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Maize productivity dynamics in response to mineral nutrient additions and legacy organic soil inputs of contrasting quality

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ABSTRACT

Residual effects of organic inputs of contrasting quality on maize productivity were investigated as a function of soil degradation in the highlands of western Kenya. Tithonia (*Tithonia diversifolia* (Hemsl.) A. Gray) green manure, cypress sawdust (*Cupressus lusitanica* Mill.), and biochar made from eucalyptus wood (*Eucalyptus saligna* Sm.) were applied at a rate of 6 t C ha^{-1} for three cropping seasons, both with and without mineral fertilizer additions (120 kg N ha^{-1}, 100 kg K ha^{-1}, 100 kg P ha^{-1}). Maize grain yield was monitored for six years beyond the initial organic matter additions. During the years when amendments were added, tithonia applications resulted in the greatest yield increases, between 153 and 183% more than the unamended control in comparison to increases by136% with biochar and by 107% with sawdust additions. In contrast to application of tithonia, peak yields with sawdust or biochar in most cases occurred 1–2 years after additions had ended. Yet during the same period, yields in fields that had previously received tithonia were on average still 71% of peak yields. Four years later, yields declined to between 28 and 22% of peak yields, whereas yields after biochar and sawdust applications declined to between 57 and 25% of peak values. Six years after organic matter additions ended, maize yields were not significantly different irrespective of additions of the quality of organic amendments. The data indicate that yield responds in the short-term to input quality and specifically the amount of applied N; while the residual effects of organic matter additions on yield dynamics may relate more to legacy effects of high crop residue return, input C quality and increasing soil C.

1. Introduction

Integrated soil fertility management programs (ISFM) have been recommended to sustainably intensify agricultural productivity through a combination of available organic resources and synthetic fertilizers (Vanlauwe et al., 2010), because agronomic productivity is tied to both the nutrient and organic carbon (OC) content of the soil (Chivenge et al., 2010; Kimetu et al., 2008; Ngoze et al., 2008; Six et al., 2002). In tropical soil degraded of OC, nutrients supplied by synthetic fertilizers alone often have low nutrient use efficiencies (Baligar and Bennett, 1986). In these soils the addition of organic residues in conjunction with inorganic nutrient sources results in greater agricultural yields than the application of inorganic fertilizers alone (Chivenge et al., 2009; Gentile et al., 2011; Kimetu et al., 2008). However, in the short term, the magnitude and direction (positive or negative) of yield response is dependent on residue quality (Gentile et al., 2011; Palm et al., 2001). In the long-term, residue quality also affects soil OC sequestration and maintenance of soil fertility (Chivenge et al., 2009; Kimetu et al., 2008).

The incorporation of low-quality organic residues into the soil can result in yield depressions in the short-term due to N immobilization, while in the long-term yields may increase once the OC has been microbially stabilized (Chivenge et al., 2010). Possible mechanisms for long-term yield improvements may include greater plant nutrition through improved cation retention, improvements in soil water retention, or beneficial alterations in the soil micro and macrobiota (Vanlauwe et al., 2001). High-quality organic residues that decompose rapidly have been shown to improve agricultural productivity in the short-term which is mainly attributed to higher amounts of nutrient additions, primarily N (Gachengo et al., 1999; Jama et al., 2000). Since these residues mineralize very quickly, and

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most of the N is released within a few weeks (Palm and Sanchez, 1991; Constantinides and Fownes, 1994).

In addition to the complexity of integrating inorganic and organic amendments, different soil fertility levels dictate the success of a particular strategy. Traditional land clearing followed by intensive agricultural practices is initially successful, even without inputs, due to inherent soil fertility built up over centuries under native vegetation (Murty et al., 2002). This soil fertility and the corresponding high crop yields are transitory, and soil fertility decreases rapidly during the initial years of cultivation after clearing from natural vegetation (Juo et al., 1995; Lehenih et al., 2005; Kimetu et al., 2008; Ngoze et al., 2008). The stage of soil degradation at which organic or inorganic additions are needed to maintain soil fertility is not well known.

When addressing soil fertility restoration for the long-term, organic matter additions should not necessarily be optimized for the greatest total nutrient additions, but rather optimize the build up of soil organic matter (SOM) and the associated soil biological, chemical, and physical changes (Lal, 2006). While additions of low-quality organic residues can result in N immobilization in the short-term (Palm et al., 1997) as discussed above, in the long-term they can lead to the build-up of SOM and improve plant nutrition. Increasing the stocks of SOM may, under many soil conditions, be the only way to sustainably restore soil fertility in the tropics (Lal, 2006). Kapkiyai et al. (1999) demonstrated that maize yields increased by 234 kg ha^{-1} for every tonne of conserved OC per hectare through soil management practices, and maize grain yield was found to increase linearly with increases in soil OC (SOC) (Lal, 1981).

