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Biochar and biochar-compost as soil amendments: Effects on peanut yield, soil properties and greenhouse gas emissions in tropical North Queensland, Australia

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ABSTRACT

This study investigated the effects of biochar and compost, applied individually or together, on soil fertility, peanut yield and greenhouse gas (GHG) emissions on a Ferralsol in north Queensland, Australia. The treatments were (1) inorganic fertilizer only (F) as a control; (2) 10 t ha^{-1} biochar + F (B + F); (3) 25 t compost + F (Com + F) ha^{-1}; (4) 2.5 t B ha^{-1} + 25 t Com ha^{-1} mixed on site + F; and (5) 25 t ha^{-1} co-composted biochar-compost + F (COMBI + F). Application of B and COMBI increased seed yield by 23% and 24%, respectively. Biochar, compost and their mixtures significantly improved plant nutrient availability and use, which appeared critical in improving peanut performance. Soil organic carbon (SOC) increased from 0.93% (F only) to 1.25% (B amended), soil water content (SWC) from 18% (F only) to over 23% (B amended) and CEC from 8.9 cmol(+)/kg (F only) to over 10.3 cmol(+)/kg (organic amended). Peanut yield was significantly positively correlated with leaf chlorophyll content, nodulation number (NN), leaf nutrient concentration, SOC and SWC for the organic amendments. Fluxes of CO_2 were highest for the F treatment and lowest for the COMBI treatment, whereas N_2O flux was highest for the F treatment and all organic amended plots reduced N_2O flux relative to the control. Principal component analysis indicates that 24 out of 30 characters in the first principal component (PRIN1) individually contributed substantial effects to the total variation between the treatments. Our study concludes that applications of B, Com, B + Com or COMBI have strong potential to, over time, improve SOC, SWC, soil nutrient status, peanut yield and abate GHG fluxes on tropical Ferralsols.

1. Introduction

Intensive agricultural development and environmental change have led to severe land degradation in many parts of the world. As population increases, the challenge is to boost agricultural production while coping with environmental change in ways that avoid further land degradation. When fertilizer, manure or compost is applied to soils it is often rapidly lost, resulting in financial costs to the farmer and leaching of major plant nutrients such as phosphorus (P), potassium (K) and nitrate nitrogen (NO_3-N), potentially leading to environmental pollution (Barrow, 2012).

Peanut (*Arachis hypogaea* L.) is an annual legume crop that provides food and helps maintain soil fertility through nitrogen fixation (Bogino et al., 2006). The special ability of leguminous crops to work symbiotically with rhizobia to produce protein is becoming increasingly important in world agriculture as this potentially leads to more sustainable agricultural systems, reducing requirements for chemical fertilizer, enhancing residual benefits to subsequent crops and increasing crop yields (Giller, 2001). Global consumption of peanuts is increasing at a rate of around 3% per annum. In 2011/12, peanut production in the world was ~35 million tons, to which Australia contributed less than 0.2 per cent (USDA, 2012). China, India and the USA are the main producers, growing 16.0, 5.5 and 1.7 million tons, respectively, accounting for 45%, 16% and 5% of the world's total respectively (USDA, 2012).

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The required mean annual temperatures for peanuts generally exceed 20 °C at planting depth and the crop also requires 500–600 mm of water during the growing season. Peanuts are N-fixing, so P, K, calcium (Ca) and sulphur (S) are the most common nutrients applied to peanuts, with magnesium (Mg), zinc (Zn), boron (B), copper (Cu), manganese (Mn) and molybdenum (Mo) also applied where deficiencies are identified (PCA, 2012). The effects of continuous cultivation on the yield of peanuts and cereals on Ferrosols in subtropical southeast Queensland have been studied previously. Yield reductions and low grain protein concentrations were observed in peanuts grown on continuously cropped soil due to nutrient deficiencies in surface and subsurface layers (Bell et al., 1995).

In northern Australia, peanuts are planted in rotation with cereal crops, pasture or sugarcane. The crop is generally planted from September to January to take advantage of summer rain and harvested after 18–24 weeks. Peanuts are mostly planted on light-colored, light textured and friable soils with good drainage and relatively high water-holding capacity and an optimal pH of 6-7, though other soils can support the crop, generally with irrigation. Well-drained soils provide proper aeration for the roots and for the nitrifying bacteria that are necessary for proper mineral nutrition of the plant. A soil organic matter content of between 1 and 2% is preferred, both to improve water-holding capacity of the soil and to supply plant nutrients (Putnam et al., 1991).

In Australia in 2010/11, 7300 ha were planted to peanuts, producing 18400 t of peanut in shell at an average yield of 2.5 t ha^{-1}, with maximum yields under irrigation of 8 t ha^{-1} (PCA, 2012). About 97.5% of national area planted to peanuts was north of the latitude equivalent to the Queensland-New South Wales border and 97% of the total production occurred north of this latitude. Songsri et al. (2009) identified water stress as the major abiotic constraint affecting peanut productivity globally. The peanut industry in Australia is likewise considered to be significantly exposed to the impacts of climate change, with production in northern Australia reduced by 30% in the last 25 years as a result of temperature increases and lower than average rainfall (Marshall et al., 2014). Meinke et al. (1996) found that 27% yield reductions from the median yield accompanied dry El Nino periods in northern Australia, while 23% increases over the median yield accompanied wet La Niña conditions.

