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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

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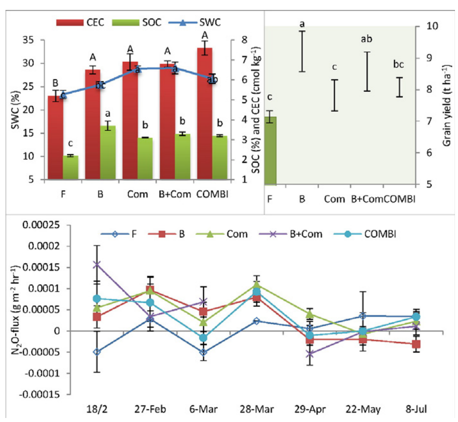
HIGHLIGHTS

- 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.

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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 plants. Soil pH, exchangeable cations, CEC, EC, NO_3^- N and NH_4^+-N contents were determined by the ARL Pty Ltd. 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 on 1:50 soil solution extracts in 0.5 M sodium bicarbonate after end-over-end shaking 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 NO_3^- N and NH_4^+-N were determined colorimetrically by an automated photometer using 1 M KCl extraction method (Rayment and Lyons, 2011).

2.2. Trial set-up

The feedstock for biochar production was waste willow wood (*Salix spp.*) derived from removal and restoration activities. 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 550 °C. The biochar was ground to <10 mm prior to delivery in a Keenan spreader. Two paired compost 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 another one compost only. The biochar (equivalent to 18 m^3 by volume) was added to 80 m^3 each of green waste and bagasse, 12.5 m^3 of chicken manure and 12 m^3 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. After composting, the COMBI amendment contained ~20% biochar. Biochar, compost and COMBI samples were collected randomly from all materials before application in the field for nutrient analysis (Table 2).

The experiment comprised five treatments in triplicate, where each replicate occupied 0.13 ha (240 m long by 6 rows with a row spacing of 0.91 m), planted following a peanut crop. The treatments were: 1) fertilizer as a control (F); 2) willow biochar (B) applied at 10 t ha^{-1}; 3) compost (Com) applied at 25 t ha^{-1}; 4) 2.5 t ha^{-1} B + 25 t ha^{-1} Com mixed on site (B + Com); and 5) co-composted biochar–compost (COMBI) applied at 25 t ha^{-1}. The experimental field was strip plowed and all amendments were applied before planting and mechanically mixed into the upper 10 cm. Maize, variety ATW1 treated with vitavax fungicide, was planted at 6000 seeds ha^{-1} on 13 February 2014. Fertilizer was applied in the row as DAP (di-ammonium phosphate; 18% N, 20% P, 1.6%S) at 186 kg ha^{-1}, as urea and muriate of potash across all treatments followed by Nipro FlowPhos 13Z (9% N, 13.5% P, 1%K, 0.9% Zn) at 30 L ha^{-1}. In addition, Rutec Zn 7000 (70%*w*/*v* Zn; 6.9%*w*/*v* N) was applied across all treatments at 0.3 L ha^{-1} twenty-one days post emergence. This equates to a total fertilizer application of 150 kg ha^{-1} N, 41 kg ha^{-1} P, 120 kg ha^{-1} K and 3 kg ha^{-1} S. Other agronomic practices were applied during the crop growth period as per usual farm practice. The total rainfall during the crop growing period was 723.2 mm.

2.3. Measurements during trial

After planting, periodic sampling and measurements of soil parameters, leaf chlorophyll, specific leaf weight and emission of carbon dioxide (CO_2) and nitrous oxide (N_2O) were undertaken from all three replicates of each treatment over all sampling dates. The measurements of CO_2 and N_2O were undertaken on days 5, 14, 21, 43, 75, 98 and 145 after planting (18 February–8 July 2014), in conjunction with SWC. CO_2 and N_2O fluxes were measured with a standard closed chamber methodology using an INNOVA 1412i field portable photoacoustic gas analyzer (LumaSense Technologies, Ballerup, Denmark). Build-up of gases in the headspace was measured over 4–8 min, depending on

Table 1
Pre-planting soil properties from samples collected at depths of 0–0.30 cm and 30–100 cm in December, 2013 (n = 9; ±SE).

Parameters	Unit	Limit of detection	0–30 cm	SE	30–100 cm	SE
Water content	%*w*/*w*		r19	0.28	21.7	0.50
pH (H_2O)	Units		5.6	0.09	6.3	0.03
pH ($CaCl_2$)	Units		5.1	0.08	6.3	0.04
Total N	%*w*/*w*		0.14	0.01	0.04	0.01
Total organic C	%*w*/*w*		2.01	0.07	0.61	0.15
C:N ratio			15.5	0.3	15.4	1.4
Carbon stock	t ha^{-1}		37.6	2.5	30.7	7.0
Colwell P	mg kg^{-1}	1.00	17.3	2.1	9.6	1.40
NH_4-N	mg kg^{-1}	nd	nd	nd	7.7	1.10
NO_3-N	mg kg$^-$1	nd	nd	nd	20.9	2.12
Conductivity	uS cm^{-1}	1.00	0.13	0.01	0.05	0.00
Exch. Na	cmol(+) kg^{-1}	0.01	0.06	0.0	0.03	0.00
Exch. K	cmol(+) kg^{-1}	0.01	0.58	0.11	0.12	0.01
Exch. Ca	cmol(+) kg^{-1}	0.01	3.9	0.45	2.5	0.23
Exch. Mg	cmol(+) kg^{-1}	0.01	0.87	0.07	0.60	0.05
Exch. Al	cmol(+) kg^{-1}	0.02	0.07	0.0		
CEC	cmol(+) kg^{-1}	0.02	5.4	0.47	nd	nd
S	mg kg^{-1}	1.00	37.4	6.3	nd	nd
Cu	mg kg^{-1}	0.05	1.7	0.14	nd	nd
Zn	mg kg^{-1}	0.05	<0.05	0.0	nd	nd
Mn	mg kg^{-1}	0.50	290	37	nd	nd
Fe	mg kg^{-1}	0.50	9.3	0.33	nd	nd
B	mg kg^{-1}	0.05	0.48	0.03	nd	nd

nd: not determined.

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	nd
Carbon (C)	%	47.5	30.6	34.7
Nitrogen (N)	%	0.38	1.19	0.95
$\delta^{15}N$	‰	n/d	+7.5	+7.8
$\delta^{13}C$	‰	nd	−24.3	−21.3
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	nd
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
Acidity	cmol(+)/kg	n/d	0.3	0.11
CEC	cmol(+)/kg	11.2	8.77	8.81
EC (1:5)	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

CEC: cation exchange capacity; EC: electrical conductivity; nd: not determined.

flux, at 45-second intervals. Duplicate soil collars (15-cm diameter) remained in place in each plot for the trial duration (n = 6 per treatment). The average GHG fluxes were calculated from all three replicates over all sampling dates of each treatment. Those values therefore encompass the temporal and spatial variability. For total GHG flux over the trial period for each treatment was calculated from the area under each temporal curve via trapezoidal integration. SWC at 0–12 cm depth was taken at planting using a HydroSense II probe (Campbell Scientific, Inc.).