Recent studies have demonstrated that biochar has the potential to improve soil fertility with particular efficacy for soils of the humid tropics (Glaser et al., 2002; Steiner et al., 2007; Major et al., 2010). Many plant residue-based biochars would be considered as being a low quality organic input with a C:N ratio generally >30 (Ippolito et al., 2015). However, the OC in biochar is in a form that is regarded as unavailable to short-term microbial mineralization (Lehmann et al., 2015) and, depending on production conditions, does not result in N immobilization (DeLuca et al., 2015). Similar to other forms of SOC, biochar has chemically active surfaces and when applied to the soil has resulted in physicochemical (Cheng et al., 2008; Liang et al., 2006), microbial (Thies et al., 2015; Warnock et al., 2007) and physical (Glaser et al., 2002) changes that can be beneficial to agricultural productivity.

Relative to other forms of organic residues, biochar is highly persistent in soil (Lehmann et al., 2015). From a soil fertility perspective, a single application of biochar to the soil may potentially enhance agricultural productivity for the long-term. However, there are no direct studies quantifying the long-term effects of biochar application on soil fertility and the interaction with inorganic fertilizer application relative to other forms of soil applied organic residues.

The objectives of this study were to quantify maize yield dynamics as a result of residual effects of the application of organic materials of contrasting quality along a gradient of soil fertility and to assess the interactive effects of fertilizer additions in conjunction with the organic residue additions along this same gradient.

2. Methods

2.1. Site description

The study site was located in the Nandi and Vihiga counties of western Kenya (34°94′23″ E Lat.; 00°13′44″ N Long.) at altitudes between 1542 and 1837 m above sea level. The rainfall pattern is bimodal with the main rainy season (long-rains) falling between March and August followed by a shorter rainy season (short-rains) falling between August and December. Mean annual precipitation for the area is around 2000 mm. The measured rainfall from two collection centers in the project area is presented in Table 1. Mean annual air temperature is 19 °C with a range of mean daily temperatures of 16–31 °C. The native vegetation is tropical highland rainforest and represents the eastern most extension of the Guineo-Congolian rainforest (Wass, 1995).

Table 1
Rainfall (mm) data from two locations adjacent to the experimental farms. Data is for the long-rain growing season and the yearly total.

	Forest station		Tea estate	
Year	Long-rain	Year total	Long-rain	Year total
2005	1276	1712	1738	2486
2006	1163	2141	1163	1712
2007	1163	1712	1397	2150
2008	1142	1686	1493	1936
2009	905	1565	982	1684
2010	1257	2117	1614	2146
2011	1152	2002	–	–
2012	844	1741	–	–

At this location a chronosequence of land conversion and soil fertility decline was established (Kinyangi, 2008). Chronosequences can be a practical method to assess soil fertility degradation and restoration dynamics in a relatively short time frame (Stevens and Walker, 1970; Hugget, 1998; Kimetu et al., 2008). As time progresses from conversion of the native vegetation, SOC, soil nutrients, and crop productivity exponentially decline (Ngoze et al., 2008).

The selected fields are located on farms converted in the year 1900 to land cleared as recently as 2002. A subset of 27 farms from this chronosequence was chosen that encompass approximately 60 linear km of distance; the most recent conversions and up to land converted in the 1950s were located within an area of 10 km^2 and the field converted before the 1950s were located at a distance of between 10 and 60 km from the younger sites (Kimetu et al., 2008; Ngoze et al., 2008). The chronosequence is located on humic Acrisols derived from granite basalt and humic Nitisols derived from biotite gneiss (Sombroek et al., 1982). The subset of farms on heavy-textured soil was chosen for this study and is texturally homogenous between experimental sites and the remaining forest (Kimetu et al., 2008; Ngoze et al., 2008). Time since conversion was determined based on Landsat imagery, private interviews, and official records (Kinyangi, 2008). Historically, the farms had received little inorganic fertilizer of between 40 kg N ha^{-1} year^{-1} and 8 kg P ha^{-1} year^{-1} (Recha et al., 2013) and have been primarily cropped to maize (*Zea mays* L.) and other cereals (e.g., finger millet, *Eleusine coracana* (L.) Gaertn.) since clearing (Crowley and Carter, 2000). The initial soil properties of the investigated farms are shown in Supplementary Tables S1 and S2.

