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Crop yield, plant nutrient uptake and soil physicochemical properties under organic soil amendments and nitrogen fertilization on Nitisols

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ABSTRACT

Sustaining soil fertility and enhancing food production on smallholder farms is a great challenge in sub-Saharan Africa. The effects of organic amendments and nitrogen fertilizer on soil physicochemical properties and barley yield were investigated in the central Ethiopian highlands. The treatments were factorial combinations of no organic amendment (control), 10 t ha^{-1} biochar only (B), 10 t ha^{-1} compost only (Com), 10 t Com ha^{-1} + 2 t B ha^{-1} and 10 t ha^{-1} co-composted biochar-compost (COMBI) as main plots, and five N fertilizer levels (0, 23, 46, 69 and 92 kg ha^{-1}) as sub-plots, with three replicates at two sites (Holetta and Robgebeya) both on Nitisols in the 2014 cropping season. Application of organic amendments and N fertilizer all significantly improved soil fertility and barley yield. The highest yield, chlorophyll content, number of productive tillers and nutrient uptake were obtained from the Com + B soil amendment at Holetta and from Com at Robgebeya. Mean grain yield responses of barley to the organic amendments were 30–49% at Holetta and 51–78% at Robgebeya, compared to the control. Fertilizer N significantly increased grain yield, chlorophyll content and N uptake at both locations. The highest grain yield obtained was at 69 kg N ha^{-1} at Holetta and at 92 kg ha^{-1} at Robgebeya. The organic amendment by N fertilizer interaction significantly influenced grain yield at both sites. Com + B and 69 kg N ha^{-1} addition resulted in the highest grain yield (5381 kg ha^{-1}) at Holetta, whereas Com and 92 kg N ha^{-1} resulted in the highest grain yield (4598 kg ha^{-1}) at Robgebeya. Organic amendments significantly improved soil properties through increases in soil water content, soil organic carbon (SOC), cation exchange capacity (CEC) and pH (0–20 cm depth). Addition of B, Com and B + Com increased SOC and CEC by 23–27% and 20–24% at Holetta and 26–34% and 19–23% at Robgebeya compared to their respective initial values. Soil pH increased from the initial value of 5.0 to 5.6 at Holetta and from 4.8 to 5.4 at Robgebeya at harvest due to biochar soil amendment. Grain yield was significantly correlated with total biomass, number of productive tillers, SOC and CEC. We conclude that application of organic amendments optimizes soil physicochemical properties and will help sustain barley yields in the Ethiopian highlands. The use of B, Com or Com + B may substantially reduce the amount of mineral fertilizer required for the sustainable production of barley in the long term.

1. Introduction

Poor soil fertility is a major constraint to agricultural productivity in the highlands of Ethiopia, where population and livestock pressure is high (Zelleke et al., 2010; Agegnehu et al., 2014a). Chemical fertilizer application has been limited to date, and improvement of agricultural productivity necessitates more than the application of chemical fertilizers alone. Core constraints include: topsoil erosion (rates estimated at 10–13 mm per annum on average); soil acidity covering ~40% of the country; soil salinity; a significant depletion of soil organic matter due to extensive use of biomass and manure as animal feed and fuel; depletion of macro and micro-nutrients, and declining soil physical properties (Zelleke et al., 2010; Regassa and Agegnehu, 2011; Agegnehu et al., 2014b). The problem is further exacerbated by widespread deforestation and a lack of land management strategies appropriate to specific soils, landscape and climate (Shiferaw and Holden, 2000; Zelleke et al., 2010).

Barley (*Hordeum vulgare* L.) is one of the main cereals cultivated in the highlands of Ethiopia, and yields are now seriously affected by low soil fertility. Barley is the fourth most important crop after maize, rice and wheat in terms of total world production, and it is also the major grain used for malting and brewing (FAO, 2013). It is also

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an important food grain and malting crop for subsistence farmers in the highlands of Ethiopia (Agegnehu et al., 2014a). It is predominantly grown from 2000 to 3500 m above sea level in Ethiopia (Mulatu and Lakew, 2011) and is nationally the fifth most important crop after tef (*Eragrostis tef*), maize, wheat and sorghum, covering an area of ~1.018 million ha but the national average yield is very low at 1.75 t ha^{-1} (CSA, 2013). Although there is a considerable potential for increased barley production, numerous factors limit yields (Mulatu and Lakew, 2011). The most important abiotic stresses include low soil fertility, low soil pH, poor soil drainage, drought and poor agronomic practices. Fertilizer use for barley production is the lowest among all the cereals, that is only 48.3% of the total area of land covered by barley compared to tef, wheat and maize receiving fertilizer on 59.7%, 69.1% and 56.3%, respectively (Mulatu and Lakew, 2011). Low barley yields can be attributed mainly to low soil pH (less than 5.5) and deficiency of nutrients, especially N and P, due to continuous cropping of cereals (Agegnehu et al., 2014a) and low levels of fertilizer application (Agegnehu et al., 2011). Plants grown on acidic soils may be limited by deficiencies of N, P, K, Ca, Mg, or Mo; toxicity of Al or Mn; reduced nutrient cycling; and reduced uptake of nutrients by plant roots and inhibition of root growth (Marschner, 2011). Soil acidity adversely affects morphological, physiological and biochemical processes in plants and thus N uptake and use efficiency (Fageria and Baligar, 2005; Marschner, 2011).

