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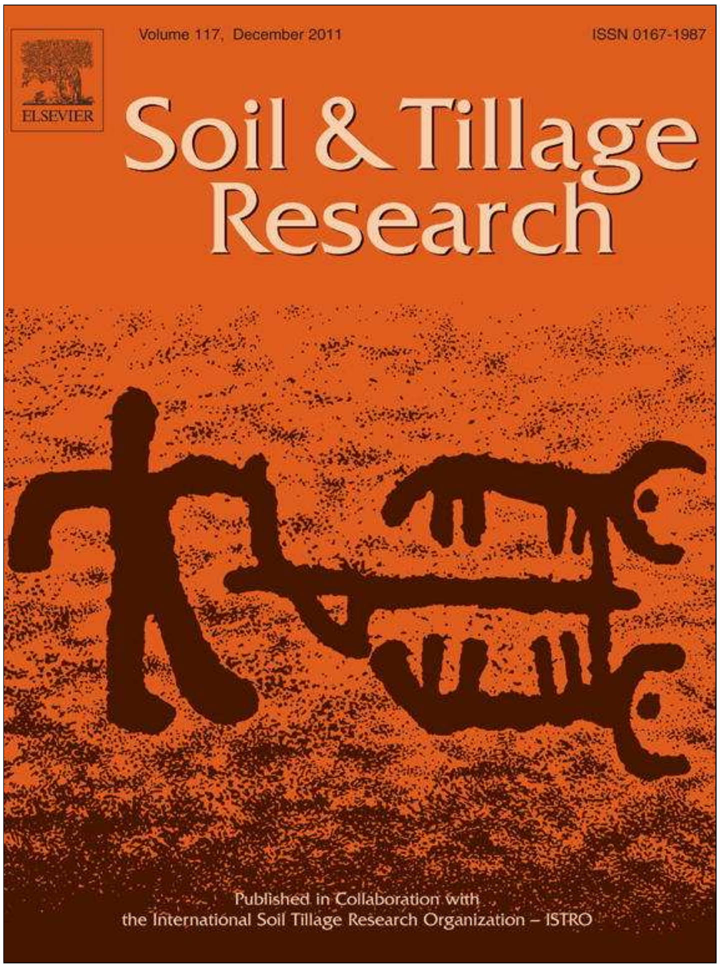
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Fertility management for maize cultivation in some soils of Western Kenya

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ABSTRACT

Soil fertility loss in Western Kenya is exacerbated by inadequate nutrient management and causes reduced maize yields. Given the diversity of soil types, cropping seasons, and the resource endowment of farmers, the magnitude of the soil fertility decline and the effectiveness of management options to counteract this decline is likely to differ. Five organic and inorganic management options were compared with farmers' practice regarding their effects on soil fertility attributes and nutrient balances/use efficiencies in maize on three contrasting soils of Western Kenya and over two cropping seasons. Irrespective of the season, organic amendments were more effective than mineral fertilizers in enhancing soil carbon stocks and the labile and non-labile C fractions. The largest soil C content (4.1%) and C pool (72 Mg ha^{-1}) were observed on the clay Nitisol after two seasons of reduced tillage, while the lowest C content (1.1%) and C pool (22 Mg ha^{-1}) were observed on the sandy Acrisol with conventional tillage. Total soil N content was consistently higher with mineral than with organic fertilizer use and more so on Nitisol than on Ferralsol or Acrisol. The soil N supplying capacity increased with the application of both organic and mineral fertilizers and reached 210 mg kg^{-1} after two weeks of anaerobic incubation of the mineral N-amended Acrisol. Bray-I P content reflected the P application rates and was highest (50–66 mg kg^{-1}) on the Acrisol with mineral P fertilizer use and lowest (1.5 mg kg^{-1}) on the Ferralsol in the unamended control treatment. Partial N and P balances were generally positive except for the mineral N-amended treatments on the Nitisol. The efficiency of applied N varied from 29 to 135 kg kg^{-1} N with lowest values in the sandy Acrisol under reduced tillage. These differential responses to management options in different soil types were reflected in maize grain yields with highest cumulative yields of 4.7–9.4 Mg ha^{-1} a^{-1} in the Nitisol and 1.4–7.4 Mg ha^{-1} a^{-1} in the Acrisol and the Ferralsol. We may conclude that the tested technology options differentially affected soil fertility and production attributes. The extent of this response depended on the cropping season and the soil type, supporting the need for site-specific nutrient management and technology targeting.

1. Introduction

Maize is the single most important food crop and a major source of household income in the rural areas of Kenya (Shisanya et al., 2009). Recently, soil fertility and maize yields in Western Kenya have been declining due to continuous cropping without adequate nutrient management (Tittonell et al., 2005). These trends appear to differ in their magnitude depending on soil types and soil fertility levels both between and within farms (Vanlauwe et al., 2006). Several technologies were proposed to enhance soil fertility and increase production including biomass transfer and improved fallows (Hartemink et al., 2000; Jama et al., 2000), application of farmyard manure (Odendo et al., 2006), inter-cropping with agro-forestry species (Nadwa, 2001) and mineral fertilizer use (Okalebo et al., 2006). Adoption rates remain low as the site- and system-specificity of these technologies are rarely taken into account (Kiptot et al., 2007; Ojiem et al., 2006). Soil fertility improvement was mostly studied in single localities but recommended at regional scale without considering the diversity of bio-physical attributes and differences in the socio-economic situations of the farmers (Tittonell et al., 2005). However, both the effectiveness and the adoptability of technical options are seen to be highly niche-specific (Ojiem et al., 2006).