2.2. Treatment applications

Beginning in 2005, organic inputs of contrasting quality were applied to sub-plots on the farms converted circa 1900, 1925, 1950, 1970, 1985, and 2000 (Kimetu et al., 2008). Leaves of *Tithonia diversifolia* (Hemsl.) A. Gray (tithonia), biochar, and sawdust were applied at the rate of 6 t C ha^{-1} for three consecutive seasons (2005 long-rains, 2005 short-rains, and 2006 long rains). Biochar was produced from *Eucalyptus saligna* Sm. wood using the traditional earthen kiln method at temperatures of approximately 400–500 °C. Sawdust was collected from a local saw-mill and was composed of primarily cypress wood (*Cupressus lusitanica* Mill.) (detailed properties in Kimetu et al., 2008; and Supplementary Table S3). One set of these plots received a complete fertilizer (N, P, K) applica-

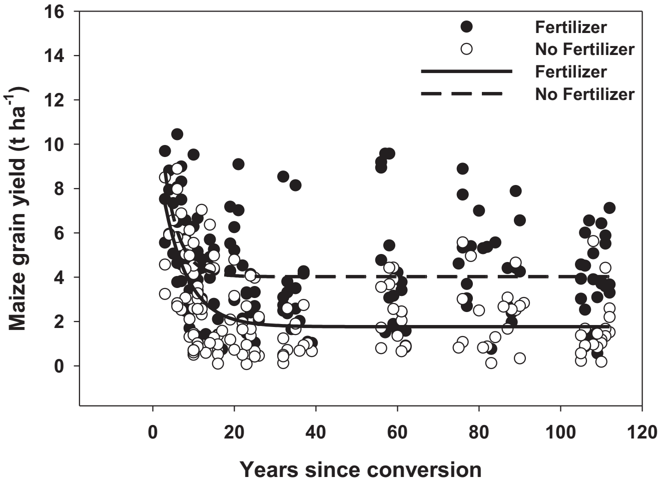

Fig. 1. Grain yield response to fertilizer additions as a function of land conversion age and soil fertility without organic amendments. Fertilizer year = $1.8 + 9.1e^{-0.17x}$; $r^2 = 0.30$; standard error of the estimate = 1.99. No fertilizer $y = 4.0 + 11.1e^{-0.28x}$; $r^2 = 0.13$; standard error of the estimate = 2.35. Year = 2005–2012.

tion in addition to the organic amendments (plot size 4 m by 4.5 m) in all years, while the other set received only P and K (plot size 2 m by 2.25 m) for the planting years 2005–2008, and from 2009 no inorganic fertilizer of any kind, in addition to the initial organic amendments described above.

These plots with organic amendments were compared to plots without organic additions (plot size 2 m by 2.25 m), in three variations: (i) full NPK fertilization; (ii) only P and K during 2005–2008 and no fertilizer since 2009; and (iii) a plot chosen at random from the farmer-managed land (FP).

The fertilizer for any of the treatments was a mixture of urea, triple super phosphate, and muriate of potash applied at 120 kg N ha^{-1}, 100 kg P ha^{-1}, and 100 kg K ha^{-1}. A completely randomized block design was used with three replicated farms per conversion age, and one replicate per farm. All of the P and K was broadcast applied at planting, while one third of the N was broadcast applied at planting and two thirds broadcast applied approximately six weeks after planting. Maize (Hybrid 614, Kenya Seed Company, P.O. Box 553-30200, Kitale, Kenya) was planted with distances of 0.75 m between rows and 0.25 m within rows. Weeding was performed using hand hoes six weeks after planting and again before silking.

Maize grain and stover yields were determined for all plots at the end of the growing season when the majority of plants had reached physiological maturity. Yields were measured on subplots of 3 m by 1.5 m and 1 m by 2.25 m (for plots with and without N and with and without organic amendments, respectively) to avoid edge effects. Total wet biomass and total wet cob weight was measured in the field with a resolution of 0.1 g. A subsample of stover and cobs was taken and dried at 60 °C to constant weight. These samples were used to correct for oven-dry total biomass and grain weights.

2.3. Greenhouse trial

In August of 2013 a greenhouse trial was established to evaluate any potential micronutrient deficiencies that were not explicitly examined in the field trials. Soil was collected between January and April of 2013 from the fertilized tithonia, biochar, sawdust, and control plots outlined above. The plots were located in the villages of Kapkarer (converted in 1922), Kiptaruswo (1973), Bonjoge/Kereri (1986), Siksik (2000), and Koibem (2002). The soil was air-dried and passed through a 2-mm sieve. The soil was then added to 0.23-m diameter 10 L plastic pots with five replicates. Nitrogen fertilizer was applied in three rates, 80, 120, and 160 kg ha^{-1}, in comparison to an unfertilized control. Granulated urea was used as the N source and was applied on a per-pot basis at the equivalent rates of 0, 0.7, 1.10, and 1.4 g pot^{-1}, respectively. All pots received 20.4 g pot^{-1} of triple super phosphate (100 kg P ha^{-1}, corresponding to the field trial rate), 0.82 g pot^{-1} of muriate of potash (100 kg K ha^{-1}, corresponding to the field trial rate), 0.11 g pot^{-1} $CaCl_2$, 0.02 pot^{-1} $MgSO_4$, 0.006 g pot^{-1} MnO_2, 0.016 g pot^{-1} $CuSO_4$, 0.005 g pot^{-1} ZnO, and 0.02 g pot^{-1} NaB.

