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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

Table 1
Physicochemical properties of pre-planting soil samples at 0–30 cm and 30–100 cm soil depth.

Item	Unit	Limit	Average 0–30 cm	SE	Average 30–100 cm	SE
Soil water content	% w/w		13.2	0.49	17.9	1.3
Bulk density	g/cm3		0.55	0.02	0.89	0.03
pH (H2O)			6.2	0.12	6.7	0.07
pH (CaCl2)			5.6	0.12	6.4	0.06
Conductivity	dS/m	1.00	0.08	0.01	0.03	0.0
Total N	%		0.06	0.00	0.01	0.00
Organic C	%		0.89	0.06	0.22	0.02
C:N ratio			14.8	0.3	22.0	0.8
Organic matter	%	0.10	1.5	0.13	n/d	n/d
Colwell P	(mg kg^{-1})	1.00	58	6	10.3	1.6
Exch. Na	cmol(+)/kg	0.01	0.08	0.0	0.05	0.0
Exch. K	cmol(+)/kg	0.01	0.68	0.11	0.26	0.03
Exch. Ca	cmol(+)/kg	0.01	6.7	0.54	3.6	0.32
Exch. Mg	cmol(+)/kg	0.01	1.6	0.14	1.4	0.21
Exch. Al	cmol(+)/kg	0.01	0.05	0.0	0.02	0.0
CEC	cmol(+)/kg	0.02	9.1	0.75	5.4	0.45
Ca: Mg Ratio		0.1	4.3	0.36	n/d	n/d
S	mg kg^{-1}	1.00	15.9	1.8	n/d	n/d
Cl	mg kg^{-1}	5	10.5	1.0	n/d	n/d
Cu	mg kg^{-1}	0.05	1.5	0.11	n/d	n/d
Zn	mg kg^{-1}	0.05	<0.05	0.0	n/d	n/d
Mn	mg kg^{-1}	0.50	119	13.3	n/d	n/d
Fe	mg kg^{-1}	0.50	14.4	1.1	n/d	n/d
B	mg kg^{-1}	0.05	0.54	0.04	n/d	n/d
NH_4–N	mg kg^{-1}	n/d	n/d	n/d	3.3	0.23
NO_3–N	mg kg^{-1}	n/d	n/d	n/d	6.1	0.42

Nitrogen concentrations in soils fell sharply with depth, with most of the N being in the top 0–0.30 m layer of soils. n/d: not determined.

production Facility: one containing compost and biochar (COMBI) and another one compost only (Com). The biochar (equivalent to 18 m^3 or 9% by volume) was added to 80 m^3 (40%) each of green waste and bagasse, 12.5 m^3 (6%) of chicken manure and 12 m^3 (6%) of compost. This windrow was paired with an adjacent windrow comprising the same volumes of green waste (43%), bagasse (43%), chicken manure (7%) and compost (7%), but without biochar. In both cases, bagasse was laid down first, green-waste mulch added on top and the windrow turned once. Then chicken manure was added and the windrows watered and turned six times. In the case of the COMBI, the biochar was then added on top of the windrow and the pile turned a further two times. Both windrows were then covered with black plastic film. They were turned and watered weekly, and the matured product was screened at 25 mm.

Table 2
Characterization of earth system willow biochar (B), compost (Com) and co-composted biochar-compost (COMBI).

Element	Unit	B	Com	COMBI
pH (H_2O)	Units	8.3	7.5	7.5
pH ($CaCl_2$)	Units	9.5	n/d	
Carbon (C)	%	47.5	30.6	34.7
Nitrogen (N)	%	0.38	1.19	0.95
δ15 N	‰	n/d	+7.5	+7.8
δ13 C	‰	n/d	−24.3	−21.3
ANC	% $CaCO_3$	2.5		
Sulfur (S)	%	0.019	0.014	0.012
Colwell phosphorus (P)	mg kg^{-1}	79.5	917	1104
Acid neutralizing capacity	% $CaCO_3$	2.5	n/d	n/d
Exch. potassium (K)	cmol(+)/kg	7.25	1.62	1.74
Exch. calcium (Ca)	cmol(+)/kg	2.20	4.15	4.15
Exch. magnesium (Mg)	cmol(+)/kg	1.45	2.38	2.30
Exch. sodium (Na)	cmol(+)/kg	0.24	0.52	0.52
Exch. aluminum (Al)	cmol(+)/kg	<0.1	<0.1	<0.1
Hydrogen (H^+)	cmol(+)/kg	n/d	0.3	0.11
CEC	cmol(+)/kg	11.2	8.77	8.81
EC	dS/m	0.71	2.3	2.0
Copper (Cu)	mg kg^{-1}	2.55	45.0	44.0
Zinc (Zn)	mg kg^{-1}	83.5	133	133
Manganese (Mn)	mg $^{kg-1}$	110	49.6	54.6
Iron (Fe)	mg kg^{-1}	0.045	246	218
Boron (B)	mg kg^{-1}	9.25	4.8	4.3
Molybdenum (Mo)	mg kg^{-1}	<0.3	<0.2	<0.2
Cobalt (Co)	mg kg^{-1}	<0.4	<0.05	<0.05

ANC: acid neutralizing capacity; CEC: cation exchange capacity; n/d: not determined.

Biochar, compost and COMBI samples were collected randomly from around and within each pile of material before application in the field to determine physicochemical characteristics. Nutrient contents of the organic amendments were analyzed in the laboratory following similar methods for soil analysis before the start of the trial (Table 2).

The experiment comprised 5 treatments in triplicate, where each replicate occupied 0.13 ha, planted following a maize crop. The treatments were: (1) recommended inorganic fertilizer (F) as a control, against which all the other treatments were compared; (2) biochar (B) applied at 10 t ha^{-1} + F; (3) compost (Com) applied at 25 t ha^{-1} + F; (4) 25 t Com ha^{-1} + 2.5 t B ha^{-1} (B + Com) mixed on site + F; and (5) co-composted biochar-compost mix (COMBI) applied at 25 t ha^{-1} + F. All amendments were applied by broadcast spreading with truck-mounted, computer-controlled distribution bins and rotary blade spreaders. Spreading occurred after primary deep ripping and disc harrowing. Amendments were then incorporated by rotary hoe prior to planting using GPS navigation control. Peanut (cv., *Menzies*) was planted on 13th January 2014 with a 4 row 'pneumatic precision planter,' with a seed placement accuracy of 1 mm. Fertilizer was applied in row at a rate of 26.6 kg N ha^{-1}, 31.6 kg P ha^{-1} as ammonium phosphate, 66.2 kg K ha^{-1} as muriate of potash, 2.6 kg S ha^{-1} and 0.54 kg Zn ha^{-1} as zinc sulfate. Other agronomic practices were applied equally for all treatments during the crop growth period as per usual on-farm practice. The total rainfall during the crop growing period was 541 mm. The crop was harvested on 17th June 2014.

2.3. Sampling and measurements

After planting, periodic sampling and measurement of soil parameters, leaf chlorophyll content, specific leaf weight and emissions of carbon dioxide (CO_2) and nitrous oxide (N_2O) were undertaken. The measurements of CO_2 and N_2O were undertaken on days 3, 10, 24, 37, 75 and 124 after planting in conjunction with soil water content (SWC) between 15 January 2014 and the 15 May

2014. For gas emission measurements a standard closed chamber methodology was used in conjunction with an INNOVA-1412 field portable photoacoustic gas analyzer (LumaSense Technologies, Denmark). With two chambers emplaced per replicate. The total average GHG emissions were calculated from all three replicates over all sample dates of each treatment. It therefore encompasses the temporal and spatial variability. For total GHG flux over the trial period the area under each treatment curve was calculated via standard integration. The intensity of gas emission per unit grain yield was calculated as the ratio of the cumulative emission of CO_2–C or N_2O–N (kg ha^{-1}) and the seed yield (kg ha^{-1}). Soil water content (SWC) at 12 cm depth was taken using a HydroSense II probe (Campbell Scientific, Inc.).

