ORIGINAL RESEARCH

Surface-applied or incorporated biochar and compost combination improves soil fertility, Chinese cabbage and papaya biomass

Justine Cox^{1,2} · Nguyen V. Hue¹ · Amjad Ahmad¹ · Kent D. Kobayashi¹

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Abstract

Many Hawaiian agricultural soils are acidic with low-nutrient retention; therefore, organic soil amendments are often used to improve soil properties and increase yields. Amendments can be incorporated for annual crops, but perennial orchards need surface application to avoid damaging surface roots. Pot trials compared responses to incorporated (IBC) or surface-applied (SBC) combination of hardwood biochar and chicken manure compost (4% v/v of each amendment) added to an Andisol and Oxisol. Soil pH was increased by 0.4–1.1 units in IBC and by 0.2–0.5 for SBC in the 0–10 cm soil layer. Both SBC and IBC increased soil total N, extractable P, Ca and Mg in the 0–10 cm soil layer. Soil pH, total C and extractable Ca were also higher in the 10–20 cm soil layer for IBC soil, indicating movement and/or leaching of amendments. Chinese cabbage biomass was 18–70% higher in the IBC and 14–47% higher in the SBC than that in the unamended soil, while papaya biomass was 23% and 19% higher in SBC and IBC, respectively. There was a greater response in the more acidic Andisol soil, with larger improvements in soil pH, plant nutrient uptake and root biomass than the Oxisol. Surface application was as effective in increasing plant growth as the incorporated amendment, providing evidence for farm scale assessment. Biochar and compost are recommended for use in tropical soils, and surface application may be beneficial to annual and perennial crops.

Keywords Surface-applied · Andisol · Oxisol · *Carica papaya* · *Brassica rapa chinensis* · Biochar

1 Introduction

Many Hawaiian agricultural soils are constrained by low fertility and lack of nutrient retention due to weathering in the tropical climate. Andisols (developed from volcanic ash, pumice and cinder) typically have a high organic matter content, very high P sorption capacity and are low in Ca, Mg and K, creating a potentially P- and Ca-deficient soil, whereas Oxisols (developed from basaltic lava) are low in nutrients, and have high Fe and Al oxides, which reduce cation retention (Uehara and Ikawa 2000). Therefore, organic

soil amendments play an important role in adding nutrients, improving nutrient retention, and reducing soil acidity in vegetable, fruit and nut production in Hawaii (Ahmad et al. 2016; Hue and Silva 2000), including commodities such as pineapples, coffee and macadamias.

Biochar, composts and manures have been identified as specific amendments to improve soil properties and crop production in Hawaii (Ahmad et al. 2014a; Berek and Hue 2016; Escobar and Hue 2008). The benefits of biochar application to soils have been shown to be due to increased moisture retention (Karhu et al. 2011; Sun and Lu 2014), increased nutrient retention (Berek et al. 2018; Glaser and Lehr 2019; Zheng et al. 2013), improved soil pH (Slavich et al. 2013; Van Zwieten et al. 2010, 2015), and improved soil microbial status (Lehmann et al. 2011; Palansooriya et al. 2019). However, biochar application is not universally successful in overcoming soil limitations, or increasing crop yields, with many examples of no effects (Jeffrey et al. 2011) perhaps due to the recalcitrant and low-nutrient properties of many biochars (Brassard et al. 2019).

Compost nutrients and labile organic matter are seen as complementary properties to the porous structure and high

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✉ Justine Cox
coxja@hawaii.edu; justine.cox@dpi.nsw.gov.au

¹ Tropical Plant and Soil Sciences, University of Hawaii, 3190 Maile Way, Honolulu, HI 96822, USA

² Present Address: NSW Department Primary Industries, 1243 Bruxner Highway, Wollongbar, NSW 2477, Australia

surface area of biochar and provide synergistic effect (Fischer and Glaser 2012; Liu et al. 2012). Attempts to examine this effect under different soil types, crops, biochar and compost types and climates often found the highest rate of biochar and compost combinations substantially increased crop yields and improved soil properties (Agegnehu et al. 2017; Di et al. 2019; Doan et al. 2015; Kammann et al. 2016; Manolikaki and Diamadopoulos 2019; Sadegh-Zadeh et al. 2018). Recent studies have ascertained that the combination is superior to the amendments on their own due to increased water-holding capacity, increased nutrient retention and nutrient use efficiency (especially N), improved soil pH and CEC, decreased soil bulk density, increased soil macro-aggregates, and suppressed disease (Agegnehu et al. 2015, 2016a, b; Akmal et al. 2019; Cao et al. 2018; Jien et al. 2018; Khorram et al. 2019; Liu et al. 2019; McDonald et al. 2019; Novak et al. 2019; Sánchez-Monedero et al. 2019). In Hawaii, several biochar and compost combinations significantly increased soil pH, reduced Al, Mn and Fe in the Oxisol, and for both the Oxisol and Ultisol, increased P, K and Ca, overcoming many plant limitations to growth (Berek et al. 2018).