Commonly applied indicators of soil fertility improvement include soil carbon fractions and the C management index (Blair et al., 1995), total nitrogen and the N supplying capacity (Mikha et al., 2006), and the available P content (George et al., 2002). These parameters have been used in combination with crop nutrient uptake, partial nutrient balances (Mussgnug et al., 2006), and nutrient use efficiencies (Cassman et al., 1998) to assess short- and long-term sustainability trends of production systems (Blair and Crocker, 2000; Tittonell et al., 2007). We hypothesize that the effectiveness of management options to enhance soil fertility and maize production is likely to vary by soil type and cropping season.

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Therefore, the objectives of the study were to assess selected technology options regarding (i) their effects on changes in soil fertility attributes (C, N and P), (ii) NP balances and (iii) the nutrient use efficiency in maize fields on three soils in Western Kenya over two cropping seasons.

2. Materials and methods

2.1. Experimental sites

The study was conducted in the short rainy season (September–November) of 2008 and the long rainy season (March–July) of 2009 at three sites in Kakamega, Western Kenya, namely (i) the Kenya Agricultural Research Institute (KARI) Kakamega, (ii) Lubao sub-location and (iii) Virhembe sub-location. The three sites were located within a 2–30 km distance from Kakamega town (034°46′E, 00°17′N). The mean temperature of the sites was 21 °C and annual rainfall ranged between 1600 and 2200 mm (Table 1). The soils of the three sites were eutric haplic Nitisol (KARI), ferralo-orthic dystric Acrisol (Lubao) and nito-rhodic haplic Ferralsol (Virhembe), according to the FAO classification (FAO, 1990). The field experiments at the KARI research farm were conducted on plots with a multi-year history of maize varietal trials with the application of mineral fertilizer. The field experiments on Lubao and Virhembe were conducted on farmers' fields where maize and common bean were grown with minimal external inputs for >10 years prior to this study. Selected soil physical and chemical properties of the sites are given in Table 1. The three sites will subsequently be referred to by their soil types as Nitisol, Acrisol and Ferralsol.

2.2. Experimental design and treatments

Six management options were comparatively assessed in a randomized complete block design. Experimental plots of 6 m × 5 m were separated by 0.5 m borders of weedy fallow. The management options included a low-input farmers practice (control treatment) without external input use, conventional manual tillage and one manual hand weeding at 14 days after maize seeding and five regionally recommended soil fertility-enhancing technologies, namely (i) farmyard manure, where well-composted dried cattle manure was manually incorporated at a rate of 5 Mg ha^{-1} during land preparation (corresponding to application rates of 60 kg N and 13 kg P ha^{-1}), and (ii) green manure using *Mucuna pruriens* var. *utilis*, whereby *Mucuna* was established two weeks prior to maize seeding at the onset of the short (20 August 2008) and the long rainy season (8 March 2009), at a 20 cm × 30 cm spacing. Mineral P was applied as triple superphosphate at a rate of 30 kg ha^{-1} to the *Mucuna* planting holes. The biomass was incorporated six weeks after seeding between the rows of 4-week-old maize using a hand hoe. (iii) Zero tillage combined with the use of *Arachis pintoi* as a cover crop. *Arachis* (accession CIAT 18744) was established at the onset of the short rainy season (20 August 2008) at a 20 × 20 cm spacing two weeks prior to maize seeding. Mineral P was applied as triple superphosphate at a rate of 30 kg ha^{-1}. After its establishment, *Arachis* was maintained as permanent live ground cover for the duration of the experiment. In addition, mineral N was applied to maize as urea at a rate of 100 kg ha^{-1} with 40, 30 and 30% provided at planting, four weeks and six weeks after maize seeding, respectively. A basal application of 100 kg P ha^{-1} was applied as triple super phosphate at maize planting. (iv) The zero tillage treatment combined with mineral fertilizer use was identical to (iii) with the exception that there was no cover crop. Finally, (v) mineral fertilizer use as in (iv) with the exception that treatment plots were tilled.

Maize cultivar HB 520 was seeded in all treatment plots on 4 September 2008 for the short and on 22 March 2009 for the long rainy season crop at a 60 cm × 25 cm spacing. Two maize seeds were used per planting hole and thinned to one plant per hill two weeks after emergence. Weeds were manually removed and weighed at 14, 28 and 42 days after maize seeding. As weeding represents a moderate disturbance of the soil, the zero-tillage treatment may better be referred to as reduced tillage.

Table 1
Geographical location, climatic conditions and selected soil characteristics of three study sites (differentiated by the dominant soil type) in Western Kenya.

