, tithonia integrated with mineral N fertilizer was significant higher than treatment with sole tithonia.

Discussions

The application of organic alone or in combination with mineral fertilizers led to increased maize yield compared to the control. On the one hand, in Mucwa good site, sole calliandra recorded a yield increase of up to 988%; on the other hand, sole tithonia recorded an increase of 474% in Mucwa poor site, while in Machang'a, manure recorded a yield increase of up to 215%. Several authors have reported increased yields as a result of applying tithonia, calliandra and manure inputs in other areas (Kihanda, 1996; Gachengo et al., 1999; Jama et al., 1999; Mugendi et al., 1999; Mutuo et al., 2000; Kimani et al., 2004; Kimetu et al., 2004; Kihanda et al., 2006; Mucheru-Muna et al., 2007). In western Kenya, yield increase of up to 200% was reported following application of tithonia biomass (Jama et al., 2000), while in central Kenya Mucheru-Muna et al. (2007) reported yield increases of up to 267% following the application of sole tithonia biomass. Mucheru-Muna et al. (2007) reported an increase of 227% using calliandra biomass in Kenya, while Mtambanengwe et al. (2006) reported an increase of 525% following manure application in Zimbabwe.

Generally, the maize grain yields were lower in the treatments with mineral fertilizer alone compared to treatments with organic and organic combined with mineral fertilizers across the three sites in the four seasons. For instance, in Machang'a, increases of 154% were reported with the application of sole manure, in Mucwa good site, increases of 151% were reported with the application of sole calliandra and in Mucwa poor site, increases of 496% were reported with the application of sole tithonia. Mtambanengwe et al. (2006) reported a yield increase of 104% following manure application against sole mineral fertilizer. This implies an increased nutrient recovery in the organic and organic integrated with mineral fertilizer treatments compared to sole mineral fertilizer treatment.

The lower yields in the mineral fertilizer treatments could be as a result of the poorly distributed rainfall (Figs. 1 and 2) during the seasons. The timing of the application of the N from the organic treatments compared to the mineral fertilizer N could also explain the difference in yields. For the organics, all the 60 kg N ha^{-1} (sole organic) and 30 kg N ha^{-1} (treatments with integration) were applied at planting when there was adequate rainfall, while the mineral fertilizer N was applied in splits (0.33% was applied 4 weeks after planting, while the other 0.66% was applied 2 weeks later after which there was a long dry spell). Consequently, the growing maize crop may not have utilized this portion of the mineral N fertilizer, thus leading to the low maize grain yields. Other researchers have observed higher maize grain yields as a result of applying organic inputs like tithonia combined with mineral fertilizers as compared to sole application of mineral fertilizers (Mugendi et al., 1999; Mutuo et al., 2000; Nziguheba et al., 2000; Kimetu et al., 2004; Mucheru-Muna et al., 2007). Nutrients supplied in less soluble forms are less prone to loss and more suitable than mineral fertilizers when rainfall tends to be irregular and then heavy (Kihanda et al., 2006) like they were in this study.

Bekunda et al. (1997) reviewed information from selected experiments in Africa, and the results indicate that continuous application of mineral fertilizer without organic inputs eventually results in a decline in crop yields. They attributed such declining yields to soil acidification through continuous mineral fertilizer application and decline in soil organic matter. The soil organic matter in the Machang'a soils was very low as depicted by the carbon concentration (Table 2). According to Telalign et al. (1991), the soil organic carbon rated low (0.5–1.5%) in all the treatments at the beginning of the experiment, and it gradually reduced as cropping continued (data not shown). This low soil organic carbon could also have reduced the response of mineral fertilizers, agreeing with Greenland (1994), who reported that at low levels of soil organic matter, crop response to inputs is relatively poor and it is difficult to maintain yields with mineral fertilizers alone. The nutrient limitation may also be directly or indirectly related to the decline in soil organic matter with the multiple loss of soil physical condition.

Across the four seasons in Machang'a, sole manure was significantly higher than manure with mineral N fertilizer. This could be as result of the manure not decomposing as fast as the other organics applied (tithonia and lantana), thereby having more organic matter which was able to retain more water moisture that could be utilized by the crop during the growing season as depicted by the higher carbon concentration in the soil in this treatment compared to other treatments (data not shown).

Machang'a has a drier environment, and the most limiting factor to crop growth is soil moisture; during the study period, an average of 227 mm per season was received (Fig. 2). Interactions occur between water and the availability of nutrients because water increases the rate of release of nutrients from organic or insoluble forms and enables transport to roots and losses from soil to occur. Eghball (2002) reported that manure application led to a higher increase in soil organic carbon compared to other treatments. Sole manure treatment was also the only treatment that showed superiority in all nutrient provision, and it could also have supplied nutrients to the maize plant throughout the season, thereby giving higher yields. Some mineralization studies (Olsen, 1986) have shown that N release from manure is low but can persist throughout the maize growth period. These results, however, do not agree with Kihanda (1996) who reported that maize grain yields above 3.5 t ha^{-1} were obtained only when both farmyard manure and NP fertilizers were applied in acid soils in Embu.

