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Benefits of biochar, compost and biochar–compost for soil quality, maize yield and greenhouse gas emissions in a tropical agricultural soil

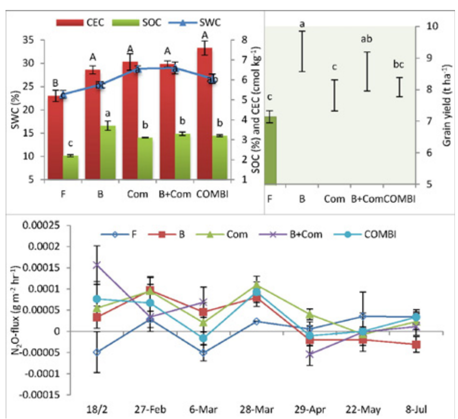
Getachew Agegnehu [a,*], Adrian M. Bass [b], Paul N. Nelson [a], Michael I. Bird [a]

[a] College of Science, Technology and Engineering, Centre for Tropical Environmental and Sustainability Science, James Cook University, PO Box 6811, Cairns, Queensland 4870, Australia
[b] Hawkesbury Institute for the Environment, University of Western Sydney, Science Road, Richmond, New South Wales 2753, Australia

HIGHLIGHTS

- Soil was amended with biochar, compost and their mixture at field level.
- Maize grain yield was significantly increased by 10–29% by organic amendments.
- Organic amendments significantly increased leaf chlorophyll and N and P content.
- Organic amendments significantly improved soil water content, OC, N, P and CEC.
- N_2O emission from biochar was the lowest over time compared to other treatments.

GRAPHICAL ABSTRACT



Grain yield, cation exchange capacity (CEC), soil organic carbon (SOC), soil water content (SWC) and N_2O emission as influenced by fertilizer (F), biochar (B), compost (Com), Com + B and co-composted biochar–compost (COMBI).

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ABSTRACT

Soil quality decline represents a significant constraint on the productivity and sustainability of agriculture in the tropics. In this study, the influence of biochar, compost and mixtures of the two on soil fertility, maize yield and greenhouse gas (GHG) emissions was investigated in a tropical Ferralsol. The treatments were: 1) control with business as usual fertilizer (F); 2) 10 t ha^{-1} biochar (B) + F; 3) 25 t ha^{-1} compost (Com) + F; 4) 2.5 t ha^{-1} B + 25 t ha^{-1} Com mixed on site + F; and 5) 25 t ha^{-1} co-composted biochar–compost (COMBI) + F. Total aboveground biomass and maize yield were significantly improved relative to the control for all organic amendments, with increases in grain yield between 10 and 29%. Some plant parameters such as leaf chlorophyll were significantly increased by the organic treatments. Significant differences were observed among treatments for the $\delta^{15}N$ and $\delta^{13}C$ contents of kernels. Soil physicochemical properties including soil water content (SWC), total soil organic carbon (SOC), total nitrogen (N), available phosphorus (P), nitrate-nitrogen (NO_3^--N), ammonium-nitrogen (NH_4^+-N), exchangeable cations and cation exchange capacity (CEC) were significantly increased by the organic amendments. Maize grain yield was correlated positively with total biomass, leaf chlorophyll, foliar N and P content, SOC and SWC. Emissions of CO_2 and N_2O were higher from the organic-amended soils than from the fertilizer-only control. However, N_2O emissions generally decreased over time for all treatments and emission from the biochar was lower compared to other treatments. Our study concludes that the biochar and biochar–compost-based soil management approaches can improve SOC, soil nutrient status and SWC, and maize yield and may help mitigate greenhouse gas emissions in certain systems.

* Corresponding author.

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1. Introduction

Soil nutrient depletion, declining agricultural productivity and anthropogenic climate change are threatening the sustainability of agricultural production in the tropics (Gruhn et al., 2000; Parry, 2007; Pender, 2009). The benefits of inorganic fertilizers have been widely demonstrated since the 'green revolution' (Vanlauwe et al., 2010), and have played a significant role in increasing agricultural production and productivity over the last half century (Gruhn et al., 2000). Shrinking land area per capita and declining soil quality have led to steady increases in fertilizer use. However, the application of inorganic fertilizer alone is not a sustainable solution for improving soil fertility and maintaining yields; rather, it has been widely realized that application of excessive inorganic fertilizer, especially nitrogen, may cause soil deterioration and other environmental problems owing to more rapid organic matter mineralization (Liu et al., 2010; Palm et al., 2001).

In most tropical environments, sustainable agriculture faces constraints due to low nutrient status and rapid mineralization of soil organic matter (Jenkinson et al., 1991; Zech et al., 1997). As a result, the cation exchange capacity (CEC) of the soils, the mineralogy of which is dominated by low-CEC clays, is further decreased. Under such conditions, the efficiency of mineral fertilizers is very low as mobile nutrients such as nitrate-nitrogen (NO_3^- N) or potassium (K^+) are readily leached from the topsoil during periods of high rainfall (Socolow, 1999). Additionally, costs of inorganic fertilizers can be prohibitive in developing countries (Sanchez, 2002). Consequently, nutrient deficiency is prevalent in many crop production systems of the tropics. Although the green revolution over the last four decades has fed the growing global population, some production practices have become increasingly unsustainable, environmentally damaging and unlikely to keep up with demand (Barrow, 2012). Thus, there is a need for a new approach: increased yields, reduced negative impacts, enhanced sustainability, with new approaches being accessible to subsistence farmers as well as commercial producers (Glaser, 2007; Lal, 2008; Sohi et al., 2010).