Leaf chlorophyll measurements were undertaken on days 23, 36, 52, 59, 74, 101 and 134 after planting in conjunction with specific leaf weight between 5 February–27 May 2014, using a chlorophyll meter (SPAD 502, Konica Minolta, Tokyo). For each measurement, duplicate readings were made on the second fully expanded leaf from the top of the main plant stem, approximately half way along the leaf, taking care to avoid veins and mid-rib. This procedure was repeated for six randomly selected plants. A hole-punch with a diameter of 8 mm was used to take a leaf disc from the middle of the leaf lamella from 18 leaves of the same age and position from each replicate at three weeks intervals. Leaf discs were transferred immediately to individual, sealed plastic bags that were kept in an insulated box above ice packs until all leaf discs were taken. Fresh leaf discs were weighed before being placed in individual aluminum foil cups and placed in an oven for drying. Leaf discs were dried at 70 °C for 48 h before reweighing them. SLW was calculated as dry weight of leaf disc per area of hole-punch, and the LWC was calculated as follows:

$$\mathrm{LWC}(\%) = \frac{\text{leaf fresh} - \text{leaf dry weight}}{\text{leaf fresh weight}} \times 100 \quad (1)$$

The number of plants was counted after complete emergence. At harvest, above-ground biomass, seed yield and mass of yield components were recorded and kernel samples were taken for analysis. The number and weight of nodules were measured on 5 randomly selected plants after 50% flowering. Total peanut pod and seed yields recorded on plot basis were converted to kg ha^{-1} for statistical analysis.

2.4. Plant and soil analysis

Fifteen leaf samples including leaves measured for leaf chlorophyll content around each station were clipped at their base and stored for the determination of C, N, P, K and NO_3–N. Phosphorus, K and NO_3–N concentrations in plants were quantified at the Analytical Research Laboratories (ARL) in New Zealand. Nitrate-N in plant tissue was determined using 2% acetic acid as the extractant (Miller, 1998). Plant K content was determined after wet digestion with sulfuric acid by atomic absorption spectrometry (Watson et al., 1990). Plant P content was determined photometrically in the same extract with the molybdenum blue method (Mills and Jones, 1996). Total plant N and C concentrations were determined using an elemental analyzer (ECS 4010CHNSO Analyzer; Costech Analytical Technologies INC., Valencia, CA, USA) fitted with a Zero Blank Auto-sampler (Costech Analytical Technologies, INC.). Stable isotope composition of oven-dried seed samples were also determined using a ThermoFinnigan DeltaV^{PLUS} Continuous-Flow Isotope Ratio Mass Spectrometer (EA-IRMS) at James Cook University's Cairns Analytical Unit. Stable isotope results are reported as per mil (‰) deviations from the VPDB reference standard scale for δ^{13}C and *from the international air standard for* δ^{15}N. Precisions (S.D.) on internal standards were better than ±0.2‰ for both isotope determinations.

Soil cores from 0 to 30 cm were taken in row at the midpoint of the growing season and after harvesting. The roots were separated soil dried in an oven to constant weight and then ground using Split Phase Motor Grinding Mill to pass through a 2 mm sieve. SOC and total soil N contents were determined as for plants. Soil pH, exchangeable cations, cation exchange capacity (CEC), electrical conductivity (EC), NO_3–N and NH_4–N contents were determined by the ARL Pty Ltd. in New Zealand. Soil pH was measured in H_2O and 0.01 M $CaCl_2$ using pH meter and a 1:2.5 soil weight: extractant-volume ratio. The EC was determined by a conductivity meter on a 1:2.5 soil: water suspension (Rayment and Higginson, 1992). Colwell P was measured by on 1:50 soil solution extracts in 0.5 M sodium bicarbonate after mixing for 16 h. The extracted P was determined colorimetrically on centrifuged and filtered extracts using a SEAL AQ2+ Discreet Analyzer (Seal Analytical Ltd., Fareham, Hampshire, UK) and the ammonium molybdate/ascorbic acid color reaction with potassium antimonyl tartrate was added to control the reaction rate (Rayment and Lyons, 2011). Exchangeable K, Na, Ca and Mg were determined using 1 M ammonium acetate extraction buffered at pH 7, using mechanical shaking at a soil: solution ratio of 1:20 (Rayment and Higginson, 1992) and atomic absorption analysis. CEC was calculated as the sum of exchangeable K, Na, Ca and Mg. Soil NH_4–N and NO_3–N were determined colorimetrically by an automated photometer using 1 M KCl extraction method (Rayment and Lyons, 2011).

2.5. Statistical analysis

The data were subjected to analysis of variance using the general linear model procedure (PROC GLM) of SAS statistical package version 9.1 (SAS Institute 2003, Cary, NC). The total variability for each trait was quantified using the following model (Gomez and Gomez, 1984).

Table 3
Effects of soil amendments on peanut seed yield (SY), total pod yield (PY), chlorophyll content (SPAD unit), nodulation number (NN) and nodulation dry weight (NDW) per plant.

Treatment	SY (kg ha^{-1})	PY (kg ha^{-1})	Av. CHLC (SPAD-unit)	NN plant^{-1}	NDW (mg plant^{-1})
Control (F)	4167 b	5617 b	45.7 b	91 c	87.4 c
B + F	5048 a	6910 a	47.7 a	112 a	108.4 a
Com + F	4921 a	6552 ab	48.4 a	101 b	95.3 bc
B + Com +F	5023 a	6786 a	48.8 a	106 ab	100.5 ab
COMBI +F	5096 a	6946 a	48.0 a	109 ab	102.8 ab
p level	0.050	0.025	0.024	0.003	0.001
LSD (0.05)	646.1	797.3	1.7	8.3	7.1
CV (%)	7.1	6.5	1.9	4.2	3.8

Av. CHLC: average chlorophyll content (average of six temporal measurements). Within each column, means with different letters are significantly different at $p < 0.05$. *Note*: LSD: least significant difference; CV: coefficient of variation.

$Y_{ij} = u + R_i + T_j + e_{ijk}$(2)where Y_{ij} is the measured value, μ = grand mean, R_i is effect of the i^{th} replication, T_j is effect of the j^{th} treatment, and e_{ijk} is the variation due to random error. Means for the treatments ($n = 5$) were compared using the MEANS statement with the least significant difference (LSD) test at the 5% probability level. Linear regression analysis was performed using replicated data between plant parameters, nutrient uptake and soil nutrient contents following the SAS REG procedure. Principal component analysis (PCA) was performed after standardizing the data using the SAS PRINCOMP procedure to distinguish the treatments as a function of the soil management and determine the most important parameters to characterize them.

3. Results

3.1. Yield and plant growth

All 'organic' amendments significantly ($p \leq 0.05$) increased the peanut seed and pod yields and leaf chlorophyll contents of plants during the crop growth period, relative to the F control (Table 3). Neither plant number nor specific leaf weight (SLW) at any growth stage of the plants was significantly different between treatments. Applications of B, Com, B + Com and COMBI increased the seed yield by 21, 18, 21 and 22% and pod yield by 23, 17, 21 and 24% compared to the F only treatment. The effect of treatments on leaf chlorophyll content became more pronounced as the crop grew. Average leaf chlorophyll content increased by 7, 10, 10 and 9% in B, Com, B + Com and COMBI amended soil, respectively, compared to the F treatment. Significant difference was not observed between organic amendments for seed yield, total biomass and chlorophyll content. SLW increased as the crop growth progressed, being the highest near physiological maturity (Fig. 1). Leaf water content was inversely correlated with specific leaf weight.

Root nodulation significantly improved crop performance, as total peanut pod yield was substantially higher in B, Com, B + Com and COMBI amended soil than in F only treated soil. Nodulation number (NN) and nodulation dry weights (NDW) differed significantly ($p < 0.01$) among treatments (Table 3). The highest average NN (112 plant^{-1}) and NDW (107 mg plant^{-1}) were recorded from B followed by the COMBI treatments, and the lowest scores were from the F treatment (Table 3). B, Com, B + Com and COMBI additions increased NN plant^{-1} by 25, 9, 17 and 20%, and NDW by 25, 9, 15 and 18%, respectively compared to the F treatment.

