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The ameliorating effects of biochar and compost on soil quality and plant growth on a Ferralsol

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Abstract. Deteriorating soil fertility and the concomitant decline in agricultural productivity are major concerns in many parts of the world. A pot experiment was conducted with a Ferralsol to test the hypothesis that application of biochar improves soil fertility, fertiliser-use efficiency, plant growth and productivity, particularly when combined with compost. Treatments comprised: untreated control; mineral fertiliser at rates of 280 mg nitrogen, 70 mg phosphorus and 180 mg potassium pot^{-1} (F); 75% F + 40 g compost pot^{-1} (F + Com); 100% F + 20 g willow biochar pot^{-1} (F + WB); 75% F + 10 g willow biochar + 20 g compost pot^{-1} (F + WB + Com); 100% F + 20 g acacia biochar pot^{-1} (F + AB); and 75% F + 10 g acacia biochar + 20 g compost pot^{-1} (F + AB + Com). Application of compost with fertiliser significantly increased plant growth, soil nutrient status and plant nutrient content, with shoot biomass (as a ratio of control value) decreasing in the order F + Com (4.0) > F + WB + Com (3.6) > F + WB (3.3) > F + AB + Com (3.1) > F + AB (3.1) > F (2.9) > control (1.0). Maize shoot biomass was positively significantly correlated with chlorophyll content, root biomass, plant height, and specific leaf weight (r = 0.99, 0.98, 0.96 and 0.92, respectively). Shoot and root biomass had significant correlations with soil water content, plant nutrient concentration, and soil nutrient content after harvesting. Principal component analysis (PCA) showed that the first component provided a reasonable summary of the data, accounting for ~84% of the total variance. As the plants grew, compost and biochar additions significantly reduced leaching of nutrients. In summary, separate or combined application of compost and biochar together with fertiliser increased soil fertility and plant growth. Application of compost and biochar improved the retention of water and nutrients by the soil and thereby uptake of water and nutrients by the plants; however, little or no synergistic effect was observed.

Additional keywords: biochar, carbon sequestration, compost, mineral fertiliser, nutrient leaching, soil quality.

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Introduction

Soil degradation processes caused by erosion, organic matter and plant nutrient depletion, and nutrient imbalances are among the major challenges affecting agricultural productivity and food security (Sanchez 2002; Foley *et al*. 2005; Lal 2009). The productivity of some lands has declined by 50% because of soil erosion and desertification (Eswaran *et al*. 2001). Annual global soil loss is estimated at 75 Gt, costing the world about US$400 billion per year (Eswaran *et al*. 2001). The deterioration of soil fertility is exacerbated by nutrient mining, unsuitable land use and management, competing uses of resources, and application of insufficient external inputs. For example, in Australia, crop production has led to a substantial loss of soil organic matter (SOM) from the cereal belt, where the long-term SOM loss often exceeds 60% from the top 0–10 cm of soil after 50 years of cereal cropping (Dalal and Chan 2001). Losses of labile components of SOM, microbial biomass and mineralisable nitrogen (N) have been higher, resulting in greater decline in soil productivity (Dalal and Chan 2001).

In the future, the long-term benefit of allocating more land to agriculture will not offset the negative environmental impacts of land degradation (Tilman *et al*. 2002). Instead, a more promising approach to ensuring food security is to increase yield from currently cultivated land where productivity is low (Foley *et al*. 2011). Sustainable agricultural intensification—increasing productivity per unit land area—is thus necessary to secure the food supply for the increasing world population (Tilman *et al*. 2011). In most tropical environments, sustainable agriculture faces significant constraints due to low nutrient status and rapid mineralisation of SOM (Zech *et al*. 1997). Decline in SOM content results in decreased cation exchange capacity (CEC). Under such circumstances, the efficiency of applied mineral fertilisers is low (Glaser *et al*. 2002; Troeh and Thompson 2005). In addition, most small-scale farmers cannot afford to apply mineral fertilisers regularly because of high costs. Therefore, nutrient deficiencies are prevalent in many crop production systems of the tropics and this constrains productivity.

Soils fertilised with compost or manure have higher contents of SOM and soil microorganisms than mineral-fertilised soils, and are more enriched in phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg) in the topsoil and NO_3-N, Ca and Mg in subsoils (Edmeades 2003; Quilty and Cattle 2011). Well-made composts are known to improve soil structure, resulting in improved air exchange, and water infiltration and retention (Fischer and Glaser 2012). Soils amended with organic fertilisers also have lower bulk density and higher porosity, hydraulic conductivity and aggregate stability than mineral-fertilised soils (Edmeades 2003; Lal 2009). Labile forms of SOM are of prime importance as a reserve and source of plant nutrients in tropical soils poor in minerals that can be weathered (Zech *et al*. 1997). However, the amount of the labile SOM is smaller and the turnover rate and release of nutrients in humid tropical soils is faster than in temperate soils. Accelerated mineralisation of SOM limits the practical application of organic fertilisers in the tropics (Zech *et al*. 1997; Kaur *et al*. 2008).

Biochar is charcoal produced by controlled pyrolysis for use as a soil amendment or in carbon (C) sequestration (Lehmann and Rondon 2006). Various studies have shown that application of biochar to soil can improve soil biophysical and chemical properties and nutrient supply to plants (Glaser *et al*. 2002; Sohi *et al*. 2010), enhance plant growth and yield (Lehmann and Rondon 2006; Chan *et al*. 2007; Major *et al*. 2010), and reduce greenhouse gas emissions through C sequestration (Van Zwieten *et al*. 2010; Ippolito *et al*. 2012; Zhang *et al*. 2012). Biochar helps to improve agricultural productivity by reducing soil acidity and by enhancing CEC and fertiliser-use efficiency (Lehmann *et al*. 2003; Steiner *et al*. 2008; Chan and Xu 2009), water retention capacity (Downie 2011) and plant-available water content (Tammeorg *et al*. 2014), and by creating a habitat for beneficial soil microorganisms (Thies and Rillig 2009). Biochar can be used to rejuvenate depleted soils, making more agricultural land available and increasing crop yields so that the need for expansion of agricultural land area is decreased (Blackwell *et al*. 2009; Barrow 2012). Biochar has significantly improved the efficiency of N fertilisers and increased plant growth and yield (Lehmann *et al*. 2003; Steiner *et al*. 2008). The long-term benefits of biochar for nutrient availability include greater stabilisation of SOM, slower nutrient release from added organic matter, and better retention of cations due to higher CEC (Lehmann *et al*. 2003; Steiner *et al*. 2008). The resultant change in soil nutrient status may affect both plant growth and productivity. Responses to biochar application will depend on the type and rate of biochar applied, as well as soil physico-chemical characteristics.