Parameter	Soil type		
	Nitisol	Acrisol	Ferralsol
Altitude (masl)	1534	1558	1569
Latitude	N 00°16.962′	N 00°19.180′	N 00°14.548′
Longitude	E 034°46.073′	E 034°47.793′	E 034°51.129′
Annual rainfall (mm)	1978	1612	2232
Mean temperature (°C)	21	21	21
Soil texture	Clay-loam	Sandy-loam	Clay
Sand (%)	12.9	61.2	10.8
Silt (%)	33.6	20.0	27.0
Clay (%)	53.5	18.8	62.2
pH (H_2O)	5.44	5.50	4.90
Total C (%)	3.98	1.18	2.77
Total N (%)	0.35	0.12	0.26
Available Bray-P (mg kg^{-1})	3.46	7.72	2.34
Exchangeable K (cmol kg^{-1})	0.72	0.24	0.80
Bulk density (g cm^{-3})	1.11	1.22	1.12

Soil analysis method: Okalebo et al. (2002).

2.3. Soil sampling and analysis

Soil samples were collected from the three study sites at the start of the experiment in August 2008 and at the end of two cropping seasons. Bulk density was sampled in three replications per treatment plot from 5 to 10 cm soil depth using standard 100 cm^3 cans. Bulk density was calculated as (1) according to standard method (Okalebo et al., 2002):

$$\text{Bulk density}\ (\text{g cm}^{-3}) = \left(\frac{\text{wt}\,1 - \text{wt}\,2}{V}\right) \quad (1)$$

whereby wt 1 is the initial weight (g) of soil after sampling, wt 2 is the final weight (g) of soil after drying in an oven at 105 °C for 2 days and *V* is the volume (cm^3) of metal cans used for sampling.

Soil samples for chemical analyses were taken at ten locations in each treatment plot at a depth of 0–15 cm, pooled, mixed thoroughly, and a sub-sample was air-dried for 7 days at 30 °C. The dried sub-samples were ground (1 mm) and stored until analysis. Total C and N were analyzed using an automatic elemental analyzer (Okalebo et al., 2002). C stock was calculated as bulk density × %C at 0–15 cm soil layer expressed in Mg ha^{-1}.

Given low content of total C (C_T) and N on the Acrisol (Table 1), samples were further analyzed for labile and non-labile C fractions, and the N supplying capacity. Labile carbon (C_L) (oxidized by 333 mM $KMnO_4$), non labile carbon (C_{NL}: $C_T - C_L$) and the C management index (CMI) were determined following Blair et al. (1995), using farmers' practice as the reference treatment (CMI = 100%). The CMI was computed as CMI = CPI × LI × 100, whereby CPI is the C pool index (C_T treatment/C_T control), LI is the lability index (L treatment/L control) and L is the lability of C (C_L/C_{NL}). A CMI > 100% indicated an improvement while a CMI < 100% indicated a decline in both total soil C content as well as C quality due to treatment application. The N supplying capacity was determined as ammonium-N mineralization after 0, 7 and 14 days of anaerobic incubation in sealed 100 mL plastic bottles at 30 °C in

Table 2
Effect of management options on total carbon content (%) in three soils of Western Kenya, over two cropping seasons. Values are means of 4 replicates. Means followed by the same letter are not significantly different (Tukey test, $P < 0.05$).

[a]Management option	Total carbon (%)					
	Nitisol		Acrisol		Ferralsol	
	[b]SR	[c]LR	SR	LR	SR	LR
FP (control)	3.99^{ns}	4.00c	1.18^{ns}	1.19c	2.78^{ns}	2.79b
FYM	4.10	4.16a	1.25	1.34a	2.92	3.04a
GM	4.10	4.15ab	1.26	1.32ab	2.87	2.95ab
ZANP	4.10	4.14ab	1.27	1.33a	2.88	2.96ab
ZNP	4.00	4.03bc	1.20	1.29c	2.80	2.82ab
NP	4.00	4.02bc	1.21	1.24bc	2.81	2.83ab

ns, non significant.
[a] FP, farmer's practice; FYM, farm yard manure; GM, green manure; ZANP, zero tillage combined with the use of a cover crop; ZNP, zero tillage combined with mineral fertilizer use; NP, mineral fertilizer.
[b] Short rainy season (September–November) 2008.
[c] Long rainy season (March–July) 2009.

the dark (Stanford and Smith, 1972). Ammonium-N was extracted with 2 N KCl and measured using an automatic analyzer (MT 7, Bran+Luebbe, Norderstedt, DE). Available P was determined by the Bray-1 method using 0.03 M NH_4F + 0.025 M HCl extracting solution (Okalebo et al., 2002).

2.4. Nutrient balances and nutrient use efficiencies

Partial N and P balances were calculated as [kg N or P applied as organic or mineral fertilizer − kg N or P uptake by maize above the unamended control].