The supply of N is one of the main factors influencing barley production. The rate of N fertilizer application depends on the purpose for which barley is grown. When barley is grown for feed or food, it is desirable to apply fertilizer at higher rate than when it is grown for malting because grain protein content is not as critical in food barley as it is in malting barley (Jankovic and Ikanovic, 2011; Agegnehu et al., 2014a). In Ethiopia, where pH, SOC and N content of most soils are low, the N fertilizer rates applied for barley production range from 23 to 46 kg N ha^{-1}. Soils with low SOC contents have low crop yield and low use efficiency of added nutrients. Soil organic matter content and bulk density can be improved upon addition of organic wastes. Soil organic matter is vital for sustainable yields as it is able to retain water and nutrients, provide a habitat and energy for soil biota and improve soil structure (Lorenz et al., 2007; Lal, 2011). Land use change and farming practices have already led to a marked reduction in SOC, and with the increased temperatures expected SOC content is likely to fall further (Raich et al., 2002). Loss of SOC reduces soil fertility and further exacerbates climate change.

Biochar and compost have been proposed as soil amendments to increase SOC levels and soil fertility. Application of compost can increase soil pH, SOC and N contents, available P, K, Ca, Mg, Na and S and decreased bulk density (Courtney and Mullen, 2008; Fischer and Glaser, 2012; Agegnehu et al., 2016). Compost addition to soil has also been shown to increase yield of barley similarly to, or beyond the effects of mineral fertilizer application (Kimpinski et al., 2003). However, annual application of high doses of compost had an inhibitory effect on enzyme activity and barley yields (Marcote et al., 2001).

Biochar has two key properties: a high affinity for nutrients and water, reducing nutrient losses and offsite pollution from nutrient leaching. Unlike compost or manure, biochar has a half-life in soil of up to several centuries (Glaser et al., 2002; Lehmann, 2007). The application of biochar alone to barley has previously not shown any significant effect on yield, but had a significant interaction effect when applied with N fertilizer (Gathorne-Hardy et al., 2009). Other studies have indicated that the combined application of biochar with compost could lead to enhanced soil fertility, improved plant growth and C sequestration potential (Schulz and Glaser, 2012; Schulz et al., 2013). The combined application of compost and biochar on Dystric Cambisol using maize crop had a synergistic

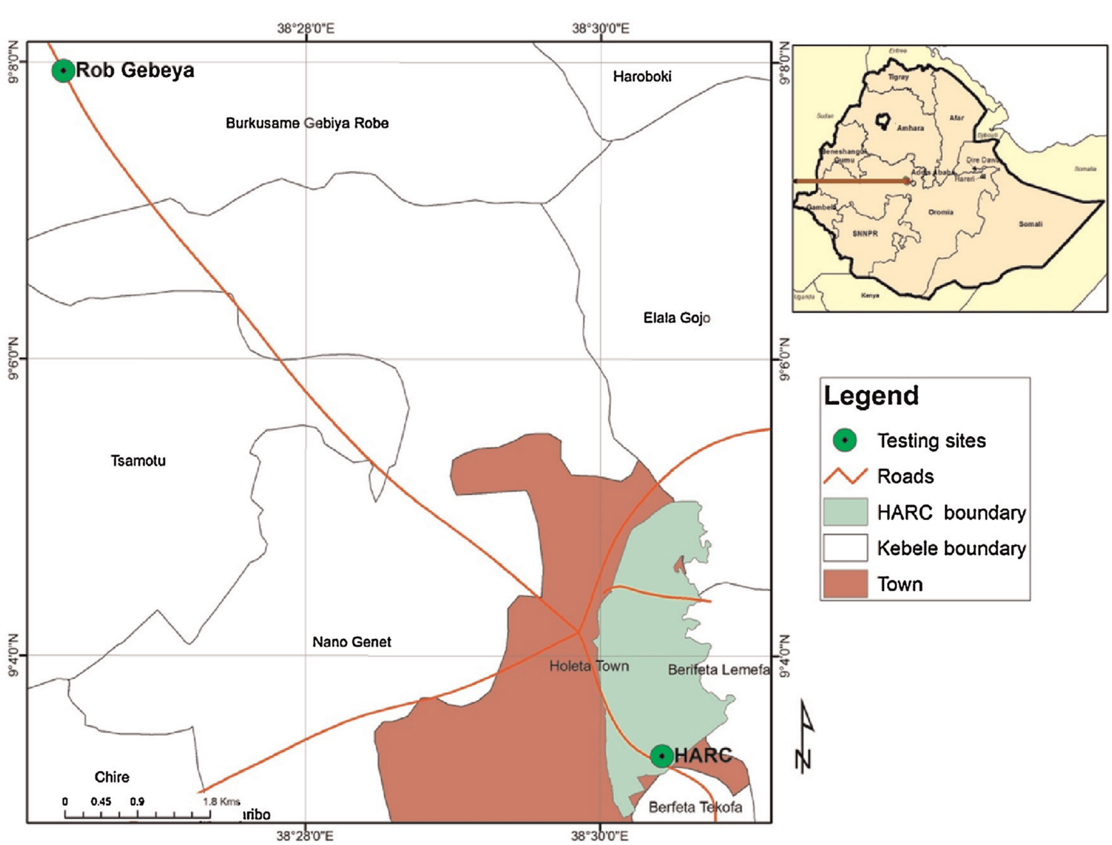

Fig. 1. Map of the experimental sites at Holetta Agricultural Research Center (HARC) and Rogebeya in the central highlands of Ethiopia.