Relative leaf chlorophyll content was measured using a SPAD-502 (Konica Minolta, Tokyo) based on transmittance at wavelength regions 650 nm (for chlorophyll) and 940 nm (as a control). The measurements were undertaken on days 38, 46, 58, 70, 88 and 102 after planting in conjunction with the collection of leaf punch samples for the determination of specific leaf weight and leaf water content. 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 from all three replicates of each treatment. A hole-punch with a diameter of 8 mm was used to take a leaf disk from the middle of the leaf lamella from leaves of the same age and position from each replicate. Leaf disks were transferred immediately to individual, sealed plastic bags that were kept in an insulated box above ice packs until processed. Leaf disks were weighed before being dried at 60 °C and re-weighed. The number of plants and cobs per plant per 5 m or row were counted at physiological maturity. The crop was harvested on 17 June 2014. After harvest, above-ground biomass, grain yield and yield components of maize were determined. Total biomass and grain yield of maize recorded on plot basis was converted to kg ha^{-1} for statistical analysis.

Ten leaf samples were clipped at their base prior to tasselling and stored for the determination of C, N, P, K and NO_3^- N contents. Total plant N and C concentrations were determined using an elemental analyzer (ECS 4010 CHNSO Analyzer; Costech Analytical Technologies INC, Valencia, CA, USA) fitted with a Zero Blank Auto-sampler (Costech Analytical Technologies, INC) at James Cook University's Advanced Analytical Centre, Cairns, Australia. Plant P, K and NO_3-concentrations were quantified at ARL. NO_3-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 and Isaac, 1990). Plant P content was determined photometrically in the same digest with the molybdenum blue method (Mills and Jones, 1996). Total N and C contents and isotopic composition of oven-dried maize grain samples were also determined using the ECS 4010 CHNSO Analyzer and a ThermoFinnigan DeltaVPLUS Continuous-Flow Isotope Ratio Mass Spectrometer (EA-IRMS) at James Cook University. Stable isotope results are reported as per mil (‰) deviations from the VPDB reference standard scale for $\delta^{13}C$ and from the international air standard for $\delta^{15}N$. Precisions on internal standards were better than ±0.2‰ for both isotope determinations.

2.4. Data analysis

The data were subjected to analysis of variance using the general linear model procedure (PROC GLM) of SAS statistical package version 9.2 (SAS Institute 2008, Cary, NC). The total variability for each trait was quantified using the following model.

$$Y_{ij} = u + R_i + T_j + e_{ijk}$$

where Y_{ij} is the measured value, μ = grand mean, R_i is effect of the ith replication, T_j is effect of the jth 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. Correlation analysis was performed between plant parameters, nutrient uptake and soil nutrient contents using the SAS CORR procedure.

3. Results

3.1. Plant growth and yield

The application of biochar and compost individually, or in combination, had positive effects on most of the measured plant parameters. The treatments yielded significantly ($p < 0.01$) higher total biomass and grain yield than F only amended (Table 3). The addition of B + F resulted in the highest maize total biomass and grain yield (Table 3). In contrast, the maximum number of plants, 4.5 m^{-2}, was recorded from the F only treatment (data not shown), in which the total biomass and grain yield were the lowest of all treatments. Compost and COMBI + F amended plots had higher 100-grain weights than other treatments, indicating that organic soil amendments had positive effects on grain filling. Compared to F alone, grain yield and total biomass were higher by 29, 10, 20 and 13% and 17.7, 14, 7.6 and 12%, respectively for B + F, Com + F, B + Com + F and COMBI + F (Table 3). There was no significant effect of treatments on harvest index.

The average leaf chlorophyll measured during the crop growth period was significantly ($p < 0.01$) increased by the organic treatments until late in the trial period, with a decrease following grain filling and leaf senescence (Fig. 1). Leaf chlorophyll was broadly similar across all plots amended by organic treatments. Addition of organic amendments increased the average leaf chlorophyll by 4.2 to 5.7% over F alone, which indicates healthier plants, explaining the higher biomass and grain yields. Analysis of variance over the sampling time revealed that soil amendments by chlorophyll sampling date interaction also significantly ($p < 0.01$) influenced leaf chlorophyll content (Fig. 1). Average specific leaf weight (SLW) and leaf water content (LWC) did not differ significantly between any treatments at any time. However, SLW increased with plant age (Table 3). Percentage LWC was inversely correlated with SLW, so the LWC decreased as the growth of plants progressed (Table 3). Despite numerical variations, significant differences were not observed among organic amendments including compost for most measurements of agronomic and soil parameters.

3.2. Plant nutrient status and grain quality

The organic amendments significantly ($p < 0.05$ and $p < 0.01$) increased foliar N and P concentrations for samples taken prior to tasseling (Table 4). Leaf N and P concentrations ranged from 3.2 to 3.6% and 0.28 to 0.40%, respectively, with the lowest being from the control (F). The leaf N and P concentrations in the B + F, Com + F, B + Com + F and COMBI + F treatments were higher by 4.7–13.4% and 10.6–41.3%,

Table 3
Effects of biochar, compost and their mixture on growth and yield of maize.

Treatments	GY (t ha^{-1})	TBY (t ha^{-1})	HI (%)	HGW (g)	Av. CHLC (SPAD-unit)	Av. SLW (mg mm^{-2})	Av. LWC (%)
Control (F)	7.14 c	17.87 b	39.9	34.7 b	47.4 b	0.049	74.4
B + F	9.21 a	21.04 a	43.8	33.5 b	49.4 a	0.049	75.3
Com + F	7.82 bc	20.81 a	37.6	38.1 a	50.0 a	0.050	74.7
B + Com + F	8.57 ab	19.46 ab	44.1	35.0 b	49.5 a	0.049	75.2
COMBI + F	8.08 bc	20.21 a	40.0	39.1 a	50.1 a	0.051	74.7
p value	0.016	0.017	0.152	0.011	0.001	0.174	0.825
LSD (0.05)	1.05	1.73	5.9	3.0	1.30	0.002	2.1
CV (%)	6.8	4.6	7.6	4.4	1.4	2.5	1.5

Within each column, means with different letters are significantly different at $p < 0.05$. Av. CHLC: average chlorophyll content (average of six temporal measurements); GY: grain yield; TBY: total biomass yield; HI: harvest index; HGW: hundred grain weight; LSD: least significant difference; CV: coefficient of variation.