In Mucwa good and poor sites, however, the manure treatment did not perform as well as in Machang'a site in comparison to the other treatments. Unlike in Machang'a, water is not the most limiting factor to growth in Mucwa (the area received an average of 556 mm per season during the study period; Fig. 1) but nutrients like N and P are the most limiting factors to growth. Hence, the lower rates of manure decomposition leading to low availability of nutrients to the maize crop could have led to the lower yields. Though the amount of N added via all these organic inputs was the same (60 kg N ha^{-1}), manure had lower N concentration than did all the other organic inputs and could have released the N slower due to the higher C:N ratio (Kimani et al., 2004).

During the short rain seasons in Machang'a, the treatments with integration of organic (lantana, mucuna and tithonia) and mineral N fertilizer inputs were significantly higher than the treatments with sole organics. This site was characterized by low soil fertility (Table 2), and the integration of the organic and mineral fertilizers could have probably led to an enhanced available N pool. The higher yields in the integration compared to the sole organic concur with results by Gachengo (1996), Mugendi et al. (1999) and Mutuo et al. (2000) on the integration of organic and mineral soil fertility inputs. Woomer and Swift (1994) demonstrated that integration of organics and mineral fertilizers can enhance the efficiency of mineral fertilizers. Integration of mineral and organic nutrient inputs can therefore be considered as a better option in increasing fertilizer use efficiency and providing a more balanced supply of nutrients (Vanlauwe et al., 2002). Kapkiyai et al. (1998) reported that combination of organic and mineral fertilizer nutrient sources has been shown to result in synergy and improved synchronization of nutrient release and uptake by plants leading to higher yields.

In Mucwa good and poor sites, however, the treatments with sole organics generally did better than did the ones with integration of mineral N fertilizer and organics with the exception of the mucuna treatment which did significantly better in the integration compared to the sole application. The rainfall during the four seasons was very unevenly distributed (Fig. 1), and the organic inputs could have conserved more soil moisture; hence there was more moisture made available to the growing maize in the organic treatments than in the treatments with integrations where there was less organic applied (in the sole organic treatments the organic input applied was double the one in the integration). The higher maize grain yields from the organic treatments could also be due to positive effects of the organic materials on soil physical and chemical properties (Murwira et al., 2002; Kimetu et al., 2004; Kihanda et al., 2006).

The consistently higher yields with sole tithonia biomass in the Mucwa poor site could be associated with the fast decomposition of tithonia, leading to rapid release of nutrients to the crop (Nziguheba et al., 1998; Gachengo et al., 1999). Tithonia contains high amounts of nutrients, especially N, and other nutrients such as phosphorus, potassium and magnesium, and may thus prevent other nutrient deficiencies such as micronutrients (Murwira et al., 2002). In addition, the P concentration of tithonia leaves is greater than the critical 2.5 g kg^{-1} threshold for net P mineralization (Palm et al., 1999), meaning addition of tithonia biomass to soil results in net mineralization rather than immobilization of P (Blair and Boland, 1978). The application of tithonia leaves would probably result in increased P availability by both net mineralization and decreased soil sorption (Nziguheba et al., 1998; George et al., 2001).

The consistently higher maize grain yields in the sole calliandra treatment in Mucwa good site could be due to build-up of soil organic matter by calliandra biomass which is of relatively low quality (Niang et al., 1996; Palm et al., 2001). The higher yields in calliandra treatment in Mucwa good site compared to other treatments however do not agree with results by other authors (Mwale et al., 2000; Kimetu et al., 2004) who reported lower yields with the addition of sole calliandra compared to other treatments like tithonia which decomposes very fast.

Conclusion

Sole tithonia biomass, sole calliandra and sole manure treatment recorded consistently higher maize grain yields in Mucwa poor site, Mucwa good site and Machang'a, respectively, across the four seasons. Generally, the treatments with application of organics resulted in higher maize grain yields compared to the treatments with sole mineral fertilizer, demonstrating the superiority of the organics in yield improvement due to their beneficial roles other than the addition of plant N like in the mineral fertilizer treatments. In Machang'a, the integrations of organics and mineral fertilizer recorded higher maize grain yields than did the sole organics, while in Mucwa good and Mucwa poor sites, sole organics performed better than the integrations of organic and mineral fertilizer across the four seasons.