Some recent studies have indicated that the simultaneous application of biochar and compost could lead to enhanced soil fertility, improved plant growth and C sequestration potential (Fischer and Glaser 2012; Schulz and Glaser 2012). Liu *et al*. (2012) showed that the combined application of compost and biochar had a synergistic, positive effect on SOM content, nutrient contents and water-holding capacity of soil under field conditions. Information on the combined effects of biochar and compost on soil fertility and crop performance in tropical soils is generally not adequate. Different methods of producing and applying compost and biochar are hypothesised to differ in their effects on soil biophysical and chemical properties, and plant growth and yield. Therefore, the objectives of this study were to determine the effect of compost and biochar applied to an infertile tropical soil on: (*i*) growth and nutrient uptake of maize, (*ii*) soil water content and chemical characteristics, and (*iii*) nutrient retention and leaching.

Materials and methods

Experimental setup

The study was a pot trial designed to determine whether soil fertility and plant productivity could be enhanced by biochar and compost applied singly or together. Willow biochar (WB; Earth Systems Pty Ltd, Melbourne, Vic.) and acacia biochar (AB; Renewable Carbon Resources Australia Pty Ltd, Charleville, Qld) produced at 500°C were selected for the soil amendments. Both biochar types were characterised by JSM-6300 scanning microscope (JEOL Ltd, Tokyo) before application; WB had more pore spaces than AB. Compost was produced from a mix of bagasse, poultry litter and municipal waste, following the standard windrow procedures for compost preparation, by King Brown Technologies (Mareeba, Qld). Chemical characteristics of the compost, WB and AB used as soil amendments in this study are given in Table 1.

The products were screened through a 4-mm sieve before being mixed with the soil. Soil used in the trial was taken from a sugarcane field (17°1.23′S, 145°24.21′E; 0–10 cm depth) in North Queensland, Australia. The soil was a Ferralsol (FAO classification, IUSS Working Group WRB 2007) developed on Quaternary basalt. Chemical properties of the experimental soil were determined for samples taken before planting (Table 1). The pot trial was conducted in a greenhouse from 7 June to 9 August 2013 at James Cook University, Cairns Campus, Queensland. During the growing period, the temperature ranged between17.6°C and 27.1°C and the mean relative humidity was 62.5%. The plastic pots used had 16-cm upper and 14-cm lower diameter, height of 16 cm, and total volume of ~2750 cm^3. A 2-kg subsample of air-dried soil, screened through a 4-mm sieve, was placed into each pot after mixing thoroughly with the amendments. All pots were then watered to approximately field capacity.

The experiment comprised the following seven combinations of compost, biochar and mineral fertiliser treatments: (*1*) untreated control; (*2*) mineral fertiliser only (F) at a rate of 280 mg N as urea, 70 mg P as triple superphosphate and 180 mg K as KCl pot^{-1}, which is equivalent to 140 kg N, 35 kg P and 90 kg K ha^{-1}; (*3*) 75% F + 40 g compost pot^{-1} (F + Com); (*4*) 100% F + 20 g WB pot^{-1} (F + WB); (*5*) 75% F + 10 g WB + 20 g compost pot^{-1} (F + WB + Com); (*6*) 100% F + 20 g AB pot^{-1} (F + AB); (*7*) 75% F + 10 g AB + 20 g compost pot^{-1} (F + AB + Com). The experiment was arranged in a randomised complete block design with four replications. Compost was applied at rates of 20 and 10 t ha^{-1}, and biochar at rates of 10 and 5 t ha^{-1}.The N content of the compost was considered and fertiliser N rate was decreased by 25% when applied together with compost, assuming that only 10–20% of the total N content of the compost is mineralised in the first year (Fischer and Glaser 2012). Nitrogen was applied in two applications: 156 mg N pot^{-1} at planting and 124 mg N pot^{-1} as topdressing at 4 weeks after planting. Eight maize (*Zea mays* L.) seeds were planted at a depth of 3 cm in each pot 1 week after the amendments had been mixed with the soil. After emergence, four plants were maintained in each pot until

Table 1. Element contents and pH of compost, willow biochar, acacia biochar and experimental soil before planting
ECEC, Effective cation exchange capacity; n.d., not determined

Element	Unit	Compost	Willow biochar	Acacia biochar	Experimental soil
pH(H_2O)		8.1	9.5	8.0	6.5
pH($CaCl_2$)		–	8.3	7.5	5.6
Carbon	g kg^{-1}	233	92.4	59.0	11.4
Nitrogen (N)	g kg^{-1}	11	0.36	0.43	0.80
Phosphorus	g kg^{-1}	3.3	1.96	0.02	0.031
Potassium	g kg^{-1}	8.9	15.4	0.09	0.30
Calcium	g kg^{-1}	14	15.2	3.9	0.86
Magnesium	g kg^{-1}	7.0	4.4	0.06	0.11
Sodium	g kg^{-1}	2.1	1.04	0.09	0.01
ECEC	g kg^{-1}	n.d.	n.d.	n.d.	1.28
Sulfur (S)	g kg^{-1}	1.5	0.07	0.05	n.d.
Ammonium-N (NH_4-N)	mg kg^{-1}	n.d.	n.d.	n.d.	11.3
Nitrate-N (NO_3-N)	mg kg^{-1}	n.d.	n.d.	n.d.	14.0
Copper	mg kg^{-1}	72.0	239.7	9.4	n.d.
Zinc	mg kg^{-1}	181.0	2571	38.0	n.d.
Manganese	mg kg^{-1}	421.5	14599	22.0	n.d.
Iron	mg kg^{-1}	17877	125898	47.0	n.d.
Boron	mg kg^{-1}	17.0	n.d.	9.3	n.d.
Molybdenum	mg kg^{-1}	2.2	n.d.	<0.3	n.d.
Cobalt	mg kg^{-1}	9.8	n.d.	<0.4	n.d.
Aluminium	mg kg^{-1}	7596	3175	400	n.d.

harvesting. Each pot was given 150 mL of water daily for 14 days after planting and 200 mL thereafter until the end of the experiment. The bottom of each pot had four holes and was lined with gauze to minimise loss of particulate matter but allow leaching of soil solution. Each pot was equipped with a sealable plastic bag at the bottom for leachate collection.