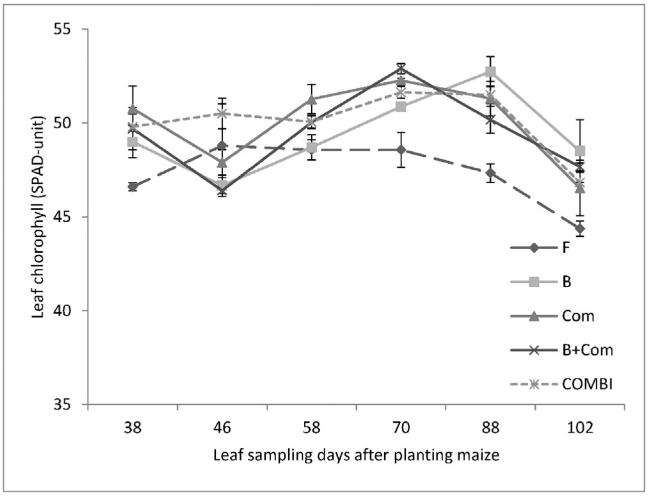

Fig. 1. Mean leaf chlorophyll content as influenced by the interaction of treatments and time of measurements after planting maize (n = 90). Error bars represent ± 1SE.

respectively, than that of F. The ratio of leaf N:P was 10.5 to 11.0 for all treatments.

Grain δ^{15}N and δ^{13}C values significantly differed among treatments, with the highest for both being from B + F, and the lowest from the F only treatment. Applications of B + F, Com + F, B + Com + F and COMBI + F increased grain δ^{15}N by 2.2, 1.5, 1.3 and 1.7 times, respectively relative to the F alone treatment (Table 4). Com + F and B + Com + F soil amendments resulted in lower δ^{13}C values of −10.9 and −11.0 ‰, respectively than other treatments. Grain contents of C and N and C:N ratios were not significantly different between any treatments (Table 4). Grain protein content did not differ significantly among the treatments (Table 4), ranging from 10.4% to 11.0%, which is within the optimum range (Gupta et al., 2009).

3.3. Soil physicochemical properties

Soil physical and chemical properties at mid-season growth stage and after harvest under the different treatments are presented in Tables 5 and 6. Soil water content (SWC) was significantly ($p < 0.05$) increased by all organic treatments on average throughout the trial with the difference between organic amendments and conventional practice being greatest in the dry season as the crop matured (Table 5). The average maximum SWC was higher by 9, 23.6, 24.5 and 14.6% as a result of the additions of B + F, Com + F, B + Com + F and COMBI + F, respectively, as compared to the F only treatment (Table 5). The treatments had no significant effect on soil bulk density.

SOC content was significantly ($p < 0.01$) increased by all organic treatments at the mid-season sampling, but not by the end of the trial period. However, soils from treatments that included biochar will have had their carbon stock increased by the amount of biochar added, with a long-term sequestration potential of 0.62 t C per ton of biochar added. This is not evident in the data presented as much of the biochar is >2 mm and hence does not contribute to the <2 mm fraction of soil analyzed. The organic amendments significantly ($p \leq 0.05$) increased some soil chemical parameters, including total N, available P, NO_3^- N and NH_4^+-N and C:N ratio at trial mid-season but a systematic difference was not apparent by the trial end-season (Table 5). Although numerically higher values were observed in soils treated with organic amendments, soil pH was not consistently and significantly influenced by any treatment at any point (Table 5).

At the mid-season sampling, the highest SOC content and C:N ratio were obtained from B + F addition, and soil N contents from Com + F and COMBI + F, but there were no statistically significant differences among Com + F, B + Com + F and COMBI + F treatments for SOC (Table 5). The highest plant available P content was obtained from COMBI + F, and soil NH_4^+-N and NO_3^- N from B + Com + F soil amendment. Applications of B + F, Com + F, B + Com + F and COMBI + F increased SOC contents 1.7, 1.4, 1.5 and 1.5 times, and N contents 1.1, 1.2, 1.1 and 1.2 times, respectively, in comparison to the F only treatment (Table 5). Biochar, Com + F, B + Com + F and COMBI + F increased soil available P 1.1, 1.4, 1.4 and 1.5 times, respectively that of the F only treatment. Soil NH_4^+-N content was increased by a factor of 1.3, 1.4, 1.9 and 1.4, and soil NO_3^- N by a factor of 1.2, 1.1, 1.7 and 1.4 with the respective application of B + F, Com + F, B + Com + F and COMBI + F compared to F (Table 5). Moreover, despite the lower magnitude of response in comparison to mid-season growth stage, C:N ratio, soil available P and NH_4^+-N were increased by the organic amendments at trial end-season. Soil NO_3^- N content showed significant response to the treatments at harvest, but with lower magnitude and inconsistent trend compared to the mid-season growth stage. SOC content by and large decreased in the order B + F > B + Com + F > COMBI + F > Com + F > F (Table 5).

Pre-planting contents of available soil P, Ca, Mg, Na, Zn and B were low, and Mn high (Hazelton and Murphy, 2007). Soil exchangeable Ca, Mg, Na and CEC were significantly ($p < 0.05$) enhanced by all organic amendments throughout the trial period. Exchangeable K and Al concentrations were significantly changed by the treatments only at mid-season growth stage, but a systematic difference was not observed at the trial end-season (Table 6). In contrast, the soil EC did not significantly vary throughout the trial period. Application of B + F, Com + F, B + Com + F and COMBI + F increased soil K content 1.2, 1.5, 1.3 and 1.6 times, and Mg content 1.1, 1.5, 1.4 and 1.4 times, respectively, compared to the F only treatment. Application of B + F, B + Com + F and COMBI + F resulted in significantly higher soil Mg content than B + F and F alone treatments. In contrast, COMBI + F-amended soil achieved the highest soil K and Na contents and CEC, but significantly reduced soil Al content compared to B + F and F only treatments. In B + F, Com + F, B + Com + F and COMBI + F treated soil CEC was higher by a factor of 1.2, 1.3, 1.2 and 1.5, and Ca by a factor of 1.2, 1.3, 1.3 and 1.5, respectively, compared to the control. Use of B + F, Com + F, B + Com + F

Table 4
Effects of biochar, compost and their mixture on leaf nutrient concentration and kernel C and N content, isotopic composition and protein content.