Three seeds of the hybrid maize variety 614 (Kenya Seed Co., P.O. Box 553-30200 Kitale, Kenya) were planted per pot and thinned to 1 plant per pot one week after planting. A 10-mm layer of coarse quartz gravel was placed on the soil surface after planting. The pots were then watered and maintained at field capacity, determined gravimetrically, for the duration of the experiment. The pots were planted on 6, August, 2013 and harvested on 9, September, 2013. At harvest the plant shoots were separated from the roots, and dried to constant weight at 60 °C.

2.4. Agronomic efficiency and statistical analyses

Agronomic efficiency was calculated based on Vanlauwe et al. (2010) and the following equation [Eq. (1)]:

$$\mathrm{AE}\left(\mathrm{kg\ \ ha^{-1}}\right) = \frac{\mathrm{YF}-\mathrm{YC}}{F_{\mathrm{appl}}} \tag{1}$$

where YF is the grain yield in kg ha^{-1} from fertilized plots, YC is the grain yield in kg ha^{-1} from the unfertilized plots, and F_{appl} is the amount of total fertilizer mass fertilizer applied in kg ha^{-1}. Organic amendments were not included in this calculation.

Statistical analyses were calculated using analysis of variance, linear or non-linear regressions (JMP, SAS Institute, Cary, NC). All procedures were performed at $P < 0.05$, unless otherwise indicated.

3. Results

3.1. Maize grain yield

As land conversion age increased, maize grain yields decreased following an exponential decay curve (Fig. 1). Average maize grain yields within five years from forest conversion were 5.6 t ha^{-1} with fertilization and 4.0 t ha^{-1} without fertilization ($P = 0.068$). Extrapolation to the first year using the exponential function predicts yields of 11.6 t ha^{-1} with fertilization, and 8.3 t ha^{-1} without fertilization. Maize grain yields with and without fertilization fell by 18% to 4.6 t ha^{-1} and 28% to 2.9 t ha^{-1} from 5 to 15 years from conversion ($P = 0.030$), respectively. Twenty to 100 years after cultivation, maize grain yields stabilized at 3.9 (70% of yield at 5 years) and 1.9 (48% of yield at 5 years) t ha^{-1} ($P = 0.0001$). However, there was considerable variability in grain yields response to fertilization.

Clear long-term trends appeared as a result of organic input with increases during the three seasons with applications (long-rains of 2005, short-rains of 2005, and the long-rains of 2006, indicated by arrows in Fig. 2) and subsequent decreases. Without fertilizer additions, the yield increases with tithonia were much more pronounced than when tithonia was added together with fertilizer (Fig. 2). Similarly, in old conversions with poorer soils, additions of tithonia were more effective than in young conversions with more productive soils, relative to the unamended controls. Total crop yields in the seasons with tithonia amendments ranged from 6 to 9 t ha^{-1} in fertilized young conversion fields, similar to those in unfertilized old conversion fields (Fig. 2).

Grain yield increased from about 6 t ha^{-1} following the first addition of tithonia to 7–8 t ha^{-1} in the year following the last addition, irrespective of inorganic fertilization. Five years after additions

