



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 by 136% 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.

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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

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.

Year	Forest station		Tea estate	
	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	–	–

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).

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 km² 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-

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