The benefits of biochar and compost applications are mostly described for amendments that have been incorporated into soil, enabling close contact between all the components. Unfortunately, in established perennial crops (e.g. trees), it is not possible to incorporate amendments due to substantial surface roots and established interrow ground-cover species which would be damaged with incorporation (Oo et al. 2018; Paulin and O'Malley 2008). The option for these crops is limited to surface application, which relies on movement of soluble nutrients with rainfall/irrigation, then biological bioturbation and vertical transport of solutes/particles over time (Major et al. 2010). Application of biochar and compost to the soil surface of a banana plantation (Bass et al. 2016) and a macadamia orchard (Galanti et al. 2019) showed little difference in yield after 12 and 7 months, respectively, suggesting surface application may not be effective in this time frame, or that the amendments did not address a constraint of those soils.

Valid comparisons between surface and incorporated applications of biochar mixes are scant and require further investigation (Bass et al. 2016). Information on the fate of biochar and compost as surface-applied amendments is limited. There is evidence that surface wildfire char infiltrates the soil, where the dissolved fraction is mobile with rainfall over time, and particulate char rate of vertical movement from 3 to 30 mm per year has been measured (Rumpel et al. 2015). However, this contrasts with significant surface biochar losses due to erosion after field surface application, of 7–55% (Rumpel et al. 2009) and 20–53% (Major et al. 2010). The risk is high for biochar lateral movement, especially down slope after rainfall events, due to the low density

and porous structure of biochar (Rumpel et al. 2015; Wang et al. 2013). It is, therefore, suggested that a combination of biochar with compost could reduce this risk of lateral movement. Substantial vertical movement of incorporated biochar has also been shown, with 50% of biochar recovered below the incorporated zone in a sandy soil (Haeefele et al. 2011) and 3.8–21.8% recovered in a range of soil types (Singh et al. 2015). Singh et al. (2015) suggested that the movement of the fine particulate or the dissolved labile components of the biochar contributed to the recovered biochar carbon.

We hypothesised that the application of a combination of wood waste biochar and chicken manure compost would increase availability and plant uptake of nutrients in two soils constrained by low-nutrient holding capacity and poor fertility. We also aim to explain some of the processes involved in the effects of the combination amendment. To address these hypotheses, we compared incorporated and surface applications of a combination of wood waste biochar and chicken manure compost on the growth and nutrient uptake of an annual (Chinese cabbage) to represent typical incorporation and a perennial (papaya) for typical surface application methods.

2 Materials and methods

2.1 Soil, biochar and compost characteristics

The Oxisol (Very fine, kaolinitic, isohyperthermic rhodic haplustox, Wahiawa series) was sourced from central Oahu, and taken from the top 20 cm from the Poamoho Research Station of the University of Hawaii at Manoa. The Andisol (Medial over pumiceous or cindery, ferrihydritic, isothermic typic hapludand, Tantalus series) was sourced from the Lyon Arboretum of the University of Hawaii at Manoa. The two soils' properties are shown in Table 1. Soils were air dried and sieved through a 4-mm mesh, then pH and EC were measured using 1:5 water extract, total C and N using LECO combustion, available P and K using Mehlich 3 extraction, bulk density (BD) using mass of known volume and water-holding capacity (WHC) using moisture content of a gravity-drained saturated soil. Chicken manure compost from an aerated process using windrows was sourced from a commercial supplier (Niu Nursery). The compost had a C:N ratio of 17.6 and further characteristics are shown in Table 1. The biochar was processed by the Landscape Ecology Corp from mixed hardwood pruning from Hilo, Hawaii, and heated to a maximum temperature of 450 °C for 2 h (properties shown in Table 1). The biochar total functional groups averaged 0.58 mmol/g with carboxylic, phenolic and lactonic groups at 0.22, 0.27 and 0.10 mmol/g, with a cation exchange capacity (CEC) of 14.7 (Berek et al. 2018).

Table 1 Soil and amendment properties at start of trial (pH and EC determined on 1:5 extract, total C and N determined by LECO combustion, available P and K by Mehlich 3 extraction)

	pH (water)	EC (dS/m)	C (%)	N (%)	P (mg/kg)	K (mg/kg)	BD (g/cm ³)	WHC (%)
Biochar	8.4	1.63	49.81	0.46	978	3954	0.52	–
Compost	7.0	3.23	29.37	1.67	6801	5440	0.87	–
Andisol	6.0	0.15	2.52	0.17	5.3	137	0.74	32
Oxisol	6.9	0.30	1.45	0.14	147.2	447	0.92	35

Compost and biochar were air dried and sieved through a 4-mm mesh.