Measurements

Plant height was recorded just before harvesting. Chlorophyll content (greenness) was measured on days 34, 48 and 52 after planting, with four replicate measurements on three leaves (youngest fully expanded leaves) per plant, using a chlorophyll meter (SPAD-502; Konica Minolta, Tokyo). Leachate was collected every 2 weeks, its volume was measured, and subsamples were kept frozen for analysis. Soil water content (SWC) was measured every week after planting, using a HydroSense II probe (Campbell Scientific Inc., Logan, UT, USA). Specific leaf weight (SLW, expressed as dry weight cm^{-2}) of plants was measured. One leaf from each plant of the same age and position was sampled 1 week before harvesting. Leaves were transferred immediately to individual, sealed plastic bags that were kept in an insulated box above ice packs until all leaves were harvested. In the laboratory, a hole-punch with a diameter of 8 mm was used to take a leaf disc from the middle of the leaf lamella. Fresh leaf discs were weighed and dried at 70°C for 48 h before reweighing them. SLW was calculated as dry weight of leaf disc per area of hole-punch.

The aboveground parts of four plants were harvested at soil level from each pot 62 days after planting. The root part of each plant from each pot was also separated judiciously from the soil, cleaned and weighed. Fresh shoots and roots were dried separately at 70°C for 72 h, and the shoot : root ratio (SRR) was determined. The shoot part of plants was used to determine content and uptake of nutrients by plants. Total plant N and C concentrations were determined using an elemental analyser (ECS 4010 CHNSO Analyzer) fitted with a zero blank auto-sampler (Costech Analytical Technologies Inc., Valencia, CA, USA). Total P, K and NO_3-N concentrations in plants were quantified at the Analytical Research Laboratories (ARL), Awatoto, New Zealand. Nitrate-N in plant tissue was determined using 2% acetic acid (Miller 1998). Plant K content was determined by atomic absorption spectroscopy after wet digestion with sulfuric acid (Watson *et al*. 1990). Plant P content was determined photometrically with the molybdenum blue method (Mills and Jones 1996).

Total C and N contents in soil were determined by the method used for plants. Exchangeable cations and P contents, electrical conductivity (EC), NO_3-N and NH_4-N were determined by ARL. The EC was determined by a conductivity meter on a 1 : 2.5 soil : water suspension (Rayment and Lyons 2010). Available soil P was determined according to Colwell (1963). Exchangeable K, sodium (Na), Ca and Mg contents were determined by 1 M ammonium acetate extraction buffered at pH 7 for 30 min (Rayment and Lyons 2010). Soil NH_4-N and NO_3-N were determined colourimetrically after extraction with 1 M KCl (Rayment and Lyons 2010). The chemical properties of compost, WB and AB were determined in the laboratory following methods similar to those used for soil analysis (Table 1). Pot leachate samples were analysed for NO_3-N, P, K, Mg, Ca and Na concentration. Nitrate concentration of the leachate was measured using a nitrate meter (B-743, HORIBA Ltd, Kyoto, Japan). Phosphorus concentration was determined photometrically using the molybdate blue method, and K, Ca, Na and Mg concentrations were measured by inductively coupled plasma-atomic emission spectroscopy at the Advanced Analytical Center, James Cook University, Townsville, Queensland.

Data analyses

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, Cary, NC, USA). The total variability for each trait was quantified by using the following model:

$$Y_{ij} = \mu + R_i + T_j + e_{ijk}$$

where Y_{ij} is total observations, μ is the 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 were compared by using the MEANS statement with the least significant difference (l.s.d.) test at $P = 0.05$. To perform the multivariate approach of correlation and principal component analysis (PCA), the data were standardised by removing treatment mean character values, followed by dividing by the corresponding character standard deviations. Correlation coefficients (r) were then calculated among plant parameters, nutrient uptake and soil nutrient contents by the SAS CORR procedure, and the PCA was performed by the SAS PRINCOMP procedure to distinguish the treatments as a function of soil management and to determine the most important parameters to characterise them.

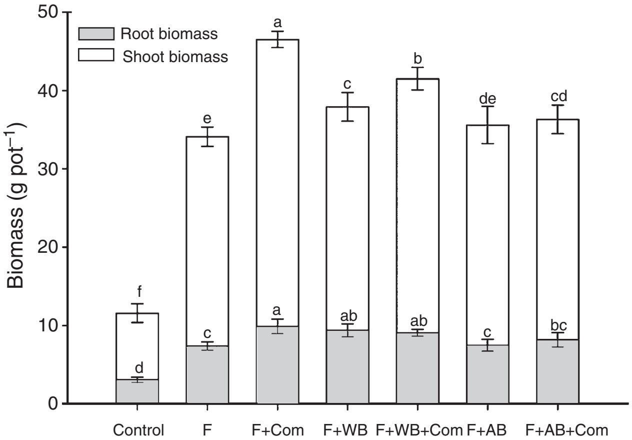

Fig. 1. Effects of treatments on root and shoot biomass (g pot^{-1}) of maize; l.s.d. ($P = 0.05$) = 2.1 and 1.1, and CV = 4.1and 9.7 for root and shoot biomass, respectively. Columns with the same letter are not significantly different at $P = 0.05$. Capped lines are standard errors. F, Mineral fertiliser; Com, compost; WB, willow biochar; AB, acacia biochar.

Results

Plant growth and nutrient uptake

The different soil fertility treatments significantly increased above- and belowground biomass, SRR, SLW, chlorophyll content and plant height of maize ($P < 0.05$ and $P < 0.001$; Fig. 1, Table 2). Shoot and root biomass were greater with F + Com than with other treatments. The shoot biomass recorded from F + Com and F + WB + Com treatments, respectively, was 4 and 3.6 times that of the control and 1.4 and 1.2 times that of the F treatment (Fig. 1). Root biomass was highest in the F + Com treatment, but the differences among F+ Com, F+ WB and F + WB + Com treatments were not statistically significant. Applications of F + Com and F + WB, respectively, produced root biomass 3.2 and 3.0 times that of the control and 1.3 and 1.3 times that of the F treatment. Comparing the two biochar types, WB addition increased root biomass over AB by 20%. However, applications of F + Com, F + WB + Com or F + AB + Com resulted in similar SRR. The shoot and root parts of plants constituted 73–79% and 21–27% of plant biomass, respectively. Plants grown with F + Com or F + WB + Com had greater chlorophyll content and plant height than the other treatments. Chlorophyll contents in the F, F + Com and F + WB + Com treatments were 1.3, 1.5 and 1.4 times that of the control (Table 2). The treatment F + WB + Com resulted in the highest SLW, with the lowest SLW in the control treatment.