Treatment	Mid-season leaf nutrient content						Kernel isotope		C and N content			Protein content (%)
	C (%)	N (%)	C:N ratio	K (%)	P (%)	N:P ratio	δ^{13}C (‰)	δ^{15}N (‰)	C (%)	N (%)	C:N ratio	
F	43.0	3.21 b	13.4	3.62	0.28 b	11.5 a	−10.7 ab	0.63 d	43.7	1.75	25.1	10.9
B + F	44.7	3.53 a	12.7	3.17	0.31 b	11.3 a	−10.6 a	1.36 a	44.3	1.67	26.5	10.4
Com + F	45.0	3.36 ab	13.4	3.66	0.38 a	9.2 b	−10.9 bc	0.96 c	44.6	1.75	25.5	11.0
B + Com + F	44.1	3.48 ab	12.7	3.77	0.39 a	9.1 b	−11.0 c	0.84 c	43.6	1.75	25.0	11.0
COMBI + F	45.4	3.64 a	12.5	4.21	0.40a	8.9 b	−10.7 ab	1.09 b	43.2	1.69	25.7	10.5
p level	0.152	0.050	0.220	0.074	0.001	0.026	0.032	0.018	0.194	0.446	0.386	0.413
LSD (0.05)	1.97	0.29	1.07	0.67	0.04	1.9	0.28	0.38	1.23	0.18	1.77	0.79
CV (%)	2.4	4.3	4.4	9.7	6.6	10.1	−1.4	20.5	1.52	5.5	3.7	3.9

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

Table 5
Treatment effects on soil physicochemical properties at the mid-season (grain filling) stage and trial end-season.

Treatments	SBD ($g\ cm^{-3}$)	Av. SWC (%)	pH (H_2O)	SOC (%)	N (%)	C:N ratio	Nutrient content ($mg\ kg^{-1}$)		
							P	NH_4^+-N	NO_3^- N
Mid-season									
F	0.75	23.3 c	5.41	2.15 c	0.15 c	14.1 c	24.0 b	30.0 c	29.6 c
B + F	0.72	25.4 bc	5.67	3.73 a	0.16 bc	23.3 a	27.0 b	38.8 bc	36.5 bc
Com + F	0.79	28.8 ab	5.82	3.11 b	0.18 a	17.8 b	34.3 a	41.3 b	32.6 bc
B + Com + F	0.81	29.0 a	5.65	3.32 b	0.17 ab	20.0 b	33.0 a	57.3 a	51.1 a
COMBI + F	0.76	26.7 abc	5.84	3.19 b	0.18 a	18.2 b	36.7 a	41.8 b	41.9 ab
p level	0.549	0.016	0.268	0.001	0.034	0.002	0.003	0.003	0.011
LSD (0.05)	0.12	3.2	0.32	0.36	0.02	3.1	5.5	10.1	10.7
CV (%)	8.6	6.3	3.0	6.1	5.4	8.7	9.4	12.8	14.9
End-season									
F	0.76	24.7	5.76	3.09	0.18	17.2	20.8 b	27.7	18.1 bc
B + F	0.78	24.5	5.92	3.34	0.17	19.6	19.5 b	29.6	14.1 c
Com + F	0.76	23.0	6.00	3.22	0.18	17.9	25.7 b	33.7	8.5 d
B + Com + F	0.78	21.8	5.86	3.34	0.18	18.6	21.2 b	31.1	23.3 a
COMBI + F	0.76	22.8	6.00	3.24	0.17	19.1	36.7 a	30.4	21.7 ab
p level	0.949	0.246	0.182	0.143	0.115	0.004	0.005	0.074	0.001
LSD (0.05)	0.09	3.07	0.23	0.22	0.009	0.71	7.76	3.98	4.70
CV (%)	5.96	7.00	2.04	3.55	2.62	2.05	16.65	6.94	14.56

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

and COMBI + F reduced Al content by 27, 64, 68 and 77%, respectively, compared to the F only treatment (Table 6).

Grain yield was correlated significantly and positively with total biomass, leaf chlorophyll, leaf N and P content, SOC and SWC (r = 0.81, 0.65, 0.74, 0.72, 0.63 and 0.64, respectively), but not significantly correlated with SLW, grain $\delta^{15}N$ content or soil NO_3^- N content. Leaf chlorophyll was correlated significantly and positively with total soil N, leaf N and P concentration and CEC of the soil (r = 0.78, 0.74, 0.69 and 0.75, respectively). Soil available P content was strongly correlated with soil CEC and exchangeable Mg and Ca (r = 0.85, 0.77 and 0.79, respectively, Table 7). Exchangeable Ca was strongly correlated with the CEC of the soil (r = 0.96, Table 7).

3.4. Greenhouse gas (GHG) emissions

The highest average emissions of CO_2 and N_2O over the entire growing season were recorded from Com + F and the lowest from the F only treatment (Fig. 2). In this study, the average CO_2 and N_2O fluxes were in the order Com + F > B + Com + F > COMBI + F > B + F > F (Fig. 2). In terms of GHG emissions relative to maize yield, the CO_2 and N_2O emissions from the Com + F treatment were higher than other treatments (Fig. 2). CO_2 emissions varied erratically over time for all treatments, and in general CO_2 emissions from the organic amended treatments were higher than those from the fertilizer only treatment (Fig. 3). N_2O emissions generally decreased over time for all treatments, and at the end of the trial period emission for B + F was lower than other treatments (Fig. 3). In general, while N_2O fluxes were higher from organic amended treatments for the first two months, after this period fluxes were significantly lower than the F only treatment.

4. Discussion

4.1. Plant growth, yield and nutrient uptake

Our findings indicate that application of all organic amendments promoted growth and productivity of maize. Total biomass and yield were significantly increased by the organic amendments, with grain yield and total biomass increments of 10–29% and 9–18%, respectively relative to the control. These improvements in crop performance are consistent with other studies (Major et al., 2010; Mekuria et al., 2014; Uzoma et al., 2011; Zhang et al., 2016) and may be attributed to improved availability of nutrients and soil moisture. Previous studies

Table 6
Treatment effects on soil chemical properties at the grain filling stage and trial end-season.

Treatments	Exchangeable cations ($cmol(+)\ kg^{-1}$)						EC ($dS\ m^{-1}$)
	Ca	Mg	K	Na	Al	CEC	
Mid-season							
F	4.1 b	0.59 b	0.49 c	0.023 c	0.22 a	5.2 b	0.110
B + F	5.1 ab	0.67 b	0.57 bc	0.023 c	0.16 b	6.5 a	0.110
Com + F	5.2 ab	0.90 a	0.72 a	0.030 ab	0.08 c	6.9 a	0.093
B + Com + F	5.1 ab	0.83 a	0.66 ab	0.027 bc	0.07 c	6.8 a	0.130
COMBI + F	6.0 a	0.82 a	0.78 a	0.033 a	0.05 c	7.6 a	0.090
p level	0.037	0.005	0.011	0.028	0.001	0.010	0.198
LSD (0.05)	1.20	0.10	0.14	0.006	0.037	1.1	0.037
CV (%)	10.7	7	12	12.5	17.1	8.6	18.7
End-season							
F	4.03 b	0.50 c	0.49	0.01 d		5.23 b	0.04
B + F	4.93 ab	0.61 bc	0.54	0.02 c		6.20 ab	0.04
Com + F	5.53 a	0.74 ab	0.54	0.02 c		6.93 a	0.04
B + Com + F	4.93 ab	0.76 a	0.61	0.03 b		6.50 ab	0.04
COMBI + F	6.13 a	0.74 ab	0.53	0.04 a		7.47 a	0.05
p level	0.050	0.008	0.285	0.001		0.035	0.648
LSD (0.05)	1.42	0.13	0.11	0.01		1.30	0.012
CV (%)	12.71	10.41	11.18	22.18		10.68	15.0

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

Table 7
Correlation coefficients among plant parameters, soil water content, contents of soil and plant nutrients tested at five soil fertility treatments in 2014 in north Queensland, Australia.