3.2. Plant nutrient uptake

All organic amendments significantly ($p < 0.05$ and $p < 0.01$) improved plant uptake of C, N, P, K and NO_3–N at mid growth stage, while at late growth stage the treatments significantly ($p \leq 0.05$) affected only NO_3–N uptake but not C, N, P and K (Table 4). The highest plant C and total N contents (44.1% and 4.1%, respectively) were obtained from B + Com and the lowest from the F treatment (Table 4). Applications of B + Com and COMBI increased plant C contents by 20.5 and 16.4% and plant N uptake by 28.1 and 21.9%, respectively compared to F only. Leaf P, K and NO_3–N concentrations at mid growth stage ranged from 0.24–0.42%, 2.8–4.2% and 371–877 mg kg^{-1}, respectively, with the highest values being from B + Com for P and NO_3–N, and COMBI for K uptake. The highest values for leaf N and P concentration were obtained from the B + Com treatment, and the lowest K from F (Table 4). However, there was no statistically significant difference between B + Com and COMBI for these parameters. The respective N and P contents of plants in the B + Com and COMBI treatments were 1.3 and 1.2, and 1.8 and 1.7 times that of the F treatment. Foliar NO_3–N, P and K content ranged from 10.2–75 mg kg^{-1}, 0.12–0.14% and 1.32–1.60%, respectively. The variability among replications for NO_3–N were large both at mid-and late plant growth stage.

The organic treatments had a significant effect on peanut seed δ^{15}N composition, but not on δ^{13}C, C or total N contents (Table 5). The highest seed δ^{15}N content was obtained from F only treatment followed by B. The treatments showed similar effects on δ^{13}C and C concentrations of peanut. The maximum N content was achieved from B and COMBI, and the lowest from B + Com treatment. Seed C: N ratios were similar for all treatments although the highest value was obtained from B + Com treatment, which had the lowest N content.

3.3. Soil physicochemical characteristics

Soil analysis results at the mid-plant growth stage and after harvesting indicated that application of all organic amendments significantly ($p \leq 0.05$ and $p \leq 0.01$) increased SOC, total N, available P, NO_3–N and NH_4–N contents, but not soil pH (Table 6). At harvest, soil C:N ratio significantly responded to the organic treatments, but not at the mid-growth stage of the plants. Significant differences were observed between the treatments for SOC at mid growth stage. COMBI addition resulted in the highest SOC, N and NO_3–N in the soil (Table 6). At mid growth stage, in B, Com, B + Com and COMBI amended soil, SOC content

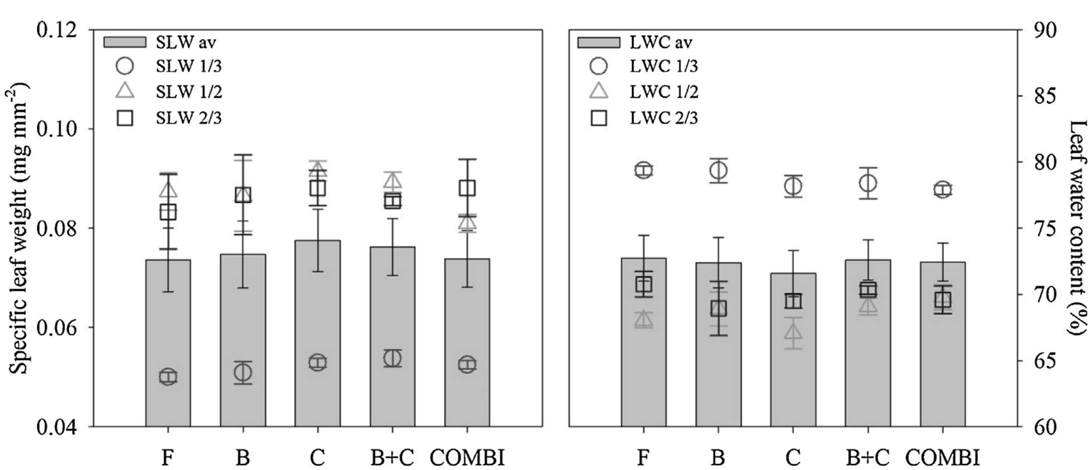

Fig. 1. Treatment effects on specific leaf weight (SLW) and leaf water content (LWC). Solid bars represent the average values for all data from the trial, circles average values from 1/3 trial duration, triangles average values from $^1/_2$ trial duration and squares average values from 2/3 trial duration. Error bars represent ± SE.

Table 4
Effects of biochar, compost and their mixture on leaf nutrient content of peanut.

Treatment	Mid-growth stage leaf nutrient concentration					Late growth stage leaf nutrient concentration				
	C (%)	N (%)	NO_3–N (mg kg^{-1})	P (g kg^{-1})	K (%)	C (%)	N (%)	NO_3–N (mg kg^{-1})	P (%)	K (%)
Control (F)	36.6 c	3.2 b	623 b	2.06 b	2.48	42.2	2.43	75.3 a	0.12	1.40
B + F	39.0 bc	3.7 ab	371 c	2.60 a	2.49	42.9	2.28	20.0 b	0.13	1.46
Com + F	40.7 abc	3.8 a	448 c	2.64 a	2.49	42.3	2.23	12.2c	0.14	1.60
B + Com + F	44.1 a	4.1 a	877 a	2.66 a	2.51	43.0	2.36	10.2 c	0.14	1.33
COMBI + F	42.6 ab	3.9 a	872 a	2.61 a	2.52	42.5	2.24	10.5 c	0.14	1.32
p level	0.045	0.038	0.001	0.003	0.965	0.65	0.63	0.001	0.44	0.30
LSD (0.05)	4.8	0.50	145	0.18	0.15	1.3	0.33	17.2	0.03	0.31
CV (%)	6.3	7.1	12.1	3.9	3.2	1.6	7.7	35.6	10.5	11.7

Within each column, means with different letters are significantly different at $p < 0.05$. LSD: least significant difference; CV: coefficient of variation.

Table 5
Changes of peanut seed C, total N, C: N ratio and C and N isotope composition (δ^{13}C, δ^{15}N) to biochar and compost applications.

Treatments	C (%)	N (%)	C:N ratio	δ^{13} C	δ^{15} N
Control (F)	61.7	5.09	12.2	-27.3	1.64 a
B + F	61.7	5.29	11.7	-27.6	1.49 ab
Com + F	61.7	5.02	12.3	-27.3	1.18 bc
B + Com + F	61.8	4.79	12.9	-27.2	1.00 c
COMBI + F	61.6	5.27	11.7	-27.3	1.04 bc
p level	0.99	0.30	0.45	0.82	0.04
LSD (0.05)	1.83	0.55	1.66	0.69	0.46
CV (%)	1.57	5.74	7.27	-1.35	19.2

Within each column, means with different letters are significantly different at $p < 0.05$. LSD: least significant difference; CV: coefficient of variation.

increased by a factor of 1.3–1.4 and the total N content increased by a factor of 1.1–1.3 compared to the control. The mean SOC decreased in the order COMBI > B > B + Com > Com > F at mid plant growth stage. Although NO_3–N content is highly variable in soils, after B and COMBI additions, the soil NO_3–N and NH_4–N contents significantly increased by a factor of 1.7 and 1.9, and 2.0 and 1.9, respectively relative to F at mid plant growth stage. Colwell soil P content was higher by a factor of 1.1, 1.2 and 1.2 owing to B, B + Com and COMBI addition, respectively than the F and Com treatments. While the total P in the compost was considerably higher than that in biochar, the available P in the soil was lower in the compost treatments than the biochar treatment. In general, lower total soil N and SOC contents were obtained after harvesting than at mid-plant growth stage, whereas the soil NO_3–N content was lower at mid-plant growth stage than after harvesting, suggesting that the demand and uptake for NO_3–N during peak plant growth stage was higher than late the plant growth stage. In contrast, higher soil P and NH_4–N contents were recorded at mid-plant growth stage than after harvesting.