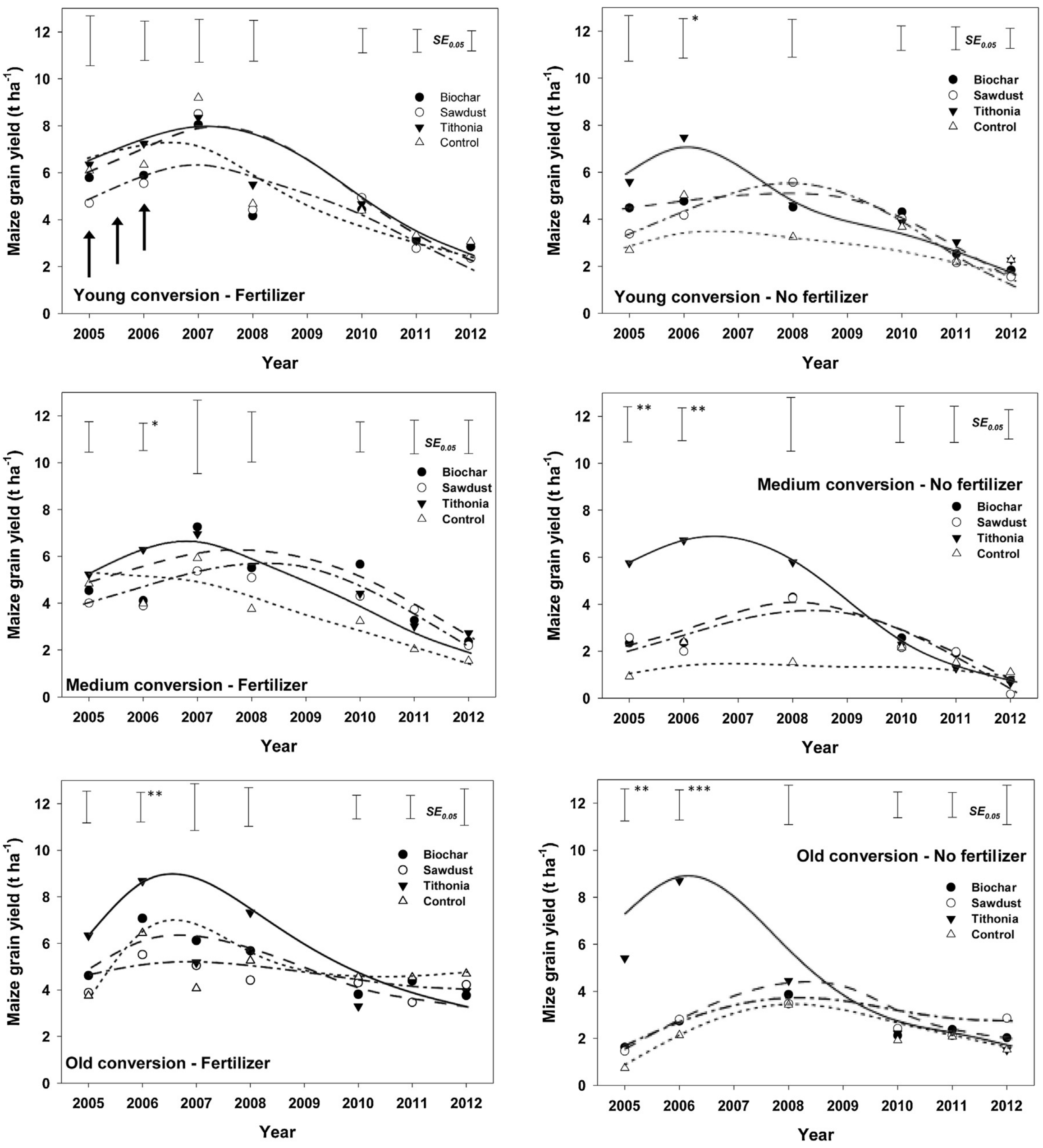

Fig. 2. Long-term yield dynamics following the additions of organic inputs of contrasting quality and the residual effects after cessation of input additions on young, medium and old agricultural conversion soil. Organic input additions occurred in 2005 and 2006 only (arrows). Bars represent standard error ($P<0.05$, $N=9$), *indicates significant P-value 0.05–0.01, **indicates significant P-value 0.01–0.001, ***indicates significant P-value <0.0001.

ceased, maize grain yield declined to 2–4 t ha^{-1} with fertilization, and to 0.7–2 t ha^{-1} without fertilization.

With fertilization, maize grain yield with biochar additions increased from 4.5–5.8 t ha^{-1} in the first year of additions to 6–8 t ha^{-1} one year after the final addition, irrespective of conversion. Seven years after the initial addition of biochar (or five years after the additions ceased) maize grain yield was 3–4 t ha^{-1}. Without fertilization, however, yields hardly increased during the period of biochar application, and in the medium and older conversions only two years after additions had stopped from 1.5–2.2 to 4 t ha^{-1}.

After the initial application of sawdust, maize grain yields with fertilization increased from 4 to 5 t ha^{-1} to 8.5 t ha^{-1} one year after the final addition in young conversions, but to only about 5 t ha^{-1} in medium and old conversions. Maize grain yields decreased to 2–4 t ha^{-1} seven years after initial application of sawdust. Without fertilization, highest yields with sawdust were observed only two years after applications had stopped, with increases from initially 1.5–3 t ha^{-1} to 3–5 t ha^{-1}, irrespective of conversion age.

3.2. Grain yield ratio

The grain yield ratio ranged from 0.73 to 5.3 and did not differ significantly as a result of any of the organic amendments when fertilizer was added (Fig. 3). Without fertilization, this was also observed in the young conversion farms, with ratios of 0.6–3.5. Without fertilization in the medium and old conversion farms the grain yield ratios were different from the rest of the fields: the grain yield ratios after applications of tithonia decreased from 12 to 16 in the first year the amendments were applied to values comparable to the rest of the fields at four years after the initial amendment application (two years after the final application). In the final year