Treatments significantly ($P < 0.01$) increased plant uptake of total N, C, P and NO_3-N relative to the control (Table 2); F + Com, F + WB or AB, and F + WB or AB + Com significantly increased plant N uptake compared with the F treatment. Plant C, N, P and K uptakes were in the ranges 4.4–19.7 g, 150–1117 mg, 15–87 mg and 354–1746 mg pot^{-1}, respectively, with the highest values in F + Com and the lowest in the control treatment (Table 2). However, there was no statistically significant difference between F + Com and F + WB + Com for N, NO_3-N and P uptake. Nitrogen and P contents of plants in the F + Com treatment were, respectively,

Table 2. Effects of treatments on plant parameters and nutrient uptake into shoot parts of plants

F, Mineral fertiliser; Com, compost; WB, willow biochar; AB, acacia biochar; SLW, specific leaf weight; l.s.d., least significant difference; CV, coefficient of variation. Within columns, means followed by the same letter are not significantly different at $P = 0.05$. $^{**}P < 0.01$; $^{***}P < 0.001$

Treatment	SLW (mg cm^{-2})	Chlorophyll content (SPAD unit)	Plant height (cm)	C uptake (g pot^{-1})	Nutrient uptake (mg pot^{-1})			
					N	NO_3-N	P	K
Control	1.98c	26.9d	78.2b	4.41e	150d	2.9c	14.8c	354d
F	2.34b	36.3c	111.0a	14.19d	648c	27.9b	60.1b	1148c
F + Com	2.58ab	40.6a	115.0a	19.66a	1117a	40.8a	86.9a	1746a
F+WB	2.58ab	39.0ab	112.0a	16.00c	943b	28.6b	69.1b	1330bc
F + WB + Com	2.66a	40.5a	114.3a	17.35b	990ab	34.3ab	86.1a	1470b
F + AB	2.56ab	37.6bc	110.5a	14.68d	771c	29.1b	60.6b	1219c
F + AB + Com	2.36b	38.1bc	112.5a	14.89d	904b	29.4b	69.6b	1316bc
Significance level	**	***	***	**	***	***	***	**
l.s.d. ($P = 0.05$)	0.28	2.1	5.8	0.98	129.4	7.9	10.5	226.0
CV (%)	7.7	4.0	3.6	4.59	11.2	10.4	11.1	12.4

7.4 and 5.9 times those in the control and 1.7 and 1.5 times those in the F treatment. Applications of biochar and compost resulted in optimal N and P uptake by plants (within the sufficiency range). Fertiliser + Com resulted in the highest plant NO_3-N uptake (41 mg pot^{-1}), whereas the lowest plant NO_3-N content was in the control (Table 2). Significant differences were not observed for NO_3-N uptake between organic amendments and mineral fertiliser except for the F + Com treatment. Mineral fertiliser alone, F + Com, F + WB + Com and F + AB + Com had plant NO_3-N contents that were, respectively, 9.6, 14, 11.8 and 10 times that of the control treatment. Overall, application of compost and biochar increased plant growth, soil nutrient status and plant N content, with shoot biomass (as a ratio of control value) decreasing in the order F + Com (4.0) > F + WB + Com (3.6) > F + WB (3.3) > F + AB + Com (3.1) > F + AB (3.1) > F (2.9) > control (1.0).

Soil characteristics

The treatments with organic components significantly ($P < 0.001$) improved SWC and decreased leachate volume (Table 3). Differences in leachate volume among treatments increased during the growing period, because the demand for water by plants depended on treatments. Therefore, the cumulative leachate volume was inversely related with the above- and belowground biomass. Soil water content was highest in soil treated with compost and biochar. Following harvest, soil organic C (SOC), total N, C : N ratio, NO_3-N and NH_4-N, available P, exchangeable cations, effective CEC (ECEC) and EC significantly responded to the treatments (Tables 3 and 4). Soil nutrient contents were higher when compost and biochar were added to soil than in the control and F treatments. The highest SOC content (33 g pot^{-1}) was obtained from F + WB, which is in agreement with the initial C content of WB. In F + WB-amended soil, SOC content increased by a factor of 1.4 and 1.5 compared with the control and F treatments, respectively (Table 3). There was a linear relationship between the amount of C added in the amendments and the SOC content at the end of the experiment. The maximum Colwell P value (108 mg pot^{-1}) was obtained from F + Com soil. Highest NO_3-N and NH_4-N contents were in F + Com and F + WB + Com treated soils (Table 3). Fertiliser + Com and F + WB + Com treated soils had higher contents of available nutrients such as K, Ca and Mg than the other treated soils (Table 4). Fertiliser + WB + Com addition especially increased soil available K, Ca and ECEC after harvesting, whereas F + Com addition resulted in the highest exchangeable Mg and Na. The Ca : Mg ratios for the different treatments ranged from 4 to 5.4 (Table 4), within the recommended range (4–6).

Table 3. Effects of treatments on cumulative leachate, soil water content and soil chemical properties after harvesting

F, Mineral fertiliser; Com, compost; WB, willow biochar; AB, acacia biochar; SWC, soil water content; SOC, soil organic carbon; l.s.d., least significant difference; CV, coefficient of variation. Within columns, means followed by the same letter are not significantly different at $P = 0.05$. **$P < 0.01$, ***$P < 0.001$

Treatment	Cumulative leachate (mL pot^{-1})	SWC (%) (g pot^{-1})	Nutrient content SOC	N	C : N ratio	Nutrient content (mg pot^{-1}) P	NO_3-N	NH_4-N
Control	715a	17.6c	23.2c	1.40c	16.6a	49.0d	1.01e	35.6c
F	189b	20.0c	22.4c	1.42c	15.8ab	68.4c	4.02d	45.0c
F + Com	58e	23.7b	30.0b	2.20a	13.6c	107.6a	17.6a	85.2a
F + WB	68e	26.3ab	33.4a	2.0ab	16.7a	95.0ab	10.8c	61.4b
F + WB + Com	54e	26.9a	28.7b	2.02ab	14.2b	97.6ab	15.8ab	86.0a
F + AB	140c	26.5ab	27.4b	1.80b	15.2ab	88.6b	14.8b	77.8a
F + AB + Com	81d	28.1a	27.8b	2.01ab	13.8c	94.2ab	8.6c	61.8b
Significance level	***	***	***	**	**	***	***	***
l.s.d. ($P = 0.05$)	18.1	3.1	3.4	0.22	1.8	15.5	2.2	13.6
CV (%)	6.5	8.8	8.1	8.4	8.0	11.3	14.3	14.2

Table 4. Effects of treatments on soil chemical properties after harvesting

F, Mineral fertiliser; Com, compost; WB, willow biochar; AB, acacia biochar; ECEC, effective cation exchange capacity; EC, electrical conductivity; l.s.d., least significant difference; CV, coefficient of variation. Within columns, means followed by the same letter are not significantly different at $P = 0.05$. **$P < 0.01$; ***$P < 0.001$