Physiological N (p-NUE) and P (p-PUE) use efficiencies were calculated as cumulative values for the two cropping seasons according to Cassman et al. (1996) as follows:

$$\text{p-NUE or p-PUE} = \frac{\text{kg of N or P uptake over the control}}{\text{kg of N or P applied}} \times 100.$$

In the input calculations, P (30 kg ha^{-1}) applied to *Mucuna* at planting and N contribution from nitrogen fixation were considered and the percentage of N derived from biological nitrogen fixation was determined by the ^{15}N natural abundance method using maize as the non-fixing reference plant. In contrast, the N contribution from N_2 fixation by *Arachis* was not considered as the biomass was not incorporated into the soil. N input from atmospheric deposition and N loses by NO_3^- leaching and N_2, N_2O and NH_3 were not taken into account.

Maize biomass was determined at harvest (16 weeks) from a 2 m × 3 m harvest area. Sub-samples (stover + grain) of 200 g were oven-dried at 70 °C to constant weight. Fifty milligram of fine-ground sample was analyzed for N concentration with an automatic elemental analyzer (EA Euro 3000). The P content was determined colorimetrically after dry-ashing (Mussgnug et al., 2006).

2.5. Statistical analysis

Data collected from each of the three sites on soil C fractions, C management index, total N, available P, maize biomass and maize N and P uptake, were subjected to analysis of variance using the SPSS statistical package (SPSS, 2008). Means were separated using Tukey test ($P < 0.05$).

3. Results

3.1. Carbon fractions and carbon management index

Soil carbon pools and fractions were differentially affected by management options in the different soils. While no significant treatment-induced changes in total C pools and fractions were observed at the end of the first (short rainy) season, there were significant differences ($P < 0.01$) in C concentrations (Table 2) and C stocks (Table 3) among management options and across sites at the end of the second (long rainy) season. Irrespective of management options, total C was generally higher on the Nitisol (4.0–4.1%) than the Ferralsol (2.8–3.0%) or the Acrisol (1.1–1.3%) while C pool changes were observed with zero tillage combined with cover crop use, ranging from 2 to 5 Mg ha^{-1} depending on the soil type. The application of farmyard manure and green manure

Table 3
Effect of management options on bulk density (BD) (g cm^{-3}) and total carbon (C) stocks (Mg ha^{-1}) in three soils of Western Kenya, over two cropping seasons. Values are means of 4 replicates. Means followed by the same letter are not significantly different (Tukey test, $P < 0.05$). BD is assumed similar for the treatments during the short rainy season.

[a]Management option	Nitisol				Acrisol				Ferralsol			
	[b]Short rainy season		[c]Long rainy season		Short rainy season		Long rainy season		Short rainy season		Long rainy season	
	BD	C stock	BD	C stock	BD	C stock	BD	C stock	BD	C stock	BD	C stock
FP (control)	1.11	66.5^{ns}	1.11^{ns}	66.6b	1.22	21.7^{ns}	1.22^{ns}	21.8c	1.12	46.7^{ns}	1.12b	46.9c
FYM	–	68.3	1.11	69.4ab	–	23.0	1.22	24.6a	–	49.0	1.12b	50.2ab
GM	–	68.3	1.11	70.1ab	–	23.1	1.22	24.2ab	–	48.3	1.12b	49.5abc
ZANP	–	68.4	1.15	71.4a	–	23.3	1.26	25.4a	–	48.4	1.15a	51.3a
ZNP	–	66.7	1.14	69.0ab	–	22.0	1.25	22.7bc	–	47.1	1.14a	49.3abc
NP	–	66.7	1.11	67.0b	–	22.3	1.22	22.8bc	–	47.2	1.12b	47.4bc

ns, non significant.
[a] FP, farmer's practice; FYM, farm yard manure; GM, green manure; ZANP, zero tillage combined with the use of a cover crop; ZNP, zero tillage combined with mineral fertilizer use; NP, mineral fertilizer.
[b] Short rainy season (September–November) 2008.
[c] Long rainy season (March–July) 2009.

Table 4
Effect of management options on labile (C_L) (oxidized by 333 mM $KMnO_4$) and non-labile (C_{NL}: $C_T - C_L$) carbon fractions, and the carbon management index (CMI) on an Acrisol in Western Kenya, over two cropping seasons. Values are means of 4 replicates. Means followed by the same letter are not significantly different (Tukey test, $P < 0.05$).

[b]Management option	Labile carbon ($mg\,g^{-1}$)		Non-labile ($mg\,g^{-1}$)		[a]CMI (%)	
	[c]SR	[d]LR	SR	LR	SR	LR
FP (control)	0.12b	0.49d	11.72[ns]	11.44c	100.0	100.0
FYM	0.13a	0.59a	12.41	12.84a	109.8a	121.8a
GM	0.13a	0.58ab	12.51	12.62ab	109.7a	119.2ab
ZANP	0.13a	0.57b	12.60	12.82a	108.2a	116.2b
ZNP	0.12b	0.51c	11.88	11.62c	102.7b	105.3c
NP	0.12b	0.50cd	12.06	11.94bc	102.2b	104.2c

ns, non significant.
[a] CMI = CPI × LI × 100; CPI = C_T treatment/C_T control; LI = L treatment/L control; L = C_L/C_{NL}; C_T = total carbon.
[b] FP, farmer's practice; FYM, farm yard manure; GM, green manure; ZANP, zero tillage combined with the use of a cover crop; ZNP, zero tillage combined with mineral fertilizer use; NP, mineral fertilizer; CPI, carbon pool index; LI, lability index; L, lability. FP (control) was reference for calculating CMI with a value of 100%.
[c] Short rainy season (September–November) 2008.
[d] Long rainy season (March–July) 2009.