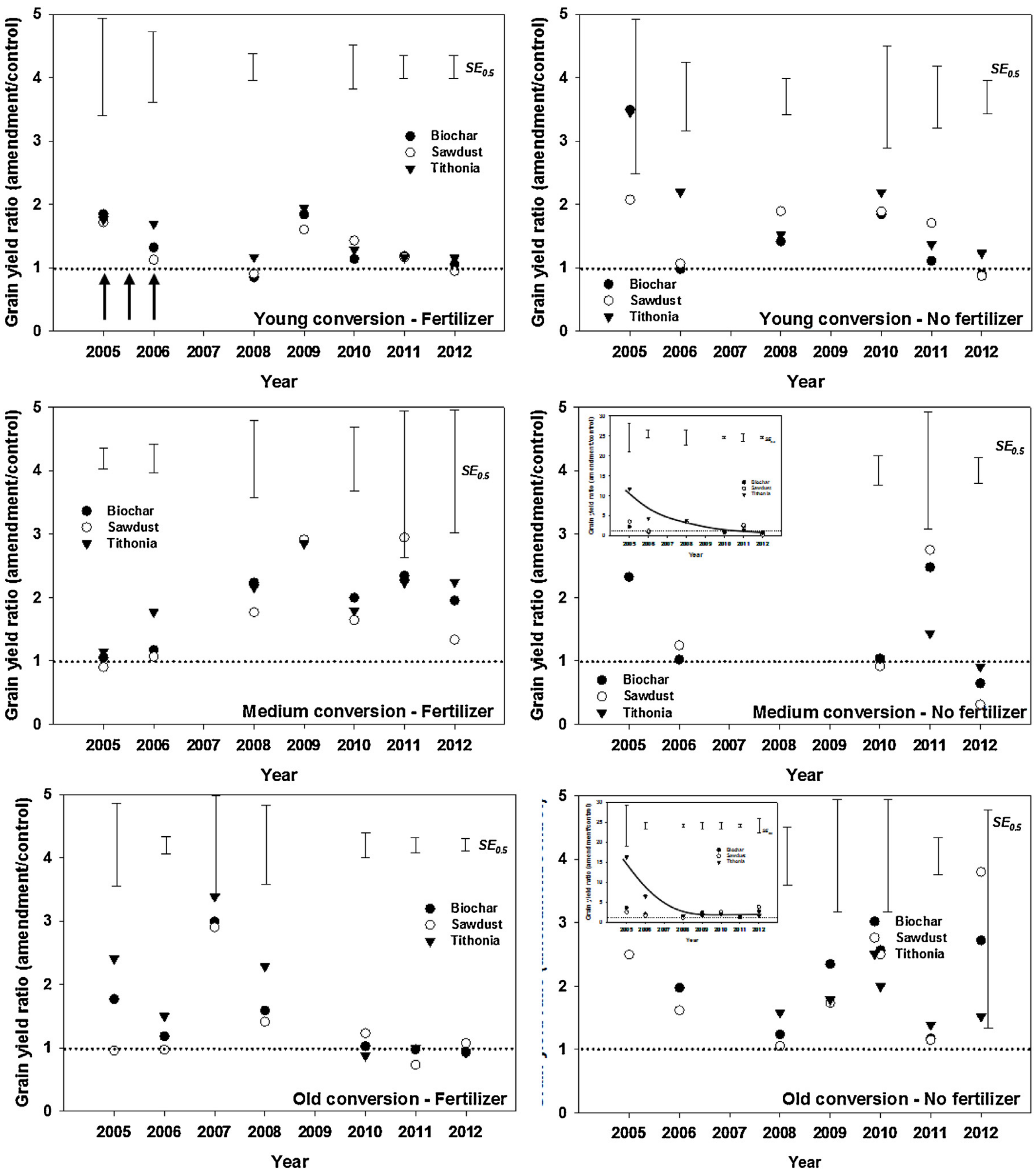

Fig. 3. Residual effects of applications of organic amendments of contrasting quality on maize grain yield in young, medium and old agricultural conversion soils. *Y*-axis is the ratio of maize grain yield (t ha^{-1}) of the organic amendment to the control. Curves are splines fitted to the data for tithonia. Organic input additions occurred in 2005 and 2006 only (arrows). Bars represent standard error ($P < 0.05$, $N = 9$), * indicates significant *P*-value 0.05-0.01, **indicates significant *P*-value 0.01–0.001, ***indicates significant *P*-value <0.0001.

of the study (seven years after the initial tithonia amendment application, five years after the final application) the grain yield ratios were 0.9 and 1.5, respectively. Over this same time period the grain yield ratios after biochar or sawdust additions decreased from 2.3 and 3.6 to and 0.6 and 0.9, respectively, in the medium conversion farms, but remained constant from 3.6 and 2.5 to and 2.7 and 3.8 in the old conversion farms.

3.3. Agronomic use efficiency

Within each individual organic amendment, agronomic use efficiency (AE) was between 200 and 900% greater ($P < 0.0001$) in the old and medium conversion farms than the young farms (Table 2). AE did not differ between the old and medium conversion farms. AE was 62% greater ($P = 0.0007$) with tithonia than sawdust and the control. AE with biochar additions was not significantly different to any other addition.