Treatment	Exchangeable cations (mg pot^{-1}) K	Ca	Mg	Na	ECEC	Ca : Mg ratio	EC (dS m^{-1})
Control	202c	1590d	190c	40.2d	2020d	8.4a	0.05c
F	210c	1660cd	192c	43.6cd	2104cd	8.7a	0.07b
F + Com	306ab	1885ab	284a	72.4a	2516a	6.5c	1.0ab
F + WB	304ab	1800b	216bc	56.4bc	2378b	8.4a	1.11a
F + WB + Com	342a	1950a	242b	64.4ab	2600a	8.1ab	0.08b
F + AB	232c	1680cd	202c	43.8cd	2158c	8.3ab	0.08b
F + AB + Com	288b	1760bc	236b	51.8bcd	2334b	7.5b	1.0ab
Significance level	***	***	***	**	**	**	**
l.s.d. ($P = 0.05$)	41.6	119.0	31.0	13.0	127	0.85	0.02
CV (%)	10.4	4.6	9.3	16.5	3.5	7.2	17.4

Table 5. Correlation coefficients among plant parameters, soil water content, soil and plant nutrient contents
SWC, Soil water content; SLW, specific leaf weight; PHT, plant height; CHLC, chlorophyll content; RB, root biomass; SB, shoot biomass. $*P<0.05$, $**P<0.01$, $***P<0.001$; ns, not significant

Parameters	Soil K	Soil P	Soil N	Plant NO_3-N	Plant K	Plant P	Plant N	SWC	SLW	PHT	CHLC	RB
SB	0.73n.s.	0.93**	0.80*	0.99***	0.99***	0.98***	0.98***	0.74*	0.92**	0.96***	0.99***	0.98***
RB	0.79*	0.94**	0.83*	0.96***	0.97***	0.97***	0.98***	0.75*	0.92**	0.95**	0.98***	
CHLC	0.77*	0.94**	0.81*	0.97***	0.98***	0.98***	0.98***	0.78*	0.94**	0.97***		
PHT	0.63n.s.	0.85*	0.68n.s.	0.96***	0.94**	0.94**	0.93**	0.74*	0.88**			
SLW	0.75n.s.	0.89**	0.77*	0.89**	0.89**	0.91**	0.91**	0.76*				
SWC	0.72n.s.	0.83*	0.79*	0.66n.s.	0.69n.s.	0.72n.s.	0.78*					
Plant N	0.83*	0.98***	0.90**	0.96***	0.98***	0.98***						
Plant P	0.81*	0.93**	0.82*	0.98***	0.98***							
Plant K	0.75*	0.95**	0.84*	0.99***								
Plant NO_3-N	0.69n.s.	0.91**	0.77*									
Soil N	0.89**	0.96***										
Soil P	0.85*											

Significant correlations were observed between plant growth parameters, plant nutrient concentrations, SWC and soil chemical properties ($P<0.05$, $P<0.01$ and $P<0.001$). Maize shoot biomass was positively significantly correlated with leaf chlorophyll content, root biomass, plant height, SLW and SWC ($r=0.99$, 0.98, 0.96, 0.92 and 0.74, respectively) under different soil fertility treatments (Table 5). However, the amount of leachate collected as percolated water was negatively correlated with shoot and root biomass, leaf chlorophyll content, SLW and SWC (data not shown). Shoot and root biomass, chlorophyll content and plant height were significantly correlated with plant and soil contents of N, NO_3-N and P (Table 5). Plant N content was positively correlated with SWC, soil N, P and K contents, and plant NO_3-N, P and K concentrations, but soil K content was not significantly correlated with shoot biomass, plant height, SLW, plant NO_3-N concentration or SWC. The PCA revealed that the first two principal components (PC1 and PC2) accounted for ~91% of the total variation of the treatments, of which 84% was contributed by PC1 (Table 6). The first eigenvector has similar weights on all of the characters. Thus, most characters in PC1 individually contributed comparable effects (0.186–0.255) to the total variation of the treatments (Table 6). The second eigenvector has positive loadings on the variables soil N and K contents, SOC, SWC and ECEC. Each vector corresponds to one of the analysis variables and is proportional to its component loading. For instance, the biplot of PC1 and PC2 showed that the variables F + Com, F + WB + Com, F + WB, F+ AB + Com and control load heavily on the first component, whereas the variables F and F + AB load heavily on the second component (Fig. 2).

Table 6. Percentage, cumulative variances and eigenvectors on the first four principal components (PC1–4) for 18 characters in seven treatments
SOC, soil organic carbon; ECEC, effective cation exchange capacity

Parameter	PC1	PC2	PC3	PC4
Eigenvalue	15.1	1.17	0.65	0.51
%Variance	84.00	6.49	3.62	2.84
Cumulative	84.00	90.49	94.11	96.95
Character		*Eigenvectors*		
Plant N concentration	0.255	–0.037	0.015	0.130
Soil P content	0.254	0.119	0.015	0.011
Chlorophyll content	0.252	–0.169	–0.040	0.087
Plant P concentration	0.251	–0.145	0.101	0.060
Plant K concentration	0.251	–0.160	0.103	0.026
Shoot biomass	0.250	–0.214	0.040	0.019
Root biomass	0.249	–0.142	–0.116	0.200
Plant C content	0.249	–0.217	0.020	0.021
Plant NO_3-N concentration	0.245	–0.256	0.125	–0.032
Specific leaf weight	0.240	–0.111	–0.328	–0.231
Plant height	0.234	–0.324	–0.002	0.206
Soil N content	0.234	0.358	0.059	0.048
Soil NO_3-N content	0.230	0.115	–0.056	–0.589
Soil NH_4-N content	0.228	0.125	0.064	–0.603
Soil K content	0.217	0.345	–0.022	0.176
Soil water content	0.208	0.256	–0.111	0.192
SOC content	0.194	0.394	–0.549	0.200
ECEC	0.186	0.341	0.717	0.113

Nutrient leaching

Leaching of NO_3-N, P, K, Ca, Mg and Na significantly ($P<0.01$) differed among the treatments (Table 7). Applications of F + WB + Com and F + WB significantly reduced the cumulative leaching of NO_3-N, P, exchangeable K, Ca and Mg (Table 7). The greatest leaching of NO_3-N and P was recorded from the F treatment. On the other hand, leaching of K, Ca, Mg and Na was greatest for the control, followed by the F treatment (Table 7). The treatments F + WB + Com and F + WB had lower cumulative leaching of nutrients than other treatments. Most of the native available NO_3-N was leached from the control during the first crop-establishment period. Significantly higher ratios of NO_3-N, P and K uptake to leaching were obtained from soil treated with F + WB + Com (Fig. 3). By contrast, F + Com resulted in the highest ratios of NO_3-N and K uptake to initial soil content, and F + Com and F + WB + Com had similar ratios of P uptake to initial soil content. Ratios of nutrient uptake to leaching and to initial soil content were lowest for the control, followed by the F treatment (Fig. 3). There was a significant linear correlation between the amount of leaching of nutrients and the volume of leachate. Marked differences were observed among treatments