Character	SWC	Soil NH_4^+	Soil NO_3^-	CEC	Exch. K	Exch. Mg	Exch. Ca	Av. P	Total N	SOC	pH (H_2O)	Grain $\delta^{15}N$	Leaf P	Leaf N	Leaf C	SLW	CHLC	HI	TBY
GY	0.63^{*}	0.53^{*}	0.18^{ns}	0.57^{*}	0.62^{*}	0.53^{*}	0.56^{*}	0.52^{*}	0.59^{*}	0.64^{*}	0.58^{*}	0.41^{ns}	0.72^{**}	0.74^{**}	0.55^{*}	-0.35^{ns}	0.65^{**}	0.55^{*}	0.81^{**}
TBY	0.65^{**}	0.63^{*}	0.21^{ns}	0.54^{*}	0.56^{*}	0.46^{ns}	0.52^{*}	0.50^{*}	0.56^{*}	0.57^{*}	0.65^{**}	0.15^{ns}	0.71^{**}	0.75^{**}	0.55^{*}	-0.33^{ns}	0.74^{**}	-0.11^{ns}	
HI	0.25^{ns}	0.14^{ns}	0.55^{*}	-0.06^{ns}	-0.20^{ns}	-0.30^{ns}	-0.02^{ns}	0.20^{ns}	0.44^{ns}	0.27^{ns}	0.08^{ns}	-0.11^{ns}	0.10^{ns}	0.52^{*}	0.60^{*}	-0.15^{ns}	-0.10^{ns}		
CHLC	0.59^{*}	0.52^{*}	0.28^{ns}	0.75^{**}	0.62^{*}	0.71^{**}	0.63^{**}	0.65^{**}	0.78^{**}	0.60^{*}	0.72^{**}	0.47^{ns}	0.69^{**}	0.74^{**}	0.63^{*}	0.54^{*}			
SLW	0.14^{ns}	0.67^{**}	0.54^{*}	0.56^{*}	0.31^{ns}	0.35^{ns}	0.51^{*}	0.60^{*}	0.63^{*}	0.10^{ns}	0.23^{ns}	0.48^{ns}	0.37^{ns}	0.51^{*}	0.56^{*}				
Leaf C	0.17^{ns}	0.28^{ns}	0.19^{ns}	0.74^{**}	0.56^{*}	0.53^{*}	0.67^{**}	0.59^{*}	0.62^{*}	0.52^{*}	0.44^{ns}	0.32^{ns}	0.54^{*}	0.60^{*}					
Leaf N	0.28^{ns}	0.16^{ns}	0.58^{*}	0.64^{*}	0.52^{*}	0.43^{ns}	0.52^{*}	0.42^{ns}	0.53^{*}	0.60^{*}	0.25^{ns}	0.54^{*}	0.44^{ns}						
Leaf P	-0.60^{*}	0.71^{**}	0.20^{ns}	0.75^{**}	0.74^{**}	0.83^{**}	0.67^{**}	0.80^{**}	0.53^{*}	0.55^{**}	0.58^{*}	0.79^{**}							
Grain $\delta^{15}N$	-0.55^{*}	0.57^{*}	0.36^{ns}	0.66^{**}	0.60^{*}	0.67^{**}	0.60^{*}	0.73^{**}	0.68^{**}	0.35^{ns}	0.44^{ns}								
pH-H_2O	0.36^{ns}	0.17^{ns}	-0.27^{ns}	0.56^{*}	0.55^{*}	0.38^{ns}	0.67^{**}	0.42^{ns}	0.33^{ns}	0.22^{ns}									
SOC	-0.33^{ns}	0.23^{ns}	0.54^{*}	0.56^{*}	0.39^{ns}	0.42^{ns}	0.45^{ns}	0.47^{ns}	0.52^{*}										
Total N	-0.16^{ns}	0.59^{*}	0.15^{ns}	0.63^{*}	0.44^{ns}	0.75^{**}	0.51^{*}	0.75^{**}											
Av. P	-0.32^{ns}	0.58^{*}	0.19^{ns}	0.85^{***}	0.66^{**}	0.77^{**}	0.79^{*}												
Exch. Ca	-0.26^{ns}	0.37^{ns}	0.07^{ns}	0.96^{***}	0.71^{**}	0.53^{*}													
Exch. Mg	-0.51^{*}	0.75^{**}	0.34^{ns}	0.71^{**}	0.75^{**}														
Exch. K	-0.63^{*}	0.55^{*}	0.12^{ns}	0.77^{**}															
CEC	-0.33^{ns}	0.53^{*}	0.26^{ns}																
Soil NO_3^-	-0.15^{ns}	0.60^{*}																	
Soil NH_4^+	-0.43^{ns}																		

GY: grain yield; TBY: total biomass yield: CHLC: chlorophyll content; SLW: specific leaf weigh; SWC: soil water content; SOC: soil organic carbon: Av. P: available soil phosphorus. ns: not significant.
* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.00$.

reported that maize yield increased by 98–150% and water use efficiency by 91–139% in response to manure biochar addition (Uzoma et al., 2011), 114–444% with the application of wood and maize stalk biochars (Cornelissen et al., 2013), and 43% increase in maize total biomass due to the application of charred bark of *Acacia mangium* (Yamato et al., 2006). Major et al. (2010) found no difference in yield for 8 and 20 t ha^{-1} biochar application after one year of cropping on a savanna Oxisol in Colombia. However, maize yield in biochar amended treatments increased up to 140% relative to the control over the following three years, implying a longer-term beneficial impact of biochar on yield and soil fertility.

There have been several studies of the impact of biochar application on cereals. For instance, Solaiman et al. (2012) have found that wheat seed germination increased from 93 to 98% with the addition of biochar from different feedstock at 10 t ha^{-1}, but the same rate had no significant effect on maize seed germination in New Zealand (Free et al., 2010). The positive effect of biochar on germination could be due to the change in the physical condition of soils, in that the dark color of biochar alters thermal dynamics, possibly water availability and hormonal-type effects and thus accelerates germination, improves maize growth over the first month following seedling emergence and allowing more time for growth.