3.4. Micronutrient fertilization

No significant differences in maize biomass production were found following micronutrient addition between organic amendments in any of the soils (Table 3). Maize biomass was only significantly different between N application rates in the old conversion soils.

Table 2
Agronomic use efficiencies of maize grain yield per kg of fertilizer applied. Different letters indicate significant differences, no letters are shown when main effect is not significant (Tukey's HSD, $P < 0.05$). Within conversion group $N = 33$, for all years $N = 138$.

Treatment	Conversion group	*AE* (kg grain kg^{-1} total fertilizer)		*AE* (kg grain kg^{-1} total fertilizer)
Tithonia			All years	0.022A
	Old	0.030a		
	Medium	0.030a		
	Young	0.010b		
	P-value	<0.0001		
Biochar			All years	0.017AB
	Old	0.024 a		
	Medium	0.023 a		
	Young	0.006 b		
	P-value	<0.0001		
Sawdust			All years	0.014B
	Old	0.021a		
	Medium	0.020a		
	Young	0.002b		
	P-value	<0.0001		
Control			All years	0.013B
	Old	0.020a		
	Medium	0.015a		
	Young	0.005b		
	P-value	0.0003	*P*-value	0.0007

4. Discussion

4.1. Yield responses to organic amendments

Organic input quality affected both the immediate and residual maize yield dynamics. In the short-term, the greater relative increase in yield response after tithonia additions, not seen to the same magnitude with the other amendments, is mostly ascribed to substantially greater N addition with tithonia. Annual application rates of tithonia-derived N were 1294 kg ha^{-1} year^{-1} while annual application rates of sawdust and biochar-derived N were 25 and 31 kg ha^{-1} year^{-1}, respectively (Kimetu et al., 2008). As the C:N ratio of sawdust was 446, there was a strong likelihood N immobilization depressed yields in the short-term (the first 2–3 years). Very little is known about the availability of biochar-derived N (Ippolito et al., 2015; Clough et al., 2013; Wang et al., 2012), but it is likely to be very low even with plant residue-derived biochar containing a high proportion of N (Gaskin et al., 2010). It is possible that the majority of N found in biochar is in a form that is unavailable to plants (Knicker, 2010), at least in the short-term (Bridle and Pritchard, 2004; Clough et al., 2013). As previous studies had found N to be the most limiting nutrient in the studied soils (Ngoze et al., 2008), this large difference in N application rates would have profound effects on maize yields.

4.2. Residual effects of organic amendments

After organic inputs stopped, maize yields did in general not decline immediately, but in some instances even peaked after additions had ended. Jama et al. (2000) found that half of the OC added to the soil from tithonia mineralized in two weeks, and 76% after two years (Kimetu and Lehmann, 2010). Therefore, the observed residual effects of tithonia 1–2 years after additions, are unlikely a result of the remaining OC or N from the green manure. It is more likely that the significant increase in crop growth and therefore crop residue return created a legacy effect that carried over to subsequent seasons.

In contrast, yield response to the more persistent materials (biochar and sawdust) even peaked approximately three years after initial application before maize yields for all amendments converged in 2012. With sawdust, this trend is most likely explained by N immobilization in the short term followed by a stabilization of the sawdust-derived SOM after two years followed by renewed mineralization of the SOM. Steady yield declines over the eight-year study period in the young conversions, despite the initial substantial organic matter and nutrient additions, suggest high input levels of organic matter must be sustained in order to prevent soil fertility decline.

Table 3
Maize biomass response to micronutrient fertilization in plants grown in pots. Different letters indicate significant differences, no letters are shown when main effect is not significant (Tukey's HSD, $P < 0.05$, $N = 5$).

		Treatment				
Conversion	Fertilizer (kg N ha^{-1})	Biochar	Tithonia	Sawdust	Control	*p*-Value
Young conversion Farms	80	–	–	–	7.65 ± 0.76	–
	120	9.44 ± 0.97	7.82 ± 0.79	9.30 ± 0.90	6.26 ± 0.88	0.0466
	160	–	–	–	5.53 ± 0.82	–
	P-value	–	–	–	0.1894	–
Medium conversion Farms	80	–	–	–	6.25 ± 0.76	–
	120	6.65 ± 0.78	5.93 ± 0.52	5.85 ± 0.61	6.63 ± 0.87	0.7687
	160	–	–	–	6.41 ± 0.86	–
	P-value	–	–	–	0.9475	–
Old conversion Farms	80	–	–	–	9.53 ± 1.00 AB	–
	120	10.81 ± 1.28	10.35 ± 1.28	11.15 ± 1.33	11.36 ± 1.24 A	0.8940
	160	–	–	–	8.37 ± 1.12 B	–
	P-value	–	–	–	0.0570	–