tended to enhance particularly the labile C fraction on the Acrisol in both the short and the long rainy seasons by 8–21% (Table 4). The non-labile C fraction was also enhanced by organic amendments while mineral fertilizer use showed no significant effects. Generally, labile C appeared to be a more responsive indicator to applied management options than non-labile or total C. Significant differences ($P < 0.001$) in the C management index (CMI) among management options were apparent particularly in the second season, reaching increases of +10 to +22% above the mineral fertilizer and the unamended control treatments (Table 4).

3.2. Total N, N supplying capacity, and available P

The amount of total N differed among sites and soils (Fig. 1) with 0.32–0.34% in the Nitisol, 0.21–0.24% in the Ferralsol, and 0.10–0.11% in the Acrisol. Both the application of mineral and organic amendments significantly increased total N across sites and seasons. An increase in the net-N supplying capacity of the sandy Acrisol was observed regardless of the management option applied (Fig. 2). However, the extent of this increase was more pronounced with mineral than with organic fertilizer additions and reached a maximum of 200 mg kg^{-1} soil in the mineral NP treatment.

The effect of management options on available Bray-I P was largely reflecting in the amounts of P added (Fig. 3). The mean P concentration was 45–66 mg kg^{-1} with mineral fertilizer use, 8–19 mg kg^{-1} with green manure, 4–13 mg kg^{-1} with farmyard manure and 2–5 mg kg^{-1} in the farmer practice, regardless of sites. Irrespective of the fertilizer source, a general increase in available P was observed from the first (short) to the second (long rainy) season of treatment application. In contrast, an 18–38% decline in available P was noted in the unamended control treatment after two cropping seasons. This decline was stronger on the Ferralsol than on the Nitisol or the Acrisol.

3.3. Nutrient balances and use efficiencies

Maize biomass and grain yield was significantly enhanced ($P < 0.001$) by the application of both mineral fertilizer and organic amendments (Table 5). Cumulative biomass (sum of biomass for the two seasons) ranged from 17 to 26 Mg ha^{-1} in the Nitisol, 9 to 16 Mg ha^{-1} in the Acrisol and 9 to 14 Mg ha^{-1} in the Ferralsol, while grain yields were 4.7–9.4 Mg ha^{-1} in the Nitisol and 1.4–7.4 Mg ha^{-1} in the Acrisol and the Ferralsol. Cumulative N and P uptakes for the two seasons reached a maximum of 272 kg N ha^{-1} with mineral fertilizer use on the Nitisol and a minimum of 36 kg N ha^{-1} in the green manure treatment on the Acrisol.

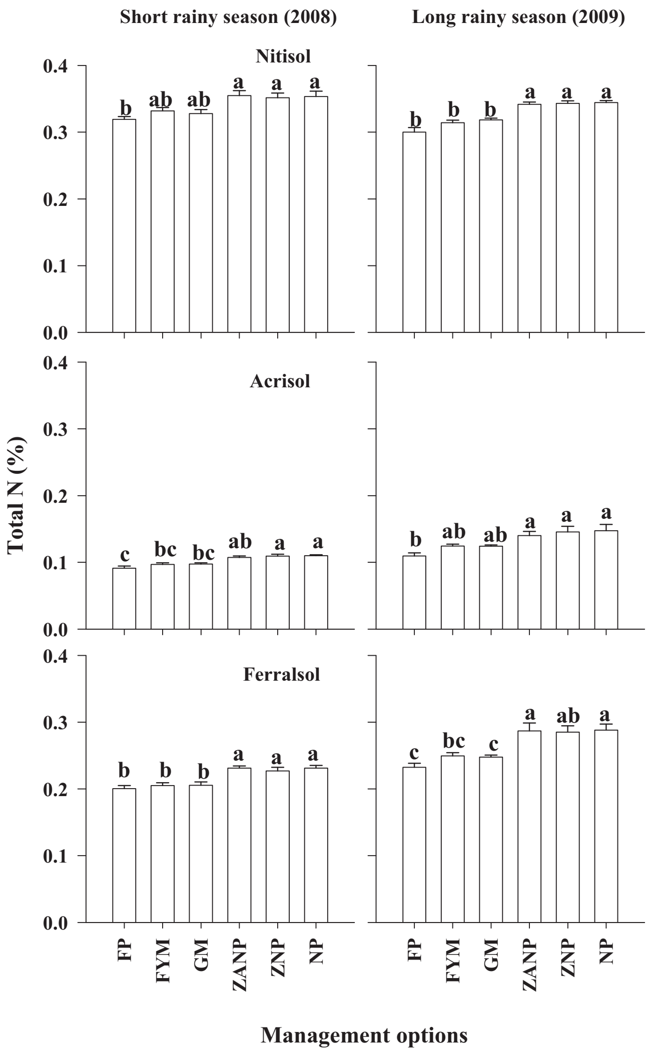

Fig. 1. The response of total nitrogen (N) to management options on three dominant soil types in Western Kenya. Data were collected at the end of the short (September–November 2008) and the long rainy season (March–July 2009). Bars are standard error of the means ($n = 4$). Data followed by the same letter in a cropping season and soil type are not significantly different by Tukey test ($P < 0.05$). FP, farmers' practice; FYM, farmyard manure; GM, green manure using *Mucuna pruriens*; ZANP, zero tillage combined with the use of mineral fertilizer and *Arachis pintoi* as cover crop; ZNP, zero tillage with mineral fertilizer use; NP, mineral fertilizer.