The average volumetric soil water content (SWC) was significantly ($p < 0.01$) improved by the organic amendments during the plant growth stage. The maximum SWC was obtained from B treated soil followed by the COMBI, and the lowest was from the F treatment (Table 6). At mid growth stage of plants, the average SWC was higher by 30, 14, 18 and 24% for the soils amended with B, Com, B + Com and COMBI, respectively, than the F treatment. The average SWC decreased in the order B > COMBI > B + Com > Com > F. However, by harvest the treatment effects were no longer statistically significant. Soil amendments had significant ($p \leq 0.05$) effects on exchangeable K, Mg, Al and CEC at mid-plant growth stage, but not on exchangeable Na, Ca and EC. Exchangeable Na was the only element significantly affected by the treatments at harvest. At mid-growth stage, plant available K, Mg and CEC increased by a factor of 1.2, 1.4 and 1.2, respectively by adding biochar compared with the control. At mid-growth stage, contents of plant-available nutrients increased in the order K > Mg > CEC > Al

Table 6
Effects of soil amendments on soil physicochemical properties at the grain filling stage and trial end-point.

Treatments	SBD (g cm^{-3})	SWC (%)	pH (H_2O)	SOC (%)	N (%)	C:N ratio	Nutrient content (mg kg^{-1})		
							P	NH_4–N	NO_3–N
Mid-point									
Control (F)	0.79	17.9 c	7.0	0.93 c	0.07 b	13.3	52.8 b	8.4 c	3.1 b
B + F	0.64	23.3 a	6.9	1.25 a	0.08 ab	15.6	58.7 ab	16.7 a	5.3 a
Com + F	0.74	20.4 b	6.9	1.15 b	0.08 ab	14.4	52.7 b	13.2 b	5.6 a
B + Com + F	0.58	21.1 b	6.9	1.19 ab	0.08 ab	14.9	63.0 a	14.1 ab	5.5 a
COMBI + F	0.82	22.2 b	6.9	1.23 a	0.09 a	13.7	60.8 ab	16.0 ab	6.0 a
p level	0.070	0.002	0.982	0.001	0.03	0.134	0.050	0.002	0.011
LSD (0.05)	0.18	1.9	0.48	0.06	0.01	1.6	8.6	3.0	1.4
CV (%)	8.9	4.8	3.6	2.8	6.1	5.8	7.8	11.7	14.8
End-point									
Control (F)	0.97	26.9	6.6	1.00b c	0.08 a	13.4 c	42.3 b	7.07 bc	7.97 c
B + F	0.91	28.3	6.7	1.08 ab	0.08 a	12.4 c	41.0 b	11.73 a	10.77 ab
Com + F	0.93	27.2	6.8	1.08 ab	0.07 ab	15.0 b	43.3 b	5.87 c	9.27 bc
B + Com + F	0.96	27.4	6.9	1.01 bc	0.06 b	16.1 ab	55.3 a	6.77 c	9.30 bc
COMBI + F	0.92	28.8	6.8	1.12 a	0.07 ab	16.7 a	44.7 b	9.47 ab	12.13 a
p level	0.623	0.281	0.599	0.019	0.045	0.001	0.024	0.005	0.050
LSD (0.05)	0.09	2.11	0.39	0.019	0.01	1.35	8.26	2.65	2.67
CV (%)	5.3	4.03	3.1	4.57	9.06	4.88	9.68	17.22	14.33

Within each column, means with different letters are significantly different at $p < 0.05$. *Note*: SBD: soil bulk density; SWC: soil water content; LSD: least significant difference; CV: coefficient of variation.

with organic treatments (Table 7). Soil bulk density was not significantly affected by the treatments (Table 6).

Seed yield was significantly ($p \leq 0.01$) positively correlated with pod yield, NN, mid-growth stage leaf P concentration and SOC (R^2 = 0.96, 0.52, 0.54 and 0.56, respectively) under the various treatments (Fig. 2). The improvement in SOC due to the addition of organic amendments showed significant positive correlations with SWC, NH_4–N and NN (R^2 = 0.72, 0.79 and 0.86, 0.71, respectively; Fig. 2). The results of principal component analysis (PCA) revealed that the first three principal components (Prin1–Prin3) accounted for ~94% of the total variation between the treatments, of which ~85% was contributed by the Prin1 and Prin2 (data not shown). The bi-plot of Prin1 and Prin2 shows the clustering of treatments F, B, Com, B + Com and COMBI (Fig. 3). Characters with larger absolute values within the first principal component influence the clustering more than those with lower absolute values. The differentiation of the treatments into different clusters was dictated by the cumulative effects of several characters. Thus, 24 out of 30 characters in the PRIN1 individually contributed substantial effects (−0.156–0.223) to the total variation of the treatments (data not shown).

3.4. Greenhouse gas fluxes

Measurement of soil greenhouse gas fluxes indicates that the average emissions of CO_2 were highest in the F treatment and lowest in the COMBI treatment. Organic amended soil reduced the emission of CO_2 by 16–33% compared to the F treatment (Fig. 4). As a consequence of higher total CO_2 flux over the trial, coupled to lower crop yield, the amount of CO_2 produced per unit of crop yield was significantly higher for the F treatment compared to organic amendments (Fig. 5), with approximately 28–46% more CO_2–C produced per unit of peanut produced in the F treatment than the organic amendments. In general, CO_2–C fluxes from soils containing amendments were lower than the F treatment. A significant exception was measured in March 2014 when CO_2–C fluxes from the B and Com treatments were approximately 0.2–0.3 kg ha^{-1} h^{-1} more than F (Fig. 6).

Fluxes of N_2O were highest in the F treatment and lowest in the Com treatment, although all amended plots did reduce N_2O flux relative to the F, with nearly 17–65% less N_2O produced per unit of peanut produced in the organic amended than F amended soil (Fig. 4). N_2O fluxes per unit peanut yield were lower in all organic amended treatments than the F treatment (Fig. 5). The organic amendments resulted in a 34–71% reduction in N_2O emission per unit yield, compared to the F only treatment (Fig. 5). N_2O flux in the B, Com and B + Com treatments exceeded that in the F treatment initially, but quickly dropped below F levels. After initially greater fluxes, only the Com treatment again exceeded F N_2O fluxes in March and May 2014 (Fig. 6).

4. Discussion

4.1. Response of peanut yield and plant growth to soil amendments

The application of organic amendments in this study had a significantly positive effect on the growth and yield of peanut, when applied together with normal fertilizer rate, supporting our second hypothesis that applications of organic amendments improve plant growth and crop yield. Our results, indicating an increase of 15 to 21% after organic amendment, are similar to those obtained in other studies. Yamato et al. (2006) reported a significant increase in peanut yield up to 50% following the application of 10 t ha^{-1} charred bark of *Acacia* biochar with 75 kg ha^{-1} of each NPK for an infertile soil in Indonesia. Peanuts grown on 15 t ha^{-1} farmyard manure biochar amended soil only in the first year along with 160, 16 and 42 kg ha^{-1} NPK resulted in yield increment of about 7% in the first year and 35% in the second year compared to only NPK fertilized plots (Islami et al., 2011).

Schulz et al. (2013) found that addition of 100 t ha^{-1} composted biochar to sandy and loamy soil increased growth of oat plants. Yield increases have also been reported for maize with the applications of 20 t ha^{-1} wood biochar + 159, 30 and 138 kg NPK ha^{-1} (Major et al., 2010) and 4 t ha^{-1} maize cob biochar + 154, 56 and 28 kg NPK ha^{-1} (Cornelissen et al., 2013). Addition of 30 t ha^{-1} biochar + 122 and 25 NP ha^{-1} resulted in wheat yield increment of 28–39% (Vaccari et al., 2011). In contrast, Sukartono et al. (2011) reported that addition of 15 t ha^{-1} cattle manure, cowdung biochar and coconut shell biochar with 135, 33 and 62 kg ha^{-1} NPK on a sandy soil resulted in 6.0, 5.9 and 5.7 t ha^{-1} maize, respectively in Indonesia. A review by Liu et al. (2013) concluded that, in spite of significant variation between individual studies, legumes generally exhibit a better response to biochar application

Table 7
Effects of soil amendments on soil chemical properties at the grain filling stage and trial end-point.