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References

Adiel RK (2004) Assessment of on-farm adoption potential of nutrient management strategies in Chuka Division, Meru South, Kenya. MSc thesis, Kenyatta University, Kenya

Bekunda AM, Bationo A, Ssali H (1997) Soil fertility management in Africa: a review of selected research trials. In: Buresh RJ, Sanchez PA, Calhoun F (eds) Replenishing soil fertility in Africa. SSSA special publication No. 51. SSSA, Madison, WI, pp 63–79

Blair GJ, Boland OW (1978) The release of P from plant material added to soil. Aust J Soil Res 16:101–111

Donovan G Casey F (1998) Soil fertility management in sub-Saharan Africa. World Bank. Technical paper. 408

Eghball B (2002) Soil properties as influenced by phosphorus and nitrogen based manure and compost applications. Agron J 94:128–135

Fertilizer Use Recommendation Project (FURP) (1987) Description of first priority trial site in the various districts. Final report, vol 24. Embu District, National Agricultural Research Laboratories, Nairobi

Gachene CKK, Palm CA, Mureithi JG (1999) Legume cover crops for soil fertility improvement in the East African region. Report of an AHI workshop held at TSBF, Nairobi, Kenya, 18th–19th February 1999

Gachengo C (1996) Phosphorus release and availability on addition of organic materials to phosphorus fixing soils. MPhil thesis, Moi University, Eldoret, Kenya

Gachengo CN, Palm CA, Jama B, Otieno C (1999) Tithonia and senna green manures and inorganic fertilizers as phosphorus sources for maize in western Kenya. Agrof Syst 44:21–26

George TS, Gregory PJ, Robinson JS, Buresh RJ, Jama BA (2001) *Tithonia diversifolia*: variations in leaf nutrient concentration and implications for biomass transfer. Agrof Syst 52:199–205

Gitari JN, Karumba S, Gichovi M, Mwaniki K (1998) Integrated nutrient management studies at Embu site. In: Legume Research Network Project annual report

Government of Kenya (1997) Mbeere District Development Plan, 1997–2001. Ministry of Planning and National Development, Nairobi

Government of Kenya (2001) The 1999 Kenya national census results. Ministry of Home Affairs, Nairobi

Greenland DJ (1994) Soil science and sustainable land management. In: Syers JK, Rimmer DL (eds). Soil science and sustainable land management. CAB International, Wallingford, pp 1–15

Ikombo BM (1984) Effects of farmyard manure and fertilizers on maize in semi-arid areas of eastern Kenya. East Afr Agric J 44:266–274

Jaetzold R, Schmidt H (1983) Farm management handbook of Kenya. Natural conditions and farm information, vol 11/C. East Kenya. Ministry of Agriculture, Kenya

Jama B, Palm CA, Buresh RJ, Niang A, Gachengo C, Nziguheba G, Amadalo B (1999) *Tithonia diversifolia* green manure for improvement of soil fertility: a review from western Kenya. ICRAF, Nairobi

Jama B, Palm CA, Buresh RJ, Niang A, Gachengo C, Nziguheba G, Amadalo B (2000) *Tithonia diversifolia* as a green manure for soil fertility improvement in western Kenya: A Review. Agrof Syst 49:201–221

Kapkiyai JJ, Karanja NK, Woomer P, Qureshi JN (1998) Soil organic carbon fractions in a long-term experiment and the potential for their use as a diagnostic assays in highland farming systems of central Kenya. Afr Crop Sci J 6: 19–28

Kihanda FM (1996) The role of farmyard manure in improving maize production in the sub-humid central highlands of central Kenya. PhD thesis, UK

Kihanda FM (1998) Improvement of farmyard manure quality through composting with high quality organic residues. Research proposal funded by the African Science-Based Development Career Awards of the Rockefeller Foundation (1998–1999). KARI, Nairobi, Kenya

Kihanda FM, Warren GP, Micheni AN (2006) Effect of manure application on crop yield and soil chemical properties in a long-term field trial of semi-arid Kenya. *Nutrient Cycling in Agroecosystems* 76:341–354

Kimani SK, Macharia JM, Gachengo C, Palm CA, Delve RJ (2004) Maize production in the central highlands of Kenya using cattle manures combined with modest amounts of mineral fertilizer. Uganda J Agric Sci 9:480–490

Kimetu JM, Mugendi DN, Palm CA, Mutuo PK, Gachengo CN, Bationo A, Nandwa S, Kung'u JB (2004) Nitrogen fertilizer equivalencies of organics of differing quality and optimum combination with inorganic nitrogen source in central Kenya. Nutr Cycling Agroecosyst 68:127–135

Micheni A, Kihanda FM, Irungu J (2004) Soil organic matter: the basis for improved crop production in arid and semi-arid climates of eastern Kenya. In: Bationo A (ed) Managing nutrient cycles to sustain soil fertility in sub-Saharan Africa. Academy, Nairobi, pp 239–248