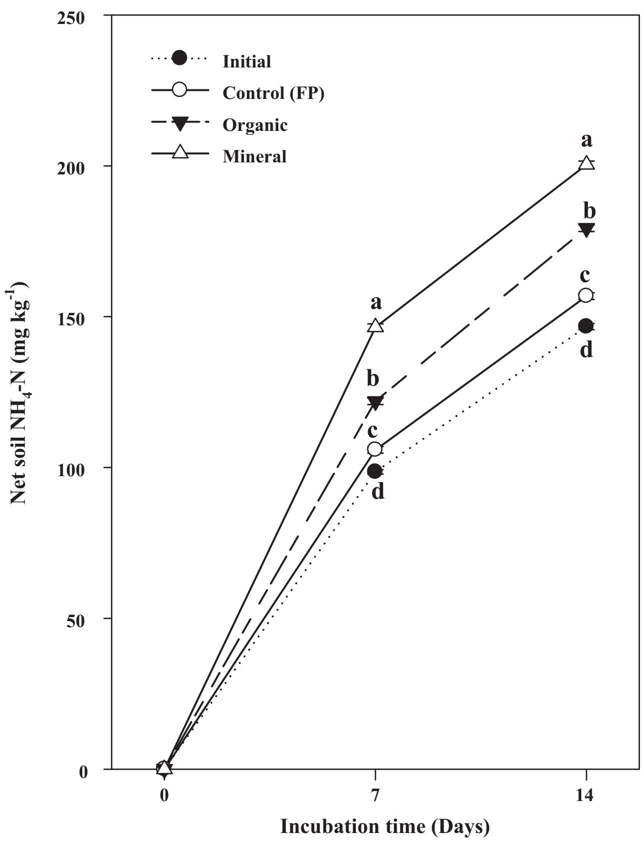

Fig. 2. Variation in net ammonium-N mineralization (soil N supplying capacity) of an Acrisol in Western Kenya, over a period of 14 days of soil incubation between the initial samples collected at planting and samples from the control (FP), organic (FYM, GM) and mineral fertilizer (ZANP, ZNP, NP) treatments collected after two seasons of treatment application. Bars are standard error of the means ($n = 4$). Data followed by the same letter in an incubation time are not significantly different by Tukey test ($P < 0.05$). FP, farmers' practice; FYM, farmyard manure; GM, green manure using *Mucuna pruriens*; ZANP, zero tillage combined with the use of mineral fertilizer and *Arachis pintoi* as cover crop; ZNP, zero tillage combined with mineral fertilizer use; NP, mineral fertilizer.