Treatments	Exchangeable cations (cmol(+)/kg)						EC (dS m^{-1})
	Ca	Mg	K	Na	CEC	Al	
Mid-point							
Control (F)	6.8	1.30 b	0.72 c	0.04	8.9 b	0.01 b	0.03
B + F	8.0	1.49 a	0.81 bc	0.05	10.3 a	0.03 a	0.04
Com + F	8.1	1.51 a	0.82 bc	0.04	10.5 a	0.02 ab	0.04
B + Com + F	7.9	1.51 a	0.93 ab	0.04	10.4 a	0.02 ab	0.04
COMBI + F	7.7	1.57 a	1.00 a	0.04	10.3 a	0.02 ab	0.04
p level	0.093	0.025	0.05	0.165	0.025	0.020	0.540
LSD (0.05)	1.0	0.15	0.18	0.01	0.93	0.01	0.01
CV (%)	7.0	5.4	11.4	15.7	4.9	18.9	19.4
End-point							
Control (F)	8.0	1.47	0.70	0.02 bc	10.3		0.04
B + F	8.0	1.41	0.77	0.03 ab	10.2		0.04
Com + F	8.2	1.47	0.80	0.02 bc	10.5		0.04
B + Com + F	8.5	1.52	0.91	0.02 c	11.0		0.04
COMBI + F	7.9	1.48	0.81	0.04 a	10.2		0.05
p level	0.961	0.955	0.247	0.026	0.911		0.648
LSD (0.05)	2.28	0.32	0.19	0.01	2.14		0.012
CV (%)	14.97	11.44	12.53	20.59	10.91		15.0

Within each column, means with different letters are significantly different at $p < 0.05$. *Note*: LSD: least significant difference; CV: coefficient of variation.

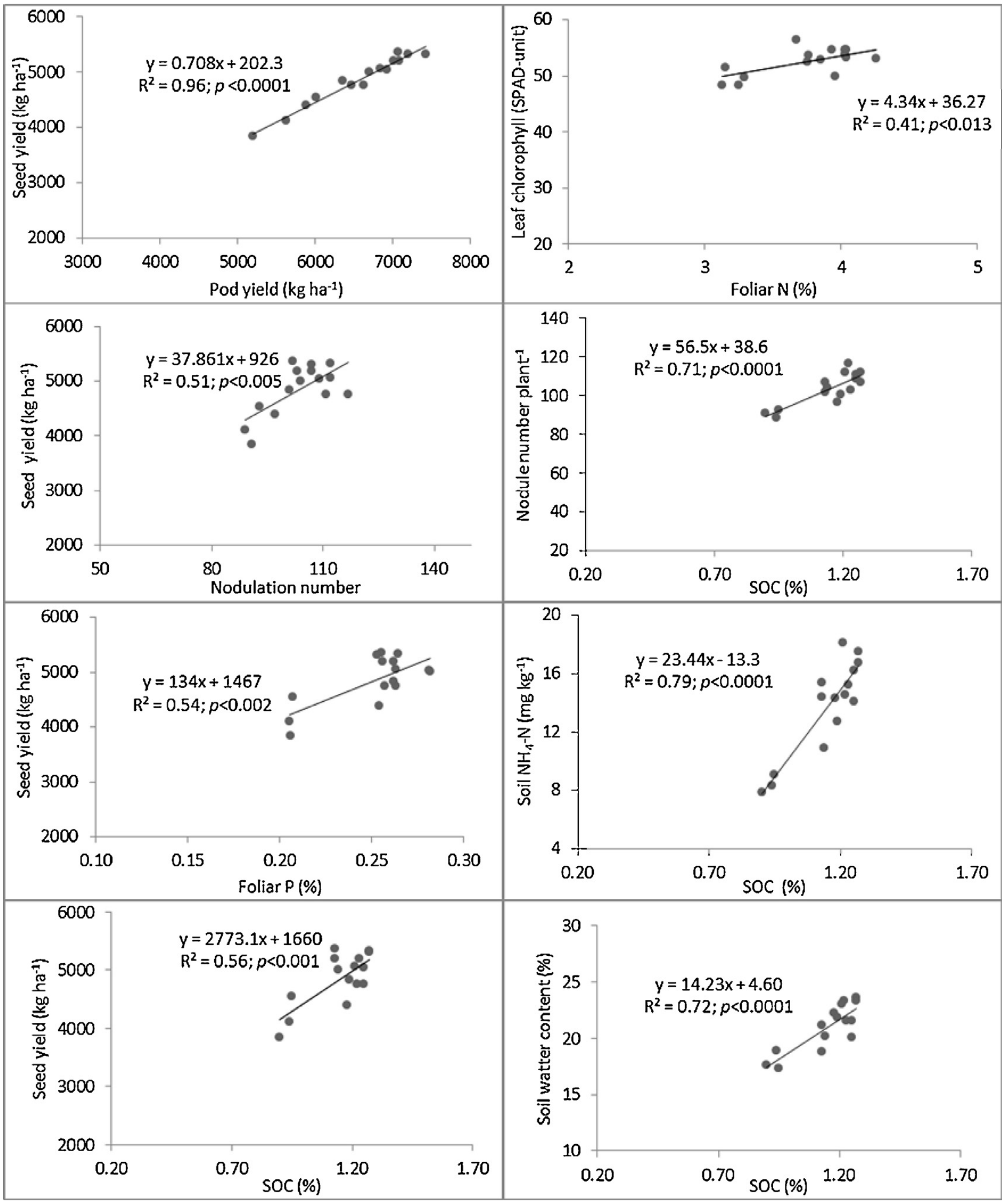

Fig. 2. Correlations of plant parameters, plant nutrient uptake and soil physicochemical properties ($n = 15$) tested at five soil fertility treatments. *Note:* SOC: soil organic carbon; NN: nodulation number.

than other crops, with average increases of 40% for seed yield and 25% for total biomass. For instance, the average increase in yield across all studies after biochar application was ~30, 29 and 14%, respectively for legumes, vegetables and grasses, and only 8, 11 and 7%, respectively for maize, wheat and rice.

Biochar soil amendment showed distinct crop productivity differences in relation to soil texture where biochar increased yield by about 30, 16, 7 and 7%, respectively for sand, clay, silt and loam soil (Liu et al., 2013). In this study, significant differences were observed in plant growth and yield between inorganic and organic treatments, but not amongst organic amendments. The yield improvement observed may be attributable to the improved nutrient and water retention capacity of the organic amendments and associated nutrient input relative to that in fertilizer-only treated soil. Thus the increase in yield due to organic amendments was in conformity with the expected improvements.