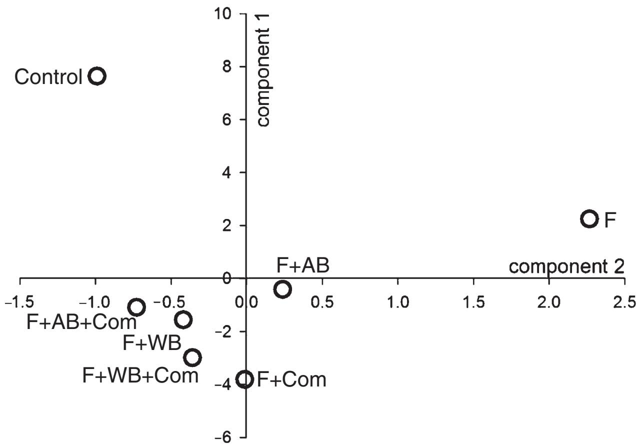

Fig. 2. Plot of principal component one and principal component two in seven treatments: F, mineral fertiliser; Com, compost; WB, willow biochar; AB, acacia biochar.

Table 7. Effect of treatments on cumulative loss of nutrients by leaching at the end of the experiment

F, Mineral fertiliser; Com, compost; WB, willow biochar; AB, acacia biochar; l.s.d., least significant difference; CV, coefficient of variation. Within columns, means followed by the same letter are not significantly different at $P = 0.05$. $^{**}P < 0.01$; $^{***}P < 0.001$

Treatment	Nutrient leached (mg pot^{-1})					
	NO_3-N	P	K	Ca	Mg	Na
Control	102.1b	0.37d	22.8a	32.7a	7.2a	4.96a
F	133.6a	1.23a	20.7b	24.1b	5.6b	2.34b
F + Com	85.7c	0.18f	10.8c	23.5b	4.4c	2.57b
F + WB	44.7ef	0.26e	6.5e	10.3d	2.3d	0.75d
F + WB + Com	35.6f	0.14g	6.4e	9.4d	2.2d	1.04cd
F + AB	69.4d	0.46c	11.0c	16.5c	3.7c	1.37c
F + AB + Com	47.9e	0.63b	8.4d	10.9d	2.6d	1.22cd
Significance level	***	***	**	***	**	**
l.s.d. ($P = 0.05$)	10.1	0.04	1.7	3.0	0.86	0.41
CV (%)	9.2	5.8	8.9	11.1	14.5	13.7

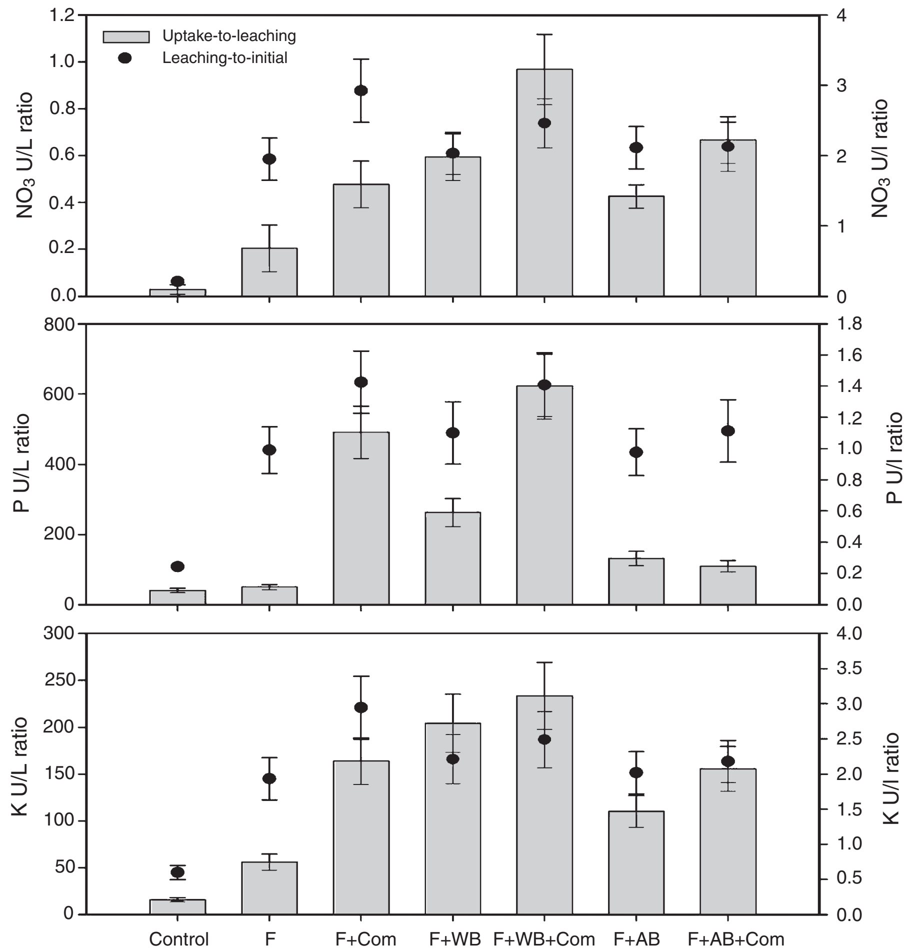

Fig. 3. Ratios of NO_3-N, P and K uptake (U) to respective cumulative leaching (L ratio, left axis), and to initial soil contents (I ratio, right axis) as influenced by the treatments ($n = 7$): F, mineral fertiliser; Com, compost; WB, willow biochar; AB, acacia biochar. Capped lines show standard errors.

in the magnitude of leaching of nutrients. Overall, as the growth of plants progressed, the leaching of nutrients was markedly reduced because of higher nutrient uptake by the plants, and hence smaller amounts left to leach.

Discussion

Plant growth and nutrient uptake

Our results showed significant increases in plant growth and biomass production with F + Com and F + WB + Com additions compared with the control and fertiliser only; the effects were due to improved availability of water and nutrients. By contrast, the F + AB treatment was no better than fertiliser alone with regard to biomass production or N, P and K uptake. Shoot and root biomass increments were higher as a result of compost addition than biomass addition with either biochar type, indicating that the amount applied and the nutrients supplied by compost were adequate. Other studies have shown that application of compost increased biomass of oats (Schulz and Glaser 2012), shoot and root biomass of ryegrass (Khan and Joergensen 2012), and biomass of rice and cowpea (Lehmann *et al*. 2003). There were also significant effects resulting from biochar type; higher total biomass was obtained from WB than from AB. This plant growth differential may be due to WB having a higher nutrient retention capacity because of greater pore spaces and ability to supply plants with nutrients. The effect of biochar on soil physical and chemical properties depends on feedstock type and pyrolysis conditions (Novak *et al*. 2009*b*). Singh *et al*. (2010) indicated that wood biochars had higher total C but lower contents of ash, total N, P, K, sulfur (S), Ca, Mg, aluminium (Al), Na, copper and CEC than manure-based biochars.