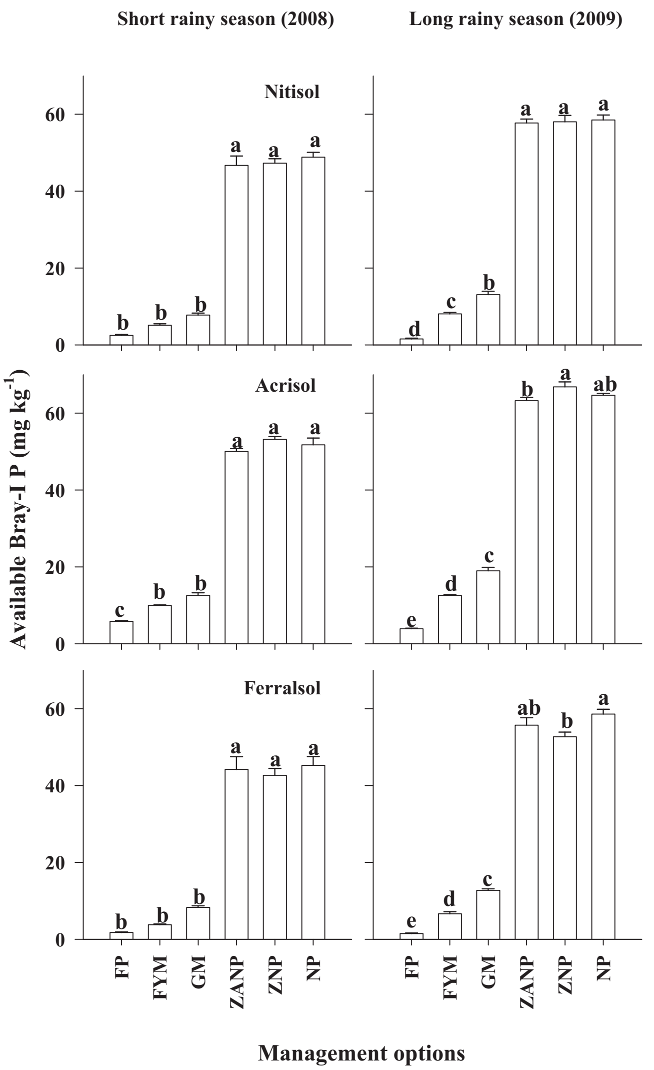

Fig. 3. The response of available Bray-I phosphorus (P) to management options on three dominant soil types in Western Kenya. Data were collected at the end of the short rainy season (September–November) of 2008 and the long rainy season (March–July) of 2009. Bars are standard error of the means ($n = 4$). Data followed by the same letter in a cropping season and soil type are not significantly different by Tukey test ($P < 0.05$). FP, farmers' practice; FYM, farmyard manure; GM, green manure using *Mucuna pruriens*; ZANP, zero tillage combined with the use of mineral NP fertilizer and *Arachis pintoi* as cover crop; ZNP, zero tillage combined with mineral fertilizer use; NP, mineral fertilizer.

With the addition of organic amendments, N balances tended to be positive while being generally negative with mineral fertilizer use in the Nitisol. In contrast, P balances were highly positive (+124 to +134 kg P ha^{-1}) with mineral fertilizers and neutral to slightly positive with organic amendments (+2 to +54 kg P ha^{-1}). The positive effects of organic amendment on N and P balances were generally more on the Acrisol and the Ferralsol than on the Nitisol. Combining zero tillage with the use of a cover crop had the largest positive effect on the partial balances of N (+143 kg ha^{-1}) and P (175 kg ha^{-1}). The use efficiency of applied N by maize was more with mineral (71–136%) than with organic amendments (39–78%) and was highest on the Nitisol and lowest on the Acrisol. The reverse trend was observed in the case of P with generally higher use efficiencies from organic than from mineral fertilizer sources. The largest P use efficiency occurred with the application of farmyard manure (62–80%), irrespective of the soil type.

4. Discussion

4.1. Effects of soil type

Soils differ in their inherent attributes, determining C and nutrient stocks as well as nutrient availability or supplying capacity (Brady and Weil, 2002). Thus, the two clay soils (Nitisol and Ferralsol) had generally higher values in key fertility attributes than the sandy Acrisol, except for the availability of P which was linked to soil pH and clay content as reported elsewhere (Tisdale et al., 1993). Thus, the highly acidic clay Ferralsol had the lowest available P content and P fixation has been reported to widely occur in Western Kenya (George et al., 2002). While lime for soil pH correction is neither available in the region nor affordable by the small-scale farmers, the use of organic amendments may provide a low-cost alternative to not only enhance soil C but also to buffer extreme soil pH values (Kifuko et al., 2007). Such effects of organic amendments have also been reported from other regions and soil types, i.e. acid sulfate soils in Vietnam (Becker, 2008). With their different physical and chemical attributes, the soil types also differentially affect nutrient balances and nutrient use efficiencies in maize-based cropping systems. This was reflected in a higher N balance and lower N use efficiency in the Acrisol than in the Nitisol or the Ferralsol. As the Acrisol was sandy, it is possible that a major share of the mineralized soil N was not taken up by the maize crop and may have been lost by leaching (Dawson et al., 2008; Tittonell

Table 5
Partial nitrogen (N) and phosphorus (P) balances and use efficiencies of maize on three contrasting soil types in Western Kenya. Data are cumulative of two seasons (short + long rainy seasons) of treatment application calculated from applied organic and mineral fertilizers and maize (stover + grain) nutrient uptake at harvest. Data followed by the same letter are not significantly different (Tukey test, $P < 0.05$).

Soil type	[d]Management option	Maize biomass (Mg ha^{-1})	Maize grain (Mg ha^{-1})	[c]Nitrogen				Phosphorus			
				Applied (kg ha^{-1})	Uptake (kg ha^{-1})	[a]Balance (kg ha^{-1})	[b]p-NUE (%)	Applied (kg ha^{-1})	Uptake (kg ha^{-1})	Balance (kg ha^{-1})	p-PUE (%)
Nitisol	FYM	17.4b	6.7c	120	80c	+40	67	26	20c	+3	77
	GM	17.4b	7.2bc	97	74c	+23	76	67	27c	+40	40
	ZANP	24.5a	8.3ab	200	217b	−17	109	200	66b	+134	33
	ZNP	26.2a	9.1a	200	272a	−72	136	200	76a	+124	38
	NP	26.3a	9.4a	200	272a	−72	136	200	76a	+124	38
Acrisol	FYM	11.3b	4.1b	120	62b	+58	52	26	21c	+2	80
	GM	08.8c	3.2b	90	36c	+54	40	69	15d	+54	22
	ZANP	10.7b	3.4b	200	57b	+143	29	200	25c	+175	13
	ZNP	15.0a	6.4a	200	142a	+58	71	200	41b	+159	21
	NP	15.8a	7.3a	200	151a	+49	76	200	47a	+153	24
Ferralsol	FYM	09.4b	4.0b	120	77b	+43	64	26	16b	+10	62
	GM	08.8b	3.7b	83	65b	+18	78	67	17b	+50	25
	ZANP	12.6a	5.8a	200	162a	+38	81	200	33a	+167	17
	ZNP	13.8a	6.4a	200	173a	+27	87	200	35a	+165	18
	NP	14.3a	6.8a	200	185a	+15	93	200	37a	+163	19