The impact of biochar on maize yield has been studied in both temperate and tropical cropping systems, with a range of results dependent on biochar type, soil type, climate and time. Negative effects on yield have been attributed to a combination of biochar type and soil conditions (Butnan et al., 2015; Rajkovich et al., 2012). Gaskin et al. (2010) reported that biochar addition to a sandy loam soil, in a temperate climate, induced effects on yield, both positive and negative, depending on biochar type. In most cases, in tropical soils, biochar addition has led to increases of variable magnitude, and in some cases to considerable yield increases of 20–200% (Kimetu et al., 2008; Martinsen et al., 2014; Yamato et al., 2006). Zhu et al. (2015) also reported that biochar + NPK amendment of a red soil increased maize total biomass by 2.7–3.5 and 1.5–1.6 times compared to that of NPK only and biochar only amendments. The effect was attributed to biochar nutrient content (21–36% of effect) and indirect increases in fertility (35–42% of effect). This implies that biochar amendment is very beneficial on red Ferralsols, which are low in pH and have low availability of major plant nutrients, such as P and some exchangeable cations.

Chlorophyll content, an indicator of photosynthetic activity, is related to the N content in green plants and serves as a measure of the response of crops to N fertilizer application and soil nutrient status (Minotta and Pinzauti, 1996). Studies have shown that application of biochar and compost with fertilizer significantly increased the leaf chlorophyll content of crops compared to fertilizer alone (Adekayode and Olojugba, 2010; Agegnehu et al., 2015). The increase in leaf chlorophyll with plant age suggests increased availability of nutrients and water over time due to the organic amendments. In this study, while Com + F, B + Com + F and COMBI + F all improved the overall plant growth and yield, B + F provided the greatest yield benefit; confirming its importance for improving long-term soil fertility and crop yield, in agreement with the findings of other studies (Cornelissen et al., 2013; Doan et al., 2015; Zhang et al., 2016).

Without amendment, the soil used in this study had low plant-available contents of some nutrients. Among macronutrients, N, K and P are required in the greatest quantities by most cereals. The separate or combined application of biochar and compost significantly increased soil nutrient status during the crop growth period indicating that their usage may prove beneficial for crop nutrition and yield. Although differences were observed among treatments, leaf N, P and K concentrations were in the reported sufficiency range for all treatments, with 2–5%, 1–5% and 0.2–0.5% and 1–5%, respectively, considered sufficient (Motsara and Roy, 2008). However, differences between organic and inorganic amendments in leaf N and P contents were obvious. Other studies have shown that use of biochar stimulates plant growth and

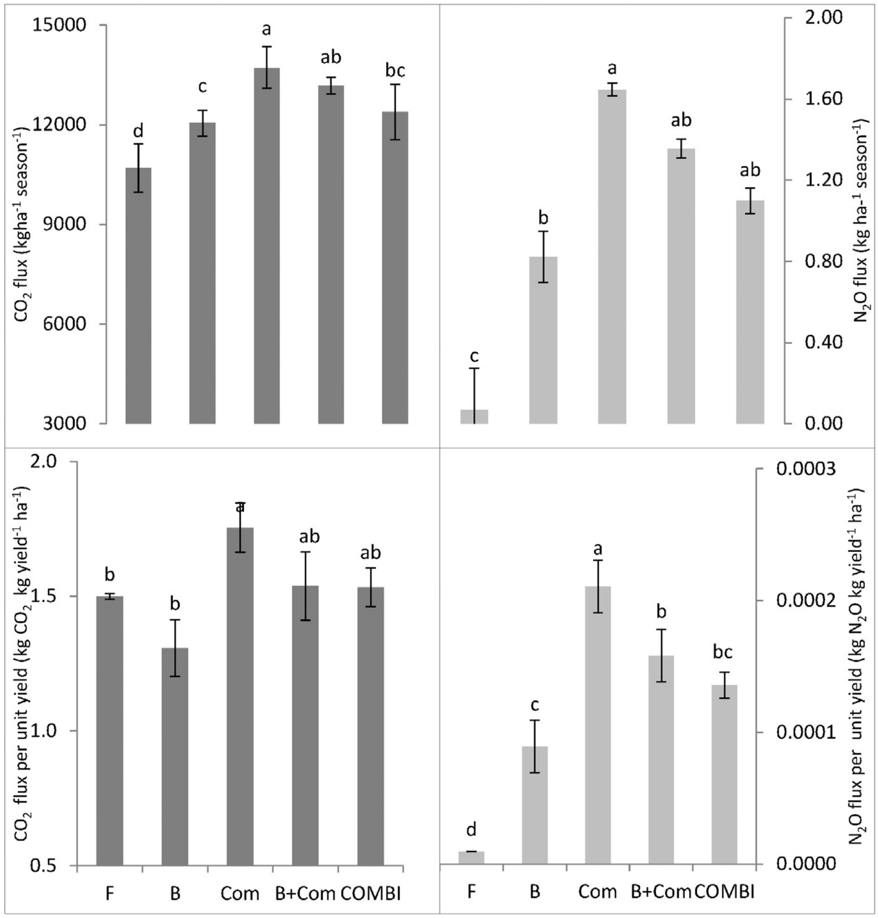

Fig. 2. The upper half shows the average emissions of CO_2 and N_2O over the whole growing season for each treatment; LSD ($p = 0.05$) = 963 and 0.35, and CV = 4.1 and 27.3 for CO_2 and N_2O, respectively). The lower half shows units of CO_2-C and N_2O-N produced per unit of maize grain yield (kg CO_2-C and N_2O-N ha^{-1} kg $yield^{-1}$ ha^{-1}); LSD ($p = 0.05$) = 0.24 and 0.00005, and CV = 8.2 and 20.1 for CO_2 and N_2O, respectively). Columns with the same letter are not significantly different at p = 0.05. Error bars represent ±1SE.

increases fertilizer use efficiency, especially when biochar is combined with fertilizer (Alburquerque et al., 2013; Schulz and Glaser, 2012; Steiner et al., 2008) and compost (Doan et al., 2015; Schulz et al., 2013). According to Steiner et al. (2008), the total N recovery in soil, crop residues and grains was considerably higher with compost (16.5%), biochar (18.1%), and biochar + compost treatments (17.4%) than with mineral fertilizer alone (10.9%).

