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Soil properties, greenhouse gas emissions and crop yield under compost, biochar and co-composted biochar in two tropical agronomic systems

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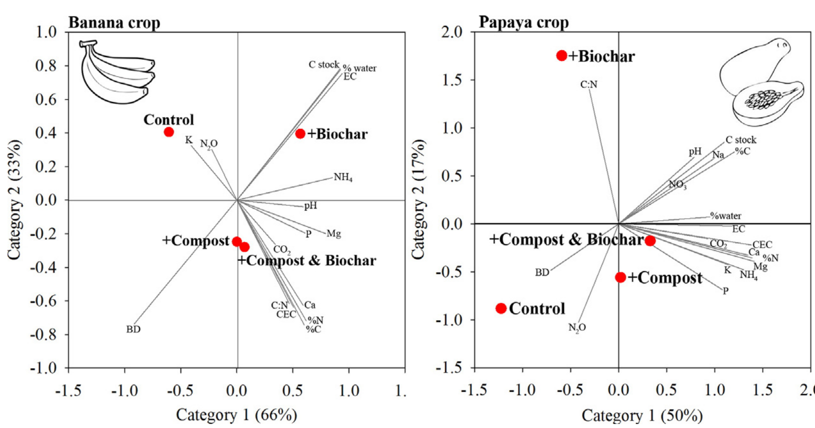
HIGHLIGHTS

- Biochar and compost amendment has potential to improve tropical agriculture.
- We monitored soil health, gas fluxes and crop yield under biochar and compost.
- Biochar improved soil nutrient content, water retention and reduced N_2O emissions.
- Biochar significantly reduced banana yield performance and did not affect papaya yield.
- Organic amendment is not an 'always win' scenario for tropical agriculture.

GRAPHICAL ABSTRACT



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ABSTRACT

The addition of organic amendments to agricultural soils has the potential to increase crop yields, reduce dependence on inorganic fertilizers and improve soil condition and resilience. We evaluated the effect of biochar (B), compost (C) and co-composted biochar (COMBI) on the soil properties, crop yield and greenhouse gas emissions from a banana and a papaya plantation in tropical Australia in the first harvest cycle. Biochar, compost and COMBI organic amendments improved soil properties, including significant increases in soil water content, CEC, K, Ca, NO_3, NH_4 and soil carbon content. However, increases in soil nutrient content and improvements in physical properties did not translate to improved fruit yield. Counter to our expectations, banana crop yield (weight per bunch) was reduced by 18%, 12% and 24% by B, C and COMBI additions respectively, and no significant effect was observed on the papaya crop yield. Soil efflux of CO_2 was elevated by addition of C and COMBI amendments, likely due to an increase in labile carbon for microbial processing. Our data indicate a reduction in N_2O flux in treatments containing biochar. The application of B, C and COMBI amendments had a generally positive effect on soil properties, but this did not translate into a crop productivity increase in this study. The benefits to soil nutrient content, soil carbon storage and N_2O emission reduction need to be carefully weighed against potentially deleterious effects on crop yield, at least in the short-term.

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1. Introduction

The human population is expected to reach 9.6 billion by the year 2050 (U.N. Population Division, 2013). Soil degradation is a significant global problem that increasingly restricts gains in agricultural output. Indeed, the effects of enhanced rates of soil erosion and plant and soil nutrient imbalances are recognized as significant obstructions to agricultural productivity and food security (Sanchez, 2002; Foley et al., 2005; Lal, 2009) and there is growing evidence that yield increases for many staple crops have plateaued (Grassini et al., 2013). Future allocation of more land for agriculture will be insufficient to offset these concurrent negative environmental impacts (Tilman et al., 2002). Thus, increasing the productivity of currently utilized land is of importance and of particular relevance in tropical areas where depletion of soil organic matter (SOM), low soil nutrient content and declining cation exchange capacity (CEC) lead to reduced productivity and low nutrient use efficiency. Consequently, the improvement of soil properties through the addition of organic amendments is a potential pathway to improved soil characteristics such as water content, bulk density, pH and exchangeable cations.

Composted material has been widely investigated as an organic amendment for improving soil quality and increasing agricultural output. In general, studies have shown significant yield benefits when adding compost (Amlinger et al., 2007) resulting from reduction of soil bulk density (BD), improvements to soil pore volume and water conductivity (Carter et al., 2004), improved water retention (Tejada et al., 2006; Evanylo et al., 2008) and reduced soil erosion. However, compost is generally not stable over medium to long-term timescales meaning for significant improvements to SOM to be made regular reapplication is required over extended periods.