In recent years, application of biochar to soil has emerged as a strategy for sequestering carbon, reducing greenhouse gas (GHG) emissions and improving soil quality (Lehmann et al., 2006; Liang et al., 2014; Vaccari et al., 2011). Evidence shows that the application of biochar can play a significant role in improving SOC (Glaser et al., 2002), water holding capacity (Abel et al., 2013; Atkinson et al., 2010), soil aeration, increased soil base saturation, nutrient retention and availability, decreasing fertilizer needs and nutrient leaching (Laird, 2008; Lehmann et al., 2003; Steiner et al., 2007), stimulation of soil microbes, increased microbial biomass and activity (Thies and Rillig, 2009), enhancing crop growth and yield, reducing anthropogenic GHG fluxes and increasing carbon sequestration (Lal, 2011; Lehmann et al., 2006). Carbon sequestration in soil is favored for the additional reasons of improving soil quality and achieving sustainable use of natural resources (Lal, 2008; Lal, 2011).

Maize (*Zea mays* L.) is an important crop globally, being grown on a wide variety of soil types and in a wide range of climates. In Australia, 62,200 ha were planted with maize in 2010–2011 at an average yield of 6.0 t ha^{-1} (ABS, 2012). Under irrigation and with intensive fertilizer inputs yields of 15 t ha^{-1} or more are possible. The area that could potentially be planted to maize in northern Australia is considerably larger than currently utilized although water availability is a major constraint (Chauhan et al., 2013). The yield and quality of maize are affected by soil type, water availability and nutrition (Bossio et al., 2010; Chauhan et al., 2013). Maize responds positively to N, P and K inputs, with yield also increased by liming of acid soils (Aitken et al., 1998). In north Queensland, inputs up to 80 kg ha^{-1} N, 35 kg ha^{-1} P and 50 kg ha^{-1} K may be required for optimal yield, along with zinc (Zn), sulfur (S) and molybdenum (Mo) in some cases. Moisture deficit during growth can reduce leaf size and number, leading in turn to low grain yield through reduced capacity for photosynthesis. Lobell et al. (2013) recently noted the vulnerability of maize production globally to climate change and linked observed yield declines in the last two decades to more frequent exposure of crops to temperature extremes, which in turn imposes additional water stress on crops. Basso and Ritchie (2014) on the other hand, using the same data, concluded that soil moisture deficit has been directly responsible for observed yield declines.

There has been little work on the impact of organic amendments in combination with biochar on maize growth and yield. Lashari et al. (2015) found significant improvement in soil properties, plant performance and maize yield due to the use of manure composts with biochar and pyroligneous solution on a saline soil in China over a two year period, with beneficial impacts of increasing over time. Nur et al. (2014) demonstrated that maize biomass and yield were more than doubled over two crop cycles using compost and biochar in combination on a calcareous soil in Indonesia. Similarly promising results have been obtained from the use of compost-biochar combinations on low fertility soils in Laos (Mekuria et al., 2014). In contrast to the above studies on tropical soils, Lentz et al. (2014) found only small impacts of biochar–compost applications on maize in a temperate climate. However, in all the above cases, the use of biochar and compost alone and in combination generally improved soil characteristics. The emerging picture for biochar and compost amendment use under maize is one of potentially significant benefits on degraded soils in the tropics, both in terms of soils properties and maize yield, but lower benefits to yield in temperate environments. This general assessment is dependent in detail on interactions between biochar, soil, crop, climate and time. The aims of this study were, therefore, to test the hypotheses that application of biochar, compost and biochar–compost mixes 1) improves maize growth, yield and nutrient uptake, 2) enhances soil physicochemical properties, and 3) mitigates greenhouse gas emissions in an important maize-growing climate and soil type.

2. Materials and methods

2.1. Trial site description and soil analysis

The trial site was located at Tolga, north Queensland, Australia (17.2191°S 145.4713°E; 778 m asl). The soil is a dark reddish brown Ferralsol (IUSS Working Group WRB, 2007) or Red Ferrosol (Isbell, 1996) of the Tolga series (Malcolm et al., 1999) developed on Quaternary basalt, grading from light clay at 0–0.2 m depth to medium clay at 0.5–1.0 m depth. The mean annual precipitation is 1032 mm, and mean annual minimum and maximum temperatures are 17.1 and 27.3 °C, respectively (Walkamin Research Station: 17.1347°S; 145.4281°E; 594 m asl). Pre-planting soil samples were collected in December 2013 from depths of 0–30 cm and 30–100 cm from nine locations across the trial site. The locations were selected by dividing the trial area into a 3 m × 3 m grid and randomly selecting 3 sampling points within each of the 9 grid cells. One core was taken from each point, to a depth of 0–30 cm, and these samples were combined into one composite sample for each grid cell. One core of 30–100 cm depth was also taken from each grid cell using a vehicle mounted hydraulic corer. Soil samples were analyzed by SGS Pty Ltd., Cairns, Australia (0–30 cm) or Analytical Research Laboratories (ARL) Pty Ltd., Awatoto, New Zealand (30–100 cm). Soil water content (SWC) was measured at 0–12 cm depth using a Campbell Scientific Hydrosense II soil moisture probe at each sampling location. The gravimetric SWC of each sample was also measured. Soil profiles were described and classified from 50-mm diameter cores to approximately 1 m depth (one core at each trial site), according to NCST (2009).

Pre-planting physicochemical properties of the trial soil are shown in Table 1. This moderately acidic clay soil (0–30 cm) had a comparatively high organic matter content and moderate soil pH, exchangeable K and Cu, but low electrical conductivity (EC) and cation exchange capacity (CEC). Soil cores from 0 to 30 cm were taken in the row at the mid-season growth stage and after harvesting and analyzed as described above. SOC and total soil N contents were determined as for