Chlorophyll content of leaves is a practical indicator of both potential photosynthetic productivity and general plant vigor, which is related to the N concentration in green plants and serves as a measure of the response of crops to N fertilizer application and soil nutrient status (Dana and Juan, 2004). The soil fertility effect on chlorophyll content in this study was significant in that chlorophyll content was considerably higher in organic amended plots than mineral fertilized only. All organic treatments with inorganic fertilizer led to a modest but significant improvement of leaf chlorophyll content. This is associated with increased soil available N and leaf N and may partly contribute to yield improvement. Other studies reported that the application of 40%

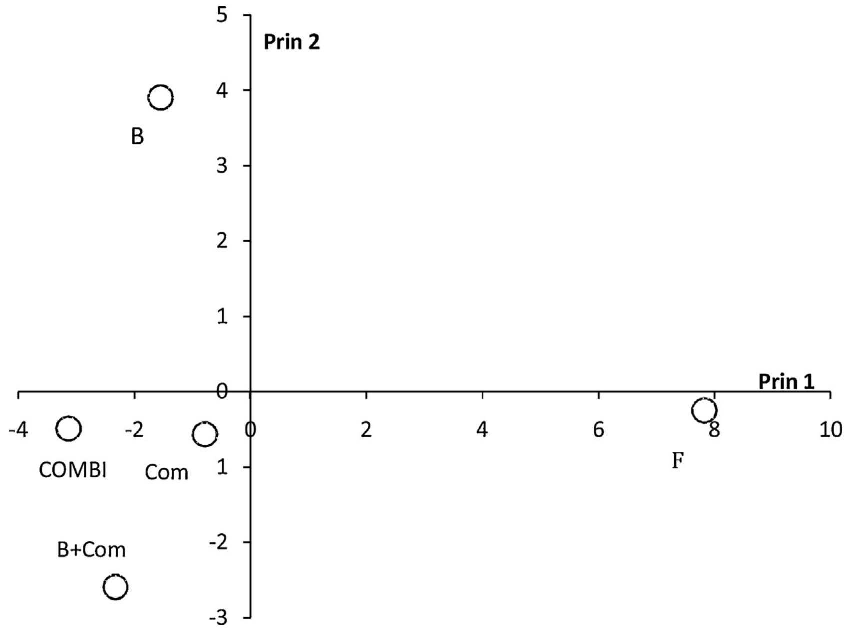

Fig. 3. Plot of principal component one and principal component two (Prin1 and Prin2) in 5 treatments. F: fertilizer; B: biochar; Com: compost; COMBI: co-composted biochar-compost.

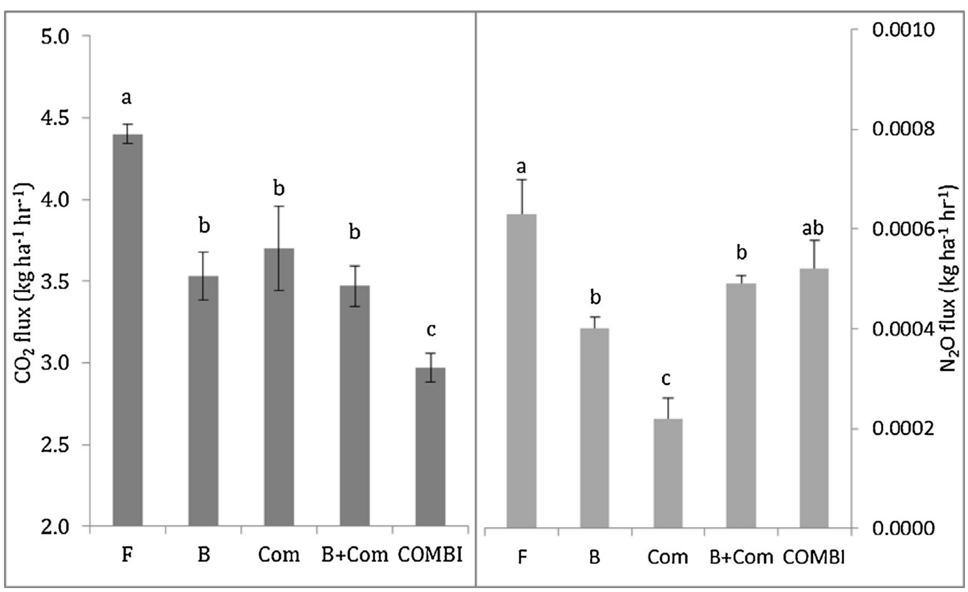

Fig. 4. The average fluxes of CO_2 and N_2O (kg ha^{-1} h^{-1}) from all treatments including all data from all sampling dates; LSD (p = 0.05) = 0.29 and 0.0001, and CV = 4.3 and 15.2 for CO_2 and N_2O, respectively). Columns with the same letter are not significantly different at p = 0.05. Error bars represent ± 1 SE.

(w/w) bamboo biochar increased chlorophyll contents of ryegrass by 20–32% (Hua et al., 2012), and maize by 8–12% due to 10 t ha^{-1} willow biochar + 140, 35 and 90 kg ha^{-1} NPK and 20 t ha^{-1} compost with the same NPK rate (Agegnehu et al., 2015) compared to fertilizer only. Minotta and Pinzauti (1996) found that total leaf chlorophyll content was almost doubled at high versus low soil fertility status with the incidence of high light.

We observed a trend of increasing leaf chlorophyll content with more advanced crop growth stage, which contributes greatly to the performance of the crop. This may be due to improved uptake of N by the growing plants supplied by the organic amendments. In spite of statistically insignificant, the highest SLW was recorded from the B and Com treatments, which is in agreement with the finding of Agegnehu et al. (2015). SLW increased across the treatments as the growth of plants progressed, with the difference being highest at plant maturity. SLW is related to the resistance or susceptibility of plant leaves to insect attack, with higher SLW providing higher resistance (Steinbauer, 2001).

4.2. Soil amendment effects on plant nutrient uptake

Organic amendments significantly improved total foliar N and C contents at mid growth stage, but not at the late growth stages of the plants, indicating that N is not limiting, not surprising for legumes as they can fix atmospheric N. Foliar NO_3–N, P and K concentrations were significantly increased due to the organic amendments during mid-plant growth stage, with the highest being from B + Com followed by COMBI. Higher NO_3–N and P uptake by the crop implies that organic amended soil maintained higher concentrations of these nutrients in the soil solution. The

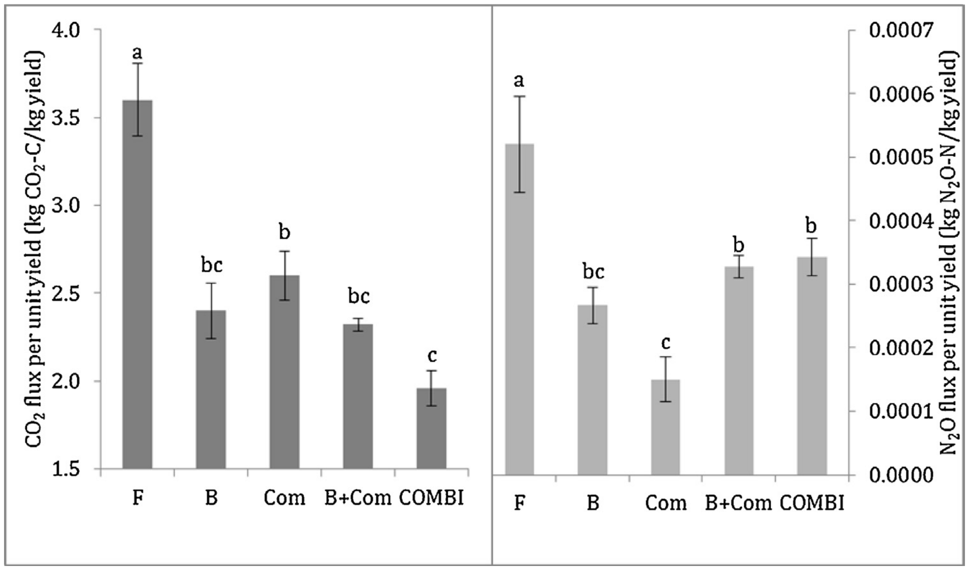

Fig. 5. Units of CO_2–C and N_2O–N produced per unit of peanut seed yield (kg CO_2–C and N_2O–N ha^{-1}/kg yield ha^{-1}); LSD ($p = 0.05$) = 0.41 and 0.0001, and CV = 8.6 and 18.9 for CO_2 and N_2O, respectively). Columns with the same letter are not significantly different at $p = 0.05$. Error bars represent ± 1 SE.