Biochar is a carbon-rich product of burning biomass in restricted or absence of oxygen–pyrolysis. The potential of biochar to improve soil fertility and sequester carbon on centennial timescales (thereby mitigating climate change) has been widely recognized (Lehmann and Joseph, 2009). Biochar is an effective carbon (C) sink in the soil because of its high proportion of recalcitrant C with hundreds to thousands of years of stability (Atkinson et al., 2010). While there has been significant work on the production and use of peanut shell biochar as both a soil amendment (e.g., Gaskin et al., 2010) and for decontamination of water (Ahmad et al., 2012) there has been little previous work on the impact of biochar or compost on peanut crops themselves. McClintock and Diop (2005) reported significant increases in above- and below-ground peanut biomass in crops grown by subsistence farmers in Senegal, along with improvements in soil effective cation exchange capacity (ECEC) and soil nutrient concentrations (K, Mg) in soils amended with compost. Yamato et al. (2006) reported a significantly increased peanut yield following biochar amendment of an infertile soil in Sumatra, with no significant change in yield for fertile soil, along with general increases in soil pH, N, available P and CEC.

Climate variability in southeast Queensland in particular, over the past 20 years, has led to a major reduction in the dry land peanut crop area, and now ~33% of the total area is rain fed only, accompanied by a major swing to irrigated production (PCA, 2013). Given that water stress has a major impact on peanut crops and that both compost and biochar can increase SWC, there is the potential to both increase peanut yield in northern Australia and to provide an element of 'drought-proofing' to peanut farming operations through the addition of compost and/or biochar amendments to soils under peanut cultivation. However, there has been no research into the effect of these amendments on crop growth and soil properties in the Australian context. Therefore, based on several studies reporting the positive effects of biochar and compost on soil fertility and productivity of a range of crops elsewhere (e.g., Fischer and Glaser, 2012; Lehmann et al., 2003; Liang et al., 2014; Liu et al., 2013), we hypothesized that the addition of biochar and compost amendments to soils under peanut could (1) enhance soil organic carbon, plant available nutrients and soil water retention; (2) improve plant growth and crop yield; and (3) reduce greenhouse gas fluxes.

2. Materials and methods

2.1. Experimental site

The soil at the site is a Ferralsol (IUSS, 2007) developed on Quaternary basalt near Mareeba on the Atherton Tablelands, north Queensland (17.0232°S 145.4027°E; 433 m asl). Ferralsols represent the most highly weathered soils in the classification system (Brady and Weil, 2008). Particle size analysis of the 0–30 cm interval indicates the soil comprised 21.9% coarse sand (0.2–2.0 mm), 40.1% fine sand (0.02–0.2 mm), 6.0% silt (0.002–0.02 mm) and 32.0% clay (<0.0002 mm). The average annual total precipitation is 880 mm with mean annual maximum and minimum air temperatures of 28.8 °C and 17.8 °C, respectively. A total of 116 rows were made available for the trial, with plantings arranged in high-density single rows. Crop rows were 0.90 m wide and 360 m in length. Treatment replicates incorporate four rows each to coincide with currently utilized farm implements and practices, with a four-row buffer zone between each treatment. Treatment sequencing was randomized and the total plot area was 0.13 ha per replicate.

One month prior to initiation of the field trial, composite soil samples from a depth of 0–30 cm and 30–100 cm were randomly collected from nine locations across the trial site. The sites were selected by dividing the trial area into a 3 × 3 grid and within each of the 9 grid cells a sampling point was randomly chosen. At each sampling point three 0–30 cm cores were taken using a vehicle mounted hydraulic corer. One core of 30–100 cm per sampling point was also taken. Soil moisture was taken at 0–12 cm using the Campbell Scientific Hydrosense II soil moisture probe at each sampling location. The soil moisture content was also measured on each sample after oven-drying. Table 1 shows the pre-planting physicochemical characteristics of the trial soil.

2.2. Experimental set-up

The feedstock for biochar production was waste willow wood (*Salix* spp.) derived from removal and restoration activities along watercourses in Victoria. The biochar (B; Earth Systems Pty. Ltd.) was produced using a containerized automated batch pyrolysis plant (Charmaker MPP20). Processing of whole logs at up to 5 t per load required over 5–7 h with highest heating temperatures of over 550 °C. The low density willow feedstock produced biochar with low bulk density (0.17–0.21 g cm^{-3}), porosity (28–37%), apparent skeletal density (0.28 g cm^{-3}), BET surface area (332 m^2 g^{-1}), total pore volume (0.20 m^3 g^{-1}) and ash yield (2.7%). The biochar was ground to <10 mm prior to field application.

Two paired compost windrows (each 60 m long, 1.5 m high and 4 m wide) were produced at the King Brown Technologies compost