The availability of essential nutrients in the correct proportion is a key factor for balanced nutrient uptake, healthy plant growth and optimum yield. For example, a 10:1 ratio of N:P is considered optimum for many crops, which was the ratio found in this study. The nutrient concentrations of plants vary with nutrient availability, plant species, growing conditions, time of sampling and plant parts sampled. The soil P supply is a limiting factor in plant growth both in alkaline (Wandruszka, 2006) and acidic soils of the humid tropics (Fageria and Baligar, 2008). In this study, leaf P content was higher on organic-amended soil and P was more available to the plants than in mineral-fertilized soil, implying that compost and biochar supplied P to the soil and also improved its availability by reducing sorption and leaching. Previous studies have indicated that amending Ferralsols with biochar and compost lowers leaching, improves the root-fertilizer contact and thus optimizes the availability of P to plants (Agegnehu et al., 2015; Lehmann et al., 2003). Mau and Utami (2014) further demonstrated that cow-dung manure biochar and mycorrhizal amendments increased the availability of P and its uptake by maize plants. Processed poultry manure and its biochar application increased the concentrations of N, P, K, Zn, Cu and Mn in maize plants, but decreased the Ca and Mg concentrations (Inal et al., 2015). Higher nutrient uptake by plants was accompanied by increased plant growth and yield. There was no difference between the N contents of kernels in any treatment. However, organic soil amendments significantly increased grain $\delta^{15}N$ compared to the fertilizer alone treatment, implying greater utilization of organic-derived N (which has higher $\delta^{15}N$ than fertilizer N) in B + F and B + Com + F treatments than in the other treatments.

4.2. Soil physicochemical properties

Application of organic amendments in this study showed substantial benefits for SWC and presumably water uptake by the plants. Although the organic amendments out-performed fertilizer-only treatments, the trends in SWC within treatments were not consistent throughout the crop growth period, which might indicate effects of rainfall and plant water uptake. Soil water content tended to decline over time, as the crop grew and dry season progressed. Overall, the effects of the amendments on SWC became more evident as the crop grew and the demand for water markedly increased. Abel et al. (2013) has shown that application of maize husk feedstock biochar increased total pore volume as well as water content by up to 16.3%. Abel et al. (2013) further demonstrated that the mass of water at permanent wilting point (PWP) of the maize feedstock biochar and maize silage biochar was 93.4% and 43.5%, respectively. This indicates the correlation between the specific surface area (SSA) of biochars and water volume at PWP, resulting from a significant higher SSA for maize feedstock biochar (217 $m^2\ g^{-1}$) and assumed corresponding higher microporosity than for maize silage biochar (6.3 $m^2\ g^{-1}$). The treatments had significant effects on SWC during the mid-season growth stage but not after harvest, suggesting that

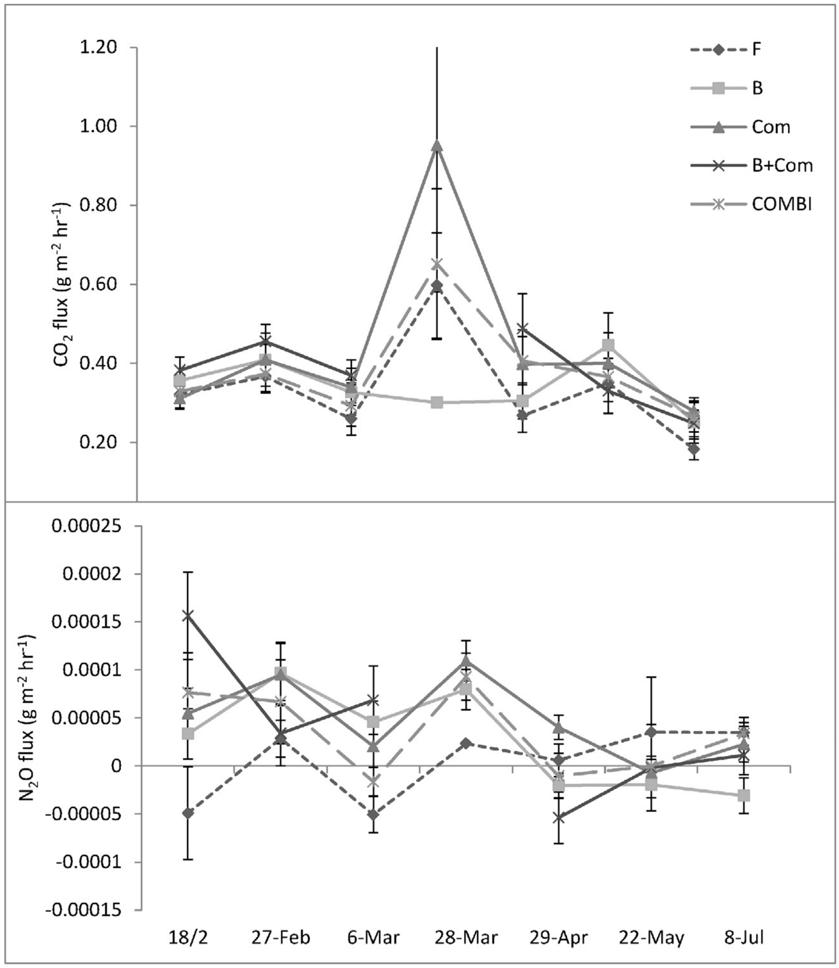

Fig. 3. The absolute increase/decrease in CO_2-C and N_2O-N flux from the four amendments compared to fertilizer only, where positive values indicate amounts above the concurrent F value and negative values indicate amounts below the concurrent F values. Measurements were carried out on days 5, 14, 21, 43, 75, 98 and 145 after planting (18 February–8 July 2014). Error bars represent ±1SE.

soil–plant interactions may have critical role in influencing the effects of soil amendments. A likely reason for the observed effects of the treatments on SWC was that greater soil water uptake by growing plants with additions of soil amendments may have reduced deep drainage beyond the root zone and evaporation.

Biochar addition, regardless of influences on yield, generally leads to improvements in soil properties, particularly total SOC content, water holding capacity, CEC and availability of nutrients (Butnan et al., 2015; Gaskin et al., 2010; Martinsen et al., 2014; Zhang et al., 2016). Increases in maize yield may have been variously linked to increased nutrient availability and SWC on the one hand, and decreased toxicity of elements such as Al on the other hand, in turn linked to changes in soil pH. Optimal soil pH is directly associated with the availability of P. Qayyum et al. (2015) found that soil pH and extractable P were significantly increased with application of low temperature coal (LTC) synthesized from sewage sludge and compost + LTC and compost + lime.

Biochar and biochar–compost addition resulted in significant improvements to soil nutrient content. Their application noticeably increased SOC, total N, available P, exchangeable Ca and CEC, by 43–73%, 14–29%, 59–117%, 31–54% and 20–41% compared to the respective initial nutrient content of the soil. However, changes in exchangeable Mg, K and Na contents were negligible relative to their initial values. Previous studies have indicated that total SOC was significantly increased due to the applications of various biochar types (Angst et al., 2014; Kimetu and Lehmann, 2010; Xie et al., 2013). Xie et al. (2013) reported that biochar addition increased SOC and N contents and decreased urea N use efficiency. Significantly higher soil P contents were obtained from Com + F, B + Com + F and COMBI + F than B + F and F alone treatments. In contrast, B + Com + F addition resulted in the maximum soil NH_4^+-N and NO_3^- N content, implying that B + Com reduced the rates of nitrification and N immobilization relative to ammonification. Lentz et al. (2014) showed that use of wood biochar produced 33% less cumulative net N mineralization and increased the soil NH_4^+-N:NO_3^- N ratio 1.8-fold compared to manure. The NO_3^- N content in compost-amended soil was most notably the lowest, possibly due to immobilization during decomposition of the compost, which had higher C:N ratio than the soil.