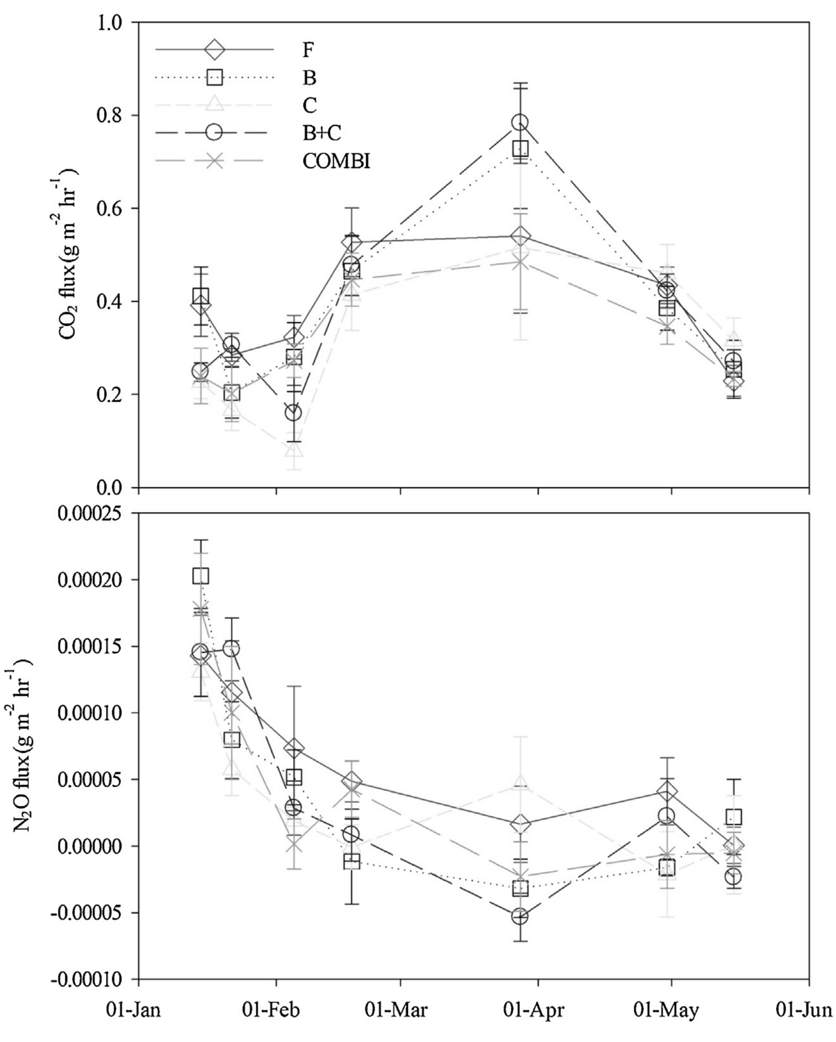

Fig. 6. The absolute increase/decrease in CO_2–C and N_2O–N flux from the four amendments compared to fertilizer only, where positive values indicate amounts above the concurrent *F* value and negative values indicate amounts below the concurrent *F* values. Error bars represent ± 1 SE.

decrease in NO_3–N, P and K concentrations with the plant age may be associated with progressive accumulation of these nutrients in biomass. Fageria (2014) reported a similar pattern of N, Ca and Mg decrease in bean plants with plant age.

Applications of B and Com singly or in combination increased foliar P contents by 11–19% at mid growth stage of plants compared to the F only treatment, implying that P is a limiting nutrient for growth at this site, as is commonly the case for of most legumes. The use of biochar and compost can supply the soil with P and improve its availability by reducing sorption and leaching. Other studies have reported that biochar and compost amended Ferralsols resulted in lower leaching and higher P uptake by plants (Agegnehu et al., 2015; Lehmann et al., 2003). Legume species differ widely in their ability to grow in soils of low P status. Hocking et al. (1997) has hypothesized that white lupin, and to a lesser extent pigeon pea, can access soil P from a pool that is relatively inaccessible to other legume species, but this is not the case for peanuts.

The stimulating effect of biochar on crop yield has been attributed to various mechanisms, depending on biochar, crop, soil type and trial conditions (Atkinson et al., 2010; Liu et al., 2013; Spokas et al., 2012). In our study, soil pH did not affect growth and yield of peanut, suggesting that the peanut yield response was due to the effect of biochar on nutrient availability and root nodulation; B, Com and their mixture increased the availability of some essential elements in the soil, including P, K and Mg. Because peanut can acquire N via nodules, P appears to be the major limiting nutrient for peanut yield on Ferralsols. Moreover, P supply is essential for the formation, development and function of nodules (Agegnehu and Tsige, 2006; Tang et al., 2001), thereby stimulating biological N fixation (Rondon et al., 2007). In our study, the organic amendments added very significant amount of available P (6–19 mg kg^{-1}), inferring that organic amendments can provide a slow-release P pool, additional to conventional fertilizer, through mineralization reactions (Slavich et al., 2013; Wang et al., 2012). This input contributes to the increase in soil available P and can be critical to alleviate the P limitation on peanut crops. Another common mechanism of biochar application to increase P availability is the liming effect that decreases P adsorption and facilitates P desorption from Al and Fe oxides (Cui et al., 2011; Glaser et al., 2002; Lehmann and Rondon, 2006; Yuan and Xu, 2011). However, this mechanism did not contribute to the increment of soil available P in our study due to the limited liming capacity of the biochar used in the study as demonstrated by the absence of any change in soil pH associated with biochar addition.

The treatment effect was significant for peanut seed isotope $\delta^{15}N$ composition, but not for $\delta^{13}C$, seed C and N content, and C:N ratio. Significantly higher $\delta^{15}N$ composition was obtained from F and B additions than other treatments, with the lowest values recorded from compost-containing treatments, suggesting promotion of atmospheric nitrogen fixation by the compost-containing treatments. The organic amendments had significant effects on root nodulation in that B, B + Com and COMBI amended soil significantly increased NN and NDW per plant. Mnalku (2011) found NN of 30–121 and NDW of 36–108 mg per plant. Other studies have shown that biochar can promote rhizobia nodulation of, and biological N fixation by, legume species (Biederman and Harpole, 2013; George et al., 2012; Quilliam et al., 2013; Tagoe et al., 2008; Xu et al., 2015).

The main reason for the higher root nodulation accompanying the organic amendments may be greater boron and molybdenum availability, whereas greater K, Ca and P availability as well as higher pH and lower N availability and Al saturation may have contributed to a lesser extent (Rondon et al., 2007). Root nodulation may be associated with other nutrients contributed by biochar and compost. For example, cobalt is an essential nutrient required by root nodule bacteria, boron is essential for legumes, and molybdenum is essential for N fixation because of its specific role in nitrogenase. Nutrient deficiencies in root nodule bacteria can affect a range of physiological functions, such as nutrient uptake, growth regulation and gene function (Sessitsch et al., 2002). Since peanut plants can fix N, leaves in the organic-amended soil displayed higher level of N (N > 3.2%) during peak growth stage (e.g., pegging stage) compared to the F treatment. In this case, increased level of total soil N including NO_3–N and NH_4–N following biochar and compost amendment did enhance leaf N. We observed a trend to increasing leaf N content from B, Com and B + Com amended soil, which might contribute to crop performance. Overall, enhanced N supply and nodulation associated with the organic amendments appears to improve peanut leaf N on a Ferralsol and this consequently may improve photosynthesis and yield.

4.3. Soil amendment effects on soil nutrient dynamics and GHG emissions

Applications of B, Com and their mixture appeared to address the major nutrient deficiencies of the soil at the trial site, which is in consistent with the results of pre-planting soil analysis results. SOC is an indicator of the soil organic matter content (SOM), which aerates the soil and helps retain water and nutrients. SOM also provides substrate for soil microbial biomass, which in turn make nutrients more plant-available. Studies have demonstrated that compost addition increased the quantity as well as the quality of SOM, thus improving soil quality (Fischer and Glaser, 2012; Rivero et al., 2004). Another study indicated that a sandy soil amended by manure and coconut shell biochars increased SOC and persisted after the harvest of the second crop, while SOC in manure treated soil was not significantly different from the fertilizer only treatment after the first and second maize harvest (Sukartono et al., 2011).