Both positive and negative yield responses have been reported for a wide variety of crops as a result of biochar application to soils (Chan and Xu 2009; Tammeorg *et al*. 2014). For instance, maize yield increased by 98–150% and water use efficiency by 91–139% as a result of manure biochar addition (Uzoma *et al*. 2011), wheat plant biomass increased by 250% following charred paper mill waste addition (Van Zwieten *et al*. 2010), and wheat grain yield increased by 18% from the use of oil mallee biochar (Solaiman *et al*. 2010). Plant growth and yield increases with biochar additions have, in most cases, been attributed to optimisation of the availability of plant nutrients (Gaskin *et al*. 2010; Glaser *et al*. 2002; Lehmann *et al*. 2003), increase in soil microbial biomass and activity (Biederman and Harpole 2013; Thies and Rillig 2009), and reduction of exchangeable Al^{3+} (Glaser *et al*. 2002; Steiner *et al*. 2007). Likewise, wood biochar addition increased wheat yield by up to 30%, with no differences in grain N content, and sustained yield for two consecutive seasons without biochar addition in the second year (Vaccari *et al*. 2011). Major *et al*. (2010) reported that maize grain yield did not increase significantly in the first year following addition of 20 t ha^{-1} of biochar (biomass-derived black C), but increased by 28%, 30% and 140% over the control for the 3 years following. Gathorne-Hardy *et al*. (2009) reported that biochar addition alone did not show a significant effect on barley yield, but applications of 50 t biochar and 80 kg N fertiliser ha^{-1} increased barley grain yield by 30%, which could be attributed to increased N-use efficiency.

Application of compost and biochar singly or together when combined with fertiliser enhanced chlorophyll content and SLW over mineral fertiliser alone, which could also indicate increased nutrient availability, vigorous plant growth and healthier plants, resulting in higher plant biomass. Chlorophyll content, an indicator of photosynthetic activity, is related to the N concentration in green plants and serves as a measure of the response of crops to N fertiliser application and soil nutrient status (Minotta and Pinzauti 1996). Hua *et al*. (2012) reported that application of bamboo biochar increased chlorophyll content of ryegrass by 20–32% compared with the control. Application of F + WB + Com resulted in the production of leaves with higher SLW than those in the control and fertiliser-only treatments (+0.68 and 0.32 mg cm^{-2}, respectively). SLW is related to leaf resistance or susceptibility to insect attack, with higher SLW conferring resistance (Steinbauer 2001).

Without amendment, the nutrient content of the soil used in this study was extremely low. Phosphorus content of the plants in the control and fertiliser-only treatments was lower than the established sufficiency ranges. Phosphorus content of maize plants in the F + WB + Com treatment was not higher than in the F + Com treatment, suggesting that WB had no effect on plant P concentration; F + Com and F + WB + Com both considerably improved nutrient content of maize plants per unit of root biomass. Higher P uptake by the crop implies that a higher concentration of P was maintained in the soil solution and available to the plants. The organic amendments in this study may have made the soil more porous and friable, which potentially enhanced root growth and development. This may have improved the root–nutrient contact in the soil and optimised nutrient availability and uptake by plants, because the effect of the amendments was particularly noticeable on root growth. Higher plant nutrient uptake was accompanied by increased shoot and root biomass.

Soil characteristics

Applications of biochar and compost had a significant influence on SWC and chemical characteristics. Post-harvest SOC content of the mineral-fertilised soil was lower than in the control, suggesting that application of mineral fertiliser alone may exacerbate the depletion of SOM through accelerated decomposition and mineralisation relative to organic inputs. Soils treated with biochar had higher SOC, and SOC remained more stable than in soils treated with manure (Sukartono *et al*. 2011). Similarly, charcoal amended soil lost 8% and 4% SOC for mineral-fertilised and unfertilised plots compared with losses of SOC from compost-amended (27%) and control plots (25%), as well as reduced exchangeable Al (Steiner *et al*. 2007). Although F + Com, F + WB + Com and F + AB + Com had a slight effect on soil C : N ratio, F + WB increased the C : N ratio the most compared with the initial value (14.2 : 1), which was reflected in the high SOC in soil treated with F + WB. This might be due to insignificant mineralisation during the growing period, so the increase in SOC could be proportional to the amount added. By contrast, mineral fertiliser had negative effect on the C : N ratio compared with the initial value. Steiner *et al*. (2008) reported that biochar and compost amendment increased soil C : N ratio after two consecutive harvests. In this study, compost and biochar additions significantly improved soil quality, including increases in SOC, exchangeable cations and water retention.

Biomass yield was significantly lower in the F + WB + Com treatment than in F + Com. However, the SOC increase in soil treated with F + Com and F + WB + Com improved nutrient content and availability compared with other treatments, which was reflected in plant growth and biomass yield. A possible explanation for this could be that increasing total SOC by compost or compost and biochar addition increased reactive surfaces and stimulated microbial growth, which may lead to a short-term immobilisation of plant-available nutrients. In the course of plant growth, these nutrients might be released through mineralisation of compost and dead microorganisms, thus leading to improved plant growth over the course of the experiment. Schulz and Glaser (2012) reported that application of biochar with compost resulted in better plant growth and C sequestration than biochar with mineral fertiliser. With biochar and biochar + compost, a significant part of the initial total C content remained after the second harvest, whereas only 58% remained in the biochar + fertiliser treatment. Nevertheless, in contrast to total C, black C contents remained almost constant during two crop growth periods without further biochar additions, but the mineral fertiliser only reduced the black C content to 75% of the original amount (Schulz and Glaser 2012).

Compost and biochar additions directly influenced the availability of native or applied nutrients, which significantly contributed to the increase in available soil K and Mg, ECEC, NO_3-N and NH_4-N after harvest compared with the control and fertiliser only. The increase in total N would be simply due to the N in the compost. Enhanced crop growth in the compost-treated soil in this study was largely due to improved nutrient availability and uptake. Higher soil macro- and micronutrient contents from compost and biochar additions may have been beneficial to plant performance, because compost + WB contains significant amounts of essential elements. By contrast, despite low N content of biochar, effects on nitrification rates that are positive (Berglund *et al*. 2004; DeLuca *et al*. 2009) or negligible or negative (Dempster *et al*. 2012) have been reported depending on soil pH (Yao *et al*. 2011). Liu *et al*. (2012) showed that compost and biochar addition increased total SOC, and plant-available Ca, K, P and Na contents by 2.5, 2.2, 2.5, 1.2 and 2.8 times, respectively, and increased the soil pH by up to 0.6 and doubled plant-available SWC compared with the control.