Soils with low CEC are often low in fertility and vulnerable to soil acidification. The buffering capacity of a soil increases with the increase in CEC and SOC content. Values of exchangeable Ca and CEC in the organic-amended soils were similar at both sampling times, indicating that the additional CEC was stable. Such stable increases in CEC have been noted in previous studies of biochar application to soil. CEC per unit soil C was up to 1.9 times higher in Anthrosols with high black carbon than in the adjacent soils (Liang et al., 2006). Xu et al. (2012) reported that the enhanced CEC increased soil fertility through greater nutrient availability as nutrients are retained in the soil against leaching. The application of 20 t ha^{-1} biochar to a low-fertility, acidic soil of Colombia led to significant increases in concentrations of several nutrients in soil solution (Major et al., 2012). In the current study, contents of most plant nutrients responded positively to organic amendments, an observation consistent with several previous studies in acidic and highly weathered tropical soils (Agegnehu et al., 2015; Lehmann et al., 2003; Slavich et al., 2013; Van Zwieten et al., 2010). In this study, soil pH-

H_2O increased from the initial value of 5.6 to the final value of 6.0 across all four organic amendments but none of the treatments differed significantly from each other, which agrees with the study of Suddick and Six (2013).

4.3. Greenhouse gas emissions

This study compared the influence of different organic amendments on CO_2 and N_2O emissions. In most measurements the CO_2 and N_2O emissions from organic amended soils were higher than from the fertilizer only treatment. Positive and negative responses of GHG emissions have both been reported as a result of biochar application to soils (Angst et al., 2013; Scheer et al., 2011; Spokas and Reicosky, 2009; Taghizadeh-Toosi et al., 2011; Zhang et al., 2012). For example, out of 16 biochar types evaluated for their impact on GHG emissions, five biochars increased, three biochars reduced and eight had no significant effect on CO_2 emission from agricultural soils; all biochars and soil combinations resulted in decreased or unaltered rates of CH_4 oxidation, and suppressed N_2O emission (Spokas and Reicosky, 2009). According to Zhang et al. (2012), biochar soil amendment decreased N_2O emission, but increased CH_4 emission. The incorporation of 30 t ha^{-1} biochar also reduced the emission of N_2O from ruminant urine patches by >50% (Taghizadeh-Toosi et al., 2011). Biochars tend to be stable in soil, resulting in lower CO_2 loss (between 0.5% and 5.8% of total added C) than other bioenergy by-products applied to soil (Cayuela et al., 2010). In contrast, biochar produced from pine waste material at a temperature of 550 °C did not show potential to curb GHG emission, where the biochar was co-applied with manure to an alkaline soil (Angst et al., 2013).

The average emission of N_2O and CO_2 from soils containing organic amendments in this study was generally greater than from the conventional fertilizer, which is in accordance with results of some previous studies (Lentz et al., 2014; Schimmelpfennig et al., 2014; Shen et al., 2014). The fluxes of both gases generally showed a declining trend over time, and both CO_2 and N_2O emissions per unit of yield were similar to or higher than the control. Nitrogen fertilizer is the main source of N_2O emission in agricultural soils. Hence, reduction of N fertilizer application rate is an efficient approach to abate N_2O emissions. Previous studies have indicated that wheat straw biochar soil amendment at 20 and 40 t ha^{-1} resulted in a reduction in N_2O emission by 10.7% and 71.8%, respectively (Zhang et al., 2012) and by more than 31% (Zhang et al., 2016) compared to N fertilizer. Lentz et al. (2014) reported that application of wood biochar resulted in 20% less CO_2 and 50% less N_2O emissions compared to manure. A review and meta-analysis by Cayuela et al. (2014) using published data from 2007 to 2013 has also shown that biochars produced from different feedstock reduced soil N_2O emissions by an average of 54% in laboratory and field studies. In contrast, Shen et al. (2014) reported that biochar amendment of a rice field increased N_2O emission compared to the NPK only treatment. The effect was ascribed to the increase either in soil NO_3^--N content (late in the rice season) or in soil NH_4^+-N content (early in the rice season). Therefore, because of the complexity of the interactions between organic amendments and soil, additional studies involving long-term field experiments need to be conducted to further strengthen our understanding of the mechanisms of CO_2 and N_2O emissions from biochar-, compost- and biochar + compost-treated soils.

5. Conclusions

The results from this field trial, on a fine-textured, basalt-derived Ferralsol indicate a strong and positive response of maize growth and yield to the application of the organic amendments, with smaller differences evident between the different organic amendments. Total biomass and grain yield were significantly increased relative to the control for all organic amendments, with increases in grain yield of 10–29% (29% in biochar treatment and 10% in the compost only treatment). SOC content was significantly increased by all organic treatments compared to the fertilizer only treatment at the mid-season sampling, but this difference had disappeared by the end of the trial. However, soils from those treatments that included biochar will have had their carbon stock increased by the amount of biochar added, with a long-term sequestration potential of 0.62 t C t^{-1} of biochar added. This is not evident in the data presented as much of the biochar is >2 mm and hence does not contribute to the <2 mm fraction of soil analyzed. Soil water content was significantly increased by all organic treatments relative to the conventional practice with the effect increasing as the crop grew and the dry season progressed. Soil available P, exchangeable Ca and CEC were significantly increased by all organic amendments throughout the trial.

Emissions of CO_2 varied erratically over time in all treatments, although in general CO_2 emissions from the organic treatments were higher than the fertilizer only treatment. N_2O emissions generally decreased over time for all treatments and emission from the biochar was lower than other treatments. Emissions of CO_2 and N_2O relative to yield from all organic amendments were similar to or higher than the control. Overall, improved soil water retention, nutrient status and nutrient uptake by plants due to the addition of organic treatments were accompanied with increased plant growth and yield. Since biochar and compost soil amendments add both macro- and micronutrients they may help achieve balanced fertilization. Based on the results from this and previous studies, feedstock type and production procedures may lead to biochar with different physicochemical properties and hence different effects on soil quality, crop performance and GHG emissions. Thus, to understand the potential significance of carbon in soil in the form of biochar, biochar + compost or co-composted biochar–compost, their characteristics and dynamics should be investigated on different soil types and different agro-ecosystems to evaluate their effects in soil–crop systems and GHG fluxes at least over three years.

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