In this study, results of soil analysis at the mid-growth stage of plants indicated that B and COMBI amended soil increased SOC content by a factor of 1.4, and total N content by a factor of 1.3 compared with the initial SOC and N contents, respectively. Recent studies have reported that SOC was significantly increased due to the applications of different biochars (Angst et al., 2014; Slavich et al., 2013; Stavi and Lal, 2013). However, the SOC and total N contents of the soil in this study (although increased) were still below levels considered sufficient (1.8% for SOC and 0.25% for N), which may be due to high N uptake by plants, and high contents of above and below-ground plant residues. This research suggests that the Ferralsol of the study area (humid tropical Queensland) is deficient in SOC and total N, in turn suggesting that successive applications of B and B + Com will be beneficial to, over time, enhance the organic matter content, nutrient status, and nutrient and water retention capacity of the soil.

Nitrate is the form of soil N that is most readily available for plant uptake. Use of COMBI resulted in the highest total soil N and NO_3–N, implying that co-composted biochar-compost has been more effective in the retention of N during the composting process and in making the N plant available in the soil than compost or biochar alone. Co-composting of poultry manure and farmyard manure with biochar has previously been shown to reduce the losses of N in the mature composts (Dias et al., 2010; Prost et al., 2013). Adding acid biochar and co-composting reduced NH_3–N loss by 58 to 63% (Doydora et al., 2011), and total N losses by up to 52% (Steiner et al., 2010).

A review by Clough et al. (2013) showed that the available N in biochar amended soil is affected by complex processes including absorption, leaching, N mineralization, nitrification and N immobilization. Biochar application often immobilizes soil mineral N because of the input of labile C and increased soil C:N ratio (Ippolito et al., 2012) or fixes N through absorption (Reverchon et al., 2014), thereby reducing the fraction of N that is available for plants from plant-based biochar (Gaskin et al., 2010). Studies have also shown that N in plant-based biochars may be less available than that in biochar from animal manures (Chan et al., 2008; Tagoe et al., 2008).

Thus in some cases biochar application can decrease soil available N and plant tissue N concentration (Bargmann et al., 2014; de Sousa et al., 2014). However, Jones et al. (2012) reported that biochar addition had limited effects on the turnover of ^{14}C-labelled SOC, dissolved organic C and N, and no long-term effect on N mineralization, NH_3 volatilization, denitrification or NH_4 sorption. Since the N absorption and immobilization effects of biochar were small in our study, reduction of leaching due to biochar addition may have played a critical role in improving N retention (Agegnehu et al., 2015; Ding et al., 2010 Zheng et al., 2013). Biochar and COMBI addition increased soil N by 14% and 29%, respectively. This may be due to the amount of N added and low C:N ratio of the soil, which limits N immobilization. Soil C:N ratio over 32 promotes N immobilization (Bruun et al., 2012; Novak et al., 2010), significantly higher than that observed in this study. This study demonstrated positive effects of biochar, compost and their mixtures on SOC content, nutrients levels and water retention capacity of Ferralsol under field conditions, in agreement with the findings of Liu et al. (2012). Soil water contents recorded throughout the crop growing period were significantly lower in the F than in the organic treatments, suggesting that organic amendments enhanced water retention capacity of the soil, which confirms recent findings (Barrow, 2012; Troy et al., 2014).

The amendment of the soil with biochar and compost significantly improved the CEC of the soil, indicating that the retention of non-acidic cations by the soils increased. CEC is an important parameter in retaining inorganic nutrients such as K^+ and NH_4^+ in soil (Lee et al., 2013), and biochar has been associated with the enhancement in CEC of some biochar-amended soils (Glaser et al., 2001; Van Zwieten et al., 2010), thereby increasing the availability and retention of plant nutrients in soil and potentially increasing nutrient use efficiency. Biochar is not only a soil conditioner that increases CEC but may act as a fertilizer itself. Because biochar contains ash and so adds nutrients such as K, Ca and Mg to the soil solution, increasing the pH of the soil and providing readily available nutrients for plant growth (Glaser et al., 2002). Recent studies suggest that a K fertilization effect associated with biochar is critical for promoting growth, biological N fixation and the competitive ability of legume species (Mia et al., 2014; Oram et al., 2014; Xu et al., 2015). In this study, high K concentrations in the Com and COMBI treatments may also have contributed to the peanut yield response associated with the organic amendments, where a significant increase in soil available K was observed. In addition to P and K, the organic amendments also increased the availability of other plant nutrients, suggesting that a general improvement of soil fertility may contribute to stimulation of the yield of peanut.

Seed yield was positively correlated with pod yield, leaf chlorophyll, SWC, SOC, plant available nutrients and uptake. The direct effect on the performance of the peanut crop of available soil nutrients and plant nutrient uptake from B, B + Com and COMBI amended soil exceeded the direct effect of available nutrients and nutrient uptake from the Com and F treatments. Correlation of seed yield with SOC was the highest, and the B, B + Com and COMBI amended soil improved the retention and availability of nutrients in this study. Available soil Mg, NO_3–N and NH_4–N had a more significant influence on the seed yield, chlorophyll content and NN than other nutrients, suggesting that these nutrients were most limiting to yield. Recent studies have also shown positive linear correlations between soil chemical characteristics, shoot and root growth of maize and wheat as a result of addition of different biochar types (Agegnehu et al., 2015; Solaiman et al., 2012).

Principal component analysis (PCA) indicated that Prin1 and Prin2 provided a reasonable summary of the data, accounting for about 85% of the total variance. In this study, several characters in the first eigenvector individually contributed similar effects to the total variation of the treatments, suggesting that the first component is primarily a measure of most characters. Thus, the differentiation of the treatments into different clusters was dictated by the cumulative effects of several characters. Other studies also compared the effects of different soil amendments using PCA (Agegnehu et al., 2015; Sena et al., 2002). According to the bi-plot of Prin1 and Prin2, the treatments can be grouped into four classes, that is F, B, Com, with COMBI along with B + Com behaving similarly, suggesting there is no difference between COMBI and B + Com added together at the point of application to the soil.

The fluxes of CO_2 and N_2O were generally lower in organic-amended plots than the control, but the magnitudes of these differences were not constant across the trial. For example, the B and B + Com at the beginning of April exceeded the control CO_2 flux by a significant amount, but this declined and the fluxes from these treatments remained similar for the rest of the trial. This implies that any labile carbon remaining in the biochar was quickly utilized and left only a relatively refractory pool from then on. Similarly, N_2O flux was highest initially for B, but this was finally significantly reduced. Kammann et al. (2012) reported that wood chip biochar addition significantly reduced CO_2 and N_2O emissions and improved the GHG-to-yield ratio under field-relevant conditions. A similar study showed that soil N_2O fluxes were from 26% to 79% lower in biochar treated plots than N_2O fluxes in control plots (Castaldi et al., 2011). A study by Zhang et al. (2012) also indicated that use of 40 t ha^{-1} wheat straw biochar decreased total global warming potential of CH_4 and N_2O by about 42% without N fertilization and 48% with N fertilization.

5. Conclusion

Our results indicate that biochar and/or compost in a range of combinations added as soil amendments with supplementary fertilizer can improve soil health and boost productivity of peanut with the additional environmental benefits of global warming mitigation. This approach can therefore contribute positively to agricultural and environmental sustainability. Biochar and biochar-compost applications positively impact soil fertility, for example, through their effect on SOC, CEC and plant available nutrients. Significant increases in peanut yield and plant available soil nutrients were observed due to biochar and compost addition in comparison to the fertilizer only treatment, indicating that application of organic amendments does provide agronomic benefits. The response of peanut to biochar and compost could be due to their effects on plant available nutrients, biological N fixation, soil water and nutrient retention, although other mechanisms cannot be discounted. There was no additional benefit of co-composting biochar with compost compared to simply adding them on the field together, although there might be benefits in terms of reducing the time of the composting process. Further research is required to verify the residual effects of biochar and biochar-compost soil amendments on sustainable crop yield, C sequestration and soil quality on Ferralsols. Moreover, the amount of conventional fertilizer that could be reduced and the resultant economic benefit because of biochar and compost addition needs to be determined for longer-term economic and environmental sustainability.

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