Soils fertilised with compost or manure have higher SOM content, porosity, hydraulic conductivity and aggregate stability and are more enriched in P, K, Ca and Mg (Edmeades 2003), as well as having lower bulk density (Tammeorg *et al*. 2014), than fertilised soils. CEC is a measure of the soils ability to hold cations, which is associated with clay and SOM content (Troeh and Thompson 2005). The ECEC of the experimental soil in this study was low, which may have caused higher leaching in mineral-fertilised than organic-amended soil during the plant growth period because of lower retention capacity of applied nutrients. In this study, the Ca : Mg ratio showed variations for different treatments. The Ca : Mg ratio has a significant influence on soil chemical properties and nutrient availability (Hazelton and Murphy 2007).

Shoot biomass showed positive significant correlations with plant height, chlorophyll content, root biomass, SLW, SWC, plant-available nutrients and nutrient uptake. The direct effect of available soil nutrients and plant nutrient uptake from soil treated with F + Com, F + WB or F + WB + Com exceeded the direct effect of available nutrients and nutrient uptake from F + AB and fertiliser-only treatments on maize growth and biomass production. The highest correlation was of plant biomass with plant nutrient uptake, and the compost and biochar amendment facilitated availability of these nutrients in this study. Positive associations between soil available nutrients and nutrient uptake might enable the choice and preparation of appropriate soil amendments. Available soil P and NO_3-N had a more significant influence on shoot and root biomass than other nutrients, meaning that these nutrients were most limiting and corresponded with the soil P and NO_3-N content before planting and uptake by plants. Solaiman *et al*. (2012) also showed positive linear correlations between soil chemical characteristics (K, P, EC, CEC, NO_3, NH_4 and S), wheat seed germination, and root and shoot growth as a result of addition of different biochar types, but a negative correlation between seed germination and Al content. From this result, it can be inferred that high shoot and root biomass, high chlorophyll content and taller plants are the traits associated with the performance of maize.

The PCA indicated that the first component (PC1) provided a reasonable summary of the data, accounting for ~84% of the total variance. That is, PC1 explained most of the variation in the entire dataset, and the other three, most of the remaining variation. It is usually believed that characters with larger absolute values closer to unity within the first principal component influence the clustering more than those with lower absolute values closer to zero (Jolliffe 2002). In this study, however, almost all 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 the whole characters. Thus, the differentiation of the treatments into different clusters was rather dictated by the cumulative effects of several characters. Similarly, Sena *et al*. (2002) compared conventionally managed plots that intensively utilised pesticides and chemical fertilisers with non-disturbed forest areas and alternatively managed plots using PCA to visualise the effects of alternative soil amendment.

Nutrient leaching

Differences in cumulative water percolation and extent of nutrient leaching among treatments were caused by variations in plant water uptake and efficiency of nutrient retention. Leaching of nutrients was significantly reduced from compost and biochar amendment compared with the control and mineral-fertilised soil, supporting our third objective. The treatment F + WB + Com had more impact in lowering the cumulative leaching of nutrients than F + AB or F + AB + Com, possibly because of more pore spaces and increased sorption capacity of biochars through oxidative reactions on the biochar surfaces over time. Singh *et al*. (2010) showed the reduction of leaching of NH_4-N by 55–93% from the applications of manure and wood biochars on different soil types. Leaching loses of NO_3-N range from 0% to 60% of the applied N fertiliser (Meisinger and Delgado 2002).

Marked differences were observed among treatments in the magnitude of leaching of nutrients at the end of the experiment. A similar study showed that charcoal application decreased the proportion of leached N and Ca on Ferralsols (Lehmann *et al*. 2003). Although N and K proved very mobile in soil, application of F + WB and F +WB + Com reduced leaching of NO_3-N by 66% and 73%, and K by 68% and 69%, respectively, compared with soil treated with fertiliser only. Thus, the retention of N and K should be specifically targeted with additions of slow-releasing nutrients and/or soil amendments. Leaching occurs at a much slower rate when most of the ions are present in exchangeable form (Troeh and Thompson 2005), or when uptake by plants increases (Lehmann *et al*. 2003). Low leaching at high nutrient availability, as found in this study, ensures sustainable soil fertility, which coincides with the findings of Lehmann *et al*. (2003). Soils that have been strongly weathered and leached often have low levels of exchangeable Ca and Mg, and plant growth may be nutrient-limited as a result (Glaser *et al*. 2002). A study by Sika (2012) indicated that biochar significantly reduced the leaching of NH_4-N (by 12–86%), NO_3-N (by 26–95%), basic cations, P and certain micronutrients. By contrast, Novak *et al*. (2009*a*) reported higher EC and K and Na concentrations of leachates, but lower concentrations of Ca, P, Mn and zinc (Zn). The degree of leaching of cations such as Ca, Mg and Na was directly related to the differential nutrient retention capacity of treatments, because the availability of these nutrients for plants was directly dependent on the soil reserve. Although the initial soil K status was sufficient for plant growth, the ratio of K uptake to initial soil K was the lowest for the control, because K uptake might be limited by the low availability of other nutrients, such as N and P.

Conclusion

This study shows that the experimental soil was deficient in plant-available nutrients, consistent with the general observation that Ferralsols of the humid tropics are nutrient-depleted and suboptimal for plant growth without additions of organic and inorganic amendments. Applications of F + Com, F + WB or F + WB + Com were more efficient in improving SOC and soil water storage capacity, and nutrient-retention capacity and nutrient-use efficiency of maize than mineral fertiliser alone. The use of compost and biochar as soil amendments reduced the loss of some nutrients through leaching, with nutrient leaching of NO_3-N, P and exchangeable bases significantly decreased as the growth of plants progressed. Although F + Com + WB or AB did not outperform F + Com in terms of biomass yield and nutrient uptake, the combined application of compost and biochar may enhance and sustain soil biophysical and chemical characteristics, because most of the compost will disappear over time through decomposition, whereas the biochar will stay in the soil for decades. Root biomass was significantly increased by F + Com, F + WB and F + WB + Com compared with other treatments. Further long-term research is required to evaluate and quantify the benefits and effects of these amendments in terms of improving and sustaining soil fertility, crop productivity and economic returns to users. Moreover, despite several positive, short-term research results, the amount of recalcitrant C supplied by biochar and compost and sequestered in the soil needs to be determined through long-term field experiments.

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