While biochar additions did not increase maize yields above the control to the same extent as tithonia, biochar additions maintained a relatively consistent yield improvement for the duration of the study period. Since N was not applied in appreciable quantities with biochar as mentioned above, other crop-limiting soil properties must have been altered by biochar additions, which could not be identified in this experiment. The greatest increases in crop production several years after additions had ended can be explained by the persistence of biochar. Two years after additions, 84% of the added biochar C was still found in the soil (Kimetu and Lehmann, 2010), and biochars with H/C ratios of less than 0.4 are expected to have mean residence times of greater than 1000 years with more than 70% remaining after 100 years (Lehmann et al., 2015).

4.3. Fertilizer response

The potential for soil fertility amelioration was greater on the older farms and more degraded soils (Solomon et al., 2007; Ngoze et al., 2008; Moebius-Clune et al., 2011), both in respect to nutrient constraints (i.e., N response) and soil physical constraints (e.g., infiltration, available water-holding capacity). Previous studies on these soils found bulk density increased with conversion age (Kinyangi, 2008). In addition, Moebius-Clune et al. (2011) found that as conversion age increased, available water-holding capacity and water-stable aggregation decreased. This response was directly correlated to SOC contents (Kinyangi, 2008, Moebius-Clune et al., 2011). As a result, maize on older farms experienced proportionally greater water stress (Supplementary Fig. S1). These constraints were largely absent in the younger conversion farms, which showed no differences between the various organic treatments, either fertilized or unfertilized (Fig. 1).

Yield response to inorganic fertilizer varied depending on the conversion age, and maize yields only responded significantly to fertilizer application ten years after conversion, whereas yield responses to tithonia amendments were found at all conversion ages. In addition the variability in yield response increased with conversion age. On average, yields with and without fertilizer in the older conversion farms ranged between 50% and 25% of the yields from the youngest farms, respectively. These yield and fertilizer response dynamics follow closely the concept of non-responsive soils outlined in Vanlauwe et al. (2010). In the young farms, the relatively high native soil fertility resulted in no yield gain and poor AE. In older farms AE and nutrient use efficiency significantly improved as the native N, P, and K levels (nutrients supplied by the fertilizer) became deficient. Stocks of soil N at the sites recently converted from forest were found to be 7.2 t N ha^{-1} in the topsoil (Kinyangi, 2008) with a mineralization rate of 511 kg N ha^{-1} year^{-1} (Ngoze, 2008); at this level of soil N mineralization the 120 kg N ha^{-1} added as mineral fertilizer may not improve plant N nutrition. However, increased variability in the response to the fertilizer and the equivalent yield increases with some of the nutrient-poor organic additions such as biochar or sawdust suggests other soil chemical and biological properties not addressed by the nutrient additions may have become limiting.

Variations in yield improvements as a result of inorganic fertilizer additions were largely equivalent (biochar and sawdust) or significantly lower (tithonia) than those in response to organic additions. However, only in the case of tithonia were absolute increases much larger than those in response to inorganic fertilization, even 1–2 years after additions ended, despite the rapid mineralization of tithonia residues discussed earlier. The equivalent or even greater increase in crop productivity with biochar or sawdust compared with inorganic fertilizer in highly fertile soils may be explained by a greater nutrient use efficiency and lower N losses as observed in other studies (Lehmann et al., 2003; Laird et al., 2010; Güereña et al., 2013). That this was not found in soil with lower fertility such as those under long-term cropping is due to the lack of nutrients that may only be compensated by additions of either inorganic fertilizers or nutrient-rich organic residues.

5. Conclusion

Sustainable land management in degraded soils of SSA and other tropical regions must include a focus on improving the SOC status in conjunction with nutrient additions through commercial mineral fertilizers and/or organic amendments. This study indicates that a critical period exists in the first 10 years after land conversion. In this window substantial additions of SOM are required in order to maintain soil fertility, even though restoration with organic amendments was possible on degraded soils 100 years after land-use conversion. High-quality and rapidly mineralizing materials are effective even 1–2 years after additions end, but soil fertility rapidly declines thereafter. In the most degraded soils, inorganic fertilizers alone are not sufficient to restore productivity and even in highly fertile soils, organic amendments are superior if applied in large quantities. Even though nutrient-poor and more persistent organic amendments show longer-lasting crop yield improvements, nutrients have to be supplied by other means and optimizing the combination of nutrient supply and organic matter enhancement remain a research priority. Long-term residual effects of rapidly and slowly decomposing organic amendments differ significantly over the period studied here but may further change over even longer periods of time. Future efforts should also explore the residual effects of a combination of these materials in addition to interactions with inorganic fertilizers.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.fcr.2015.12.017.

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