Mtambanengwe F, Mapfumo P, Vanlauwe B (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 MW (2003) Soil fertility technologies for increased food production in Chuka, Meru South District, Kenya. Master's thesis, Kenyatta University, Nairobi, Kenya

Mucheru-Muna MW, Mugendi DN, Kung'u JB, Mugwe J, Bationo A (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. Agrof Syst 69: 189–197

Mugendi DN, Nair PKR, Mugwe JN, O'Neill MK, Woomer PL (1999) Calliandra and Leucaena alley cropped with maize. Part 1: soil fertility changes and maize production in the sub-humid highlands of Kenya. Agrof Syst 46:39–50

Murwira HK, Mutuo PK, Nhamo N, Marandu AE, Rabeson R, Mwale M, Palm CA (2002) Fertilizer equivalency values of organic materials differing quality. In: Vanlauwe B, Diels J, Sanginga N and Merckx R (eds) Integrated plant nutrient management in sub-Saharan Africa: from concept to practice. CAB International, Wallingford, CT, pp 113–122

Mutuo PK, Mukalama JP, Agunda J (2000) On-farm testing of organic and inorganic phosphorous source on maize in western Kenya. In: The biology and fertility of tropical soils, TSBF report, p 22

Mwale M (2000) Effect of application of *S. sesban* prunnings on maize yields. In: The biology and fertility of tropical soils, TSBF report 1997–1998

Mwangi JN, Mugendi DN, O'Neill KM (1996) Crop yield response to incorporation of leaf prunnings in sole and alley cropping systems. East Afr Agric For J 62:209–218

Niang A, Amadalo B, Gathumbi S, Obonyo CO (1996) Yield response to green manure application from selected shrubs and tree species in western Kenya: A preliminary assessment

Nziguheba G, Mutuo PK (2000) Integration of *Tithonia diversifolia* and inorganic fertilizer for maize production. In: The biology and fertility of tropical soils, TSBF report, p 23

Nziguheba G, Palm CA, Buresh RJ, Smithson PC (1998) Soil phosphorus fractions and adsorption as affected by organic and inorganic sources. Plant and Soil 198:159–168

Nziguheba G, Palm CA, Buresh RJ, Smithson PC (2000) Soil phosphorus fractions and adsorption as affected by organic and inorganic sources. In: The biology and fertility of tropical soils, TSBF report, p 22

Olsen SR (1986) The role of organic matter and ammonium in producing high corn yields. In: Chen Y, Avnimelech Y (eds) The role of organic matter in modern agriculture. Martinus Nijhoff, Dordrecht, pp 29–54

Palm CA, Gachengo CN, Delve RJ, Cadish G, Giller KE (2001) Organic inputs for soil fertility management in tropical agroecosystems application of an organic resource data base. Agriculture, Ecosystems and Environment 83:27–42

Palm CA, Myers RJK, Nandwa SM (1997) Organic–inorganic nutrient interactions in soil fertility replenishment. In: Buresh RJ, Sanchez PA, Calhoun F (eds) Replenishing soil fertility in Africa. Soil Science Society of America special publication 51. Soil Science Society of America, Madison, WI, pp 193–218

Palm CA, Nzuguheba G, Gachengo C, Gacheru E, Rao MR (1999) Organic materials as sources of phosphorus. Agroforestry Forum 9(4):30–33

Place F, Barret CB, Freman HA, Ramisch JJ, Vanlauwe B (2003) Prospects for integrated soil fertility management using organic and inorganic inputs evidence from small holder African agricultural systems. Food Policy 28:365–378

Smaling E (1993) Soil nutrient depletion in sub-Saharan Africa. In: Van Reuler H, Prins W (eds) The role of plant nutrients for sustainable food crop production in sub-Saharan Africa. VKP, Leidschendam, pp 367–375

Telalign T, Haque I, Aduayi EA (1991) Soil, plant, water, fertilizer, animal manure and compost analysis manual. Plant Science Division Working Document 13, ILCA, Addis Ababa, Ethiopia

Vanlauwe B, Diels J, Aihou K, Iwuafor ENO, Lyasse O, Sanginga N, Merckx R (2002) Direct interactions between N fertilizer and organic matter: evidence from trials with ^{15}N-labelled fertilizer. In: Vanlauwe B, Diels J, Sanginga N, Merckx R (eds) Integrated plant nutrient management in sub-Saharan Africa: from concept to practice. CAB International Wallingford, Oxon, pp 173–184

Warren GP (1998) Effects of continuous manure application on grain yields at seven sites of trial, from 1993 to 1996. In: Kihanda FM, Warren GP (eds) Maintenance of soil fertility and organic matter in dryland areas. The Department of Soil Science, University of Reading occasional publication No. 3. The University of Reading, Reading

Woomer PL, Swift MJ (eds) (1994) The biological management of tropical soil fertility. Wiley, New York, NY