More recently, biochar (charcoal produced from biomass by pyrolysis in a low-oxygen environment for use as a soil amendment or carbon sequestration) has been investigated as an alternative/complimentary amendment to compost in agricultural soils. Interest in biochar has rapidly increased over the last decade due to the potential benefits it offers to carbon sequestration (Lehmann and Joseph, 2009; Molina et al., 2009), improved crop yields (Sohi et al., 2010; Jeffery et al., 2011; Spokas et al., 2012), non-CO_2 greenhouse gas (GHG) emission reduction (Cayuela et al., 2013) and nutrient leaching reduction (Singh et al., 2010). However, the combined application of biochar and compost has been little explored to date, despite offering the potential to synergistically improve soil properties, improve agronomic output and increase soil organic carbon (SOC) content. Liu et al. (2012) showed that application of biochar and compost under field conditions provided synergistic benefits to SOM quantity, nutrient content and soil water holding capacity, but complimentary studies, especially in tropical systems are still rare.

Research into co-composting of biochar with organics is in its infancy but available literature suggests that biochar addition during composting leads to higher nitrogen retention in the final compost product (Steiner et al., 2010) as well as heavy metal stabilization (Hua et al., 2009), more rapid volume reductions through higher carbon mineralization rates, and changes in microbial community structure (Jindo et al., 2012). The combined co-composted product (here called compost-biochar, COMBI) has potential in terms of improving crop yields (Hua et al., 2009; Dias et al., 2010; Steiner et al., 2010; Schultz and Glaser, 2012; Schultz et al., 2013; Lashari et al., 2013; Glaser et al., 2014) although more recent research suggests a minimum proportion of biochar in compost is required to produce a positive effect on plant performance (Schultz et al., 2014), and in some cases the impact of COMBI additions on yield have been negligible (Schmidt et al., 2014).

In order to expand the understanding of organic amendments influence on tropical agricultural systems we conducted field trials encompassing two common tropical crops, banana (*Musa* sp.) and papaya (*Carica papaya*) in tropical north Queensland, Australia.

Existing work shows compost additions can have positive effects on yield, soil microbial communities and disease suppression in banana crops (Shen et al., 2013) and plant performance, fruit yield and soil microbial health in papaya crops (Reddy et al., 2010). Adriano et al. (2012) showed that addition of compost could improve the organic matter content, total N, P, K, Ca and Mg in a banana plantation soil and also showed that compost additions could be as beneficial to soil alone as when combined with mineral fertilizer applications. Damatta et al. (2011a) showed that compost additions over five growth cycles significantly increased plant height and stem diameter, as well as increasing overall bunch weight. During the same trial (Damatta et al., 2011b) it was also shown that Ca and Mg levels in leaves were improved with compost addition, but K levels were below control levels.

To our knowledge this work presents the first field trial using biochar additions on a papaya crop. However, a limited amount of work has been conducted testing biochar in banana plantations. Steiner et al. (2009) applied local wood biochar to a banana crop and found no significant change to fruit production over the first year, though increases in soil pH and K uptake were observed. While no yield data was reported, Mankasingh et al. (2011) found that soils from a banana plantation amended with rice paddy husk biochar at 10 t ha^{-1} for two years showed significant improvements in soil K, Mg, Na and P, as well as increased %C and %N. The effect of biochar or compost, alone and in combination, on banana crops is uncertain, due to a current lack of studies. Current evidence suggests there may be little benefit to fruit yield in the short-term, but that soil chemistry and physical properties may be significantly enhanced. Likely the details of these interactions will be dependent on complicated interactions between biochar and compost properties, soil, crop, climate and time.

In this study we conducted field trials at a banana and papaya plantation in tropical north Queensland, Australia. Soil properties, plant performance and greenhouse gas ($CO_2 + N_2O$) emissions were monitored over the first year of the growing cycle. Specifically we aimed to test the hypotheses that 1) Both biochar and compost additions would improve soil properties, and that the synergistic effect of application of a compost/biochar blend (COMBI) would exceed the benefits of either applied independently and 2) Plant performance would be unchanged by amendment application and 3) biochar containing amendments would reduce N_2O emissions from the soil.

2. Methods

2.1. Biochar and compost production

Biochar for both trials was supplied by Earth Systems Pty Ltd. (Victoria, Australia) and derived from willow wood (*Salix* sp.). Earth Systems Pty Ltd. uses a containerized automated batch pyrolysis plant (Charmaker MPP20) to process loads up to 5 t. Processing a 5 t load takes between 5 and 7 h at standard operating temperatures (>550 °C). While most material used in these trials had a particle size <25 mm, screening was not carried out and some larger fragments remained.

Duplicate samples of biochar were submitted to the New South Wales Department of Primary Industries for analysis of pH, conductivity, colwell P, acid neutralizing capacity, exchangeable cations, cation exchange capacity, and selected nutrient and contaminant trace metals. Total carbon and total nitrogen contents were determined by dry combustion using a Costech elemental analyzer in the Advanced Analytical Centre on the JCU Cairns campus. Stable Polycyclic Aromatic Carbon (SPAC) content was determined by hydrogen pyrolysis (McBeath et al., 2015).

Compost and COMBI products were produced by King Brown Technologies Pty Ltd. (Mareeba, Australia). Two amendment windrows (each 60 m long, 1.5 m high and 4 m wide) were produced at the King Brown Technologies compost production facility: one containing compost and biochar (COMBI) and one with compost only. Four tonnes of