[a] Partial nutrient balance = [(applied N or P) − (N or P uptake over control)].
[b] Physiological N or P use efficiency (p-NUE or p-PUE) = [(kg of nutrient uptake over control)/(kg of nutrient applied)] × 100.
[c] P (30 kg ha^{-1}) applied to cover crop (*Arachis*) at planting and N contribution from nitrogen fixation were not considered as biomass of the cover crop was not incorporated into the soil. P (30 kg ha^{-1}) applied to *Mucuna* at planting and N contribution from nitrogen fixation were considered.
[d] FYM, farm yard manure; GM, green manure; ZANP, zero tillage combined with the use of a cover crop; ZNP, zero tillage combined with mineral fertilizer use; NP, mineral fertilizer.

et al., 2007). Consequently, management options will also differ in their effectiveness of improving soil fertility attributes between the soil types, strengthening the argument for a soil type-specific targeting of technology options in Western Kenya.

4.2. Effects of crop management

Regionally recommended management practices to address declining soil fertility and yield trends comprise both mineral and organic nutrient additions and generally strategies to conserve or build soil organic matter. In the present study, the application of organic amendments was generally effective to increase both the labile and then stable C fractions, probably due to an enhanced formation of soil organic matter and the activity of the microbial biomass (Jarecki and Lal, 2003; Rasool et al., 2008). This effect of organic amendments was most strongly reflected in the increase of the C management index (CMI). The CMI considers both the C pool and the C lability index and may thus provide a better indication of changes in soil productivity than C stocks or the labile C fraction alone (Blair et al., 1995). The appropriateness of the CMI as a sensitive indicator of systems response to management interventions has been shown in studies of upland rice based systems in West Africa (Becker and Johnson, 2001) and from different crop rotations on two Australian soils (Blair and Crocker, 2000). However, unlike in previous longer-term studies (i.e. 12 years of no-tillage – Olson et al., 2005), neither the C fractions nor the C pools were significantly affected by tillage regimes (zero tillage vs. tillage) possibly because of the short experimental period in the current study. Mineral fertilizer use enhanced both soil N content and crop N uptake more than organic amendments, as mineral N is readily available for plant uptake (Barber, 1984) and as the quantity of N supplied by mineral fertilizer in the present study was higher than the N additions from organic sources. The observed increase in the soil N supplying capacity following the application of organic fertilizers was consistent with previous observation (Mikha et al., 2006).

Given the generally low content of soil available P in control treatments across sites, maize production in Western Kenya is unlikely to increase without organic or mineral P additions. Consequently, P availability in maize fields soils has generally been related to the amount of P applied and the reported increases in available P from mineral fertilizers or organic amendments are consistent with earlier reports (Dobermann et al., 2002; Kwabiah et al., 2003). Among the organic amendments, green manuring resulted in higher available soil P than farmyard manure. It is likely that the mineral P applied at planting had not only stimulated the biological N_2 fixation of *Mucuna* but may also have resulted in an effective P mobilization and its subsequent recycling upon green manure incorporation (Somado et al., 2003). Such strategies may be of particular relevance in the acid and possibly P-fixing Ferralsols of the region.

The current study determined only the partial N and P balances at field scale and not complete balances as assessed elsewhere (Van den Bosch et al., 1998). However, the presented partial balances are seen to provide useful indications regarding possible nutrient mining or soil fertility build-up. Thus, the application of mineral fertilizer resulted in negative N balances in the Nitisol as mineral N strongly enhanced maize productivity and possibly stimulated the co-mineralization of native soil N (Diwani, 2009), as also apparent from the high N use efficiencies. This implies that the amount of N supplied by mineral fertilizer was probably not sufficient to meet the crop N demand (Wang et al., 2010) and may need to be supplemented further from mineral sources. While mineral N fertilizers in the present study were more efficiently used than organic N source, the rate of application will need to be better matched with crop demand to avoid excess accumulation in the soil thereby increasing the risk of N losses (Becker et al., 1994). In contrast to N, the P balances were largely positive with mineral fertilizer use, suggesting that the amount of P applied exceeded the crop P demand. However, there is evidence that at P application rates of 100 kg ha^{-1} the residual P benefits may persist for several cropping seasons depending on the environmental conditions (Tisdale et al., 1993). Again in contrast to N, the efficiency of P use by maize was more with organic than with mineral sources, suggesting that a combined application of mineral and organic N and P sources may be the most effective strategy to build soil fertility, enhance nutrient availability and stimulate their use efficiency by maize. However, the effectiveness of any of the discussed strategies appears to be highly soil type-specific, supporting the need for site-specific nutrient management and technology targeting in Western Kenya.

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