The applied amendment was a 1:1 compost:biochar blend by volume on a dry matter basis and combined at the trial establishment. The dry rate of biochar and compost application was calculated as 4% by volume each, and were combined together just prior to the application to the soil (all treatments were calculated to fill 1.53 l per pot). Therefore, 16.9 g of biochar and 28.3 g compost (dry weight) were used per pot. In the Andisol, there was 1.4 kg soil/pot and 1.6 kg/pot in the Oxisol. The rates of biochar and compost were the equivalent in the Andisol of 14.8 t/ha and 26.0 t/ha (dry weight) and 18.4 t/ha and 32 t/ha in the Oxisol.

2.2 Experimental site and design

The glasshouse trial was conducted at Magoon's greenhouse facility of the University of Hawaii at Manoa (37 25.82' N, 122 05.36' W). Tree pots (10 × 10 × 34 cm tapered, 2.65 l) were used to conduct the pot trials. The experimental design consisted of two soils (Oxisol and Andisol) with two amendment placements (surface, incorporated) compared to controls (unamended) with four replicates. Treatments were established, and each replicate pot was placed randomly on benches (blocks) in a randomised complete block design (RCBD).

2.3 Pot trial 1, Nov 2017

The mineral fertilisers required for the two soil types were calculated from both the initial soil analysis and the requirements to grow Chinese cabbage, *Brassica rapa chinensis* group, cv. (Mei Qing). The plant required 200 mg/kg soil of N, which was applied as urea (711 mg urea/pot, and therefore, 320 mg N/pot) for the Oxisol and NPK 16–16–16 (1.75 g/pot, and therefore, 280 mg N/pot) for the Andisol. This was sufficient NPK for crop growth for both soils. The 10–20 cm layers were prepared separately from the 0–10 cm soil layers. Mineral fertiliser was mixed with each soil and placed into the 10–20 cm layer of each pot at lab determined bulk density. For the 0–10 cm layer, the control and surface treatments were the same, with soils mixed with mineral fertiliser. For the surface treatment (SBC),

the compost and biochar amendments were mixed and then immediately placed on the soil surface. For the incorporated treatment (IBC), the mixed amendments were thoroughly mixed with the soil (0–10 cm layer), and placed above the 10–20 cm layer. The biochar contributed 78 mg N, 17 mg P and 67 mg K (total) per pot, and the compost contributed 473 mg N, 192 mg P and 154 mg K (total) per pot. The pots were watered and left to equilibrate for 3 days.

The pots were planted on 28 November 2017 with Chinese cabbage seedlings or with papaya (*Carica papaya* cv Sunrise) seedlings ($n=4$) making a total of 48 pots (1 plant/pot). Seedlings were started 3 weeks prior to transplanting using 50 cells trays and Sunshine peatmoss. Pots were hand watered every other day for the first 4 weeks, and then watered daily to the end of the trial, according to a regime for each soil type and crop. Water was provided to achieve field capacity and limit plant wilting; therefore, some water leaching was observed. By harvest, Chinese cabbage had 3350 ml/pot of water for Andisol and 3650 ml/pot for Oxisol applied. Papaya plants had 6150 ml/pot of water for Andisol and 6790 ml/pot for Oxisol applied. Plant above ground biomass was harvested after 8 weeks for Chinese cabbage and 14 weeks for papaya, dried at 70 °C till it reached constant weight and weighed. The surface amendment remaining on top of the SBC treatments that was loose was carefully removed and discarded, where the amendment was not embedded and part of the soil profile. This meant that the IBC and SBC would not be comparable in terms of absolute C contribution from the amendments. The pot was cut horizontally with a knife at the 10 cm line to split the 0–10 and 10–20 cm layers. Roots from both layers were separated from the soil, placed in bags and refrigerated until assessment. Soil was collected, air dried and sieved to pass a 2-mm mesh.

2.4 Pot trial 2, May 2018

The second pot trial was a replication of the 1st trial using Chinese cabbage crop only, and the two soil types, with identical methodology. The repeat experiment was performed only on the short-term crop, in a different season to examine this influence. Three-week-old Chinese cabbage seedlings were transplanted on 1 May 2018, 3 days after

initial watering and equilibrating. Plants were watered every other day for the first 2 weeks and then daily. By harvest, 6030 ml/pot of water for Andisol and 6390 ml/pot for Oxisol had been applied. Plants were harvested after 5 weeks as growth was faster in the warmer season, and soil and root samples were collected from each layer for each pot, as described in the first pot trial.

2.5 Soil analyses

Total C and N were determined by combustion using a LECO C–N analyser (TruSpec CN). Soil available nutrients P, Na, Mg, K, and Ca were determined by Mehlich 3 extraction (2.0 g in 20 ml) as described by Mehlich (1984) and measured using an ICP spectrometer (PerkinElmer Optima series). Soil pH and EC were measured in a 1:1 mixture of soil and deionised water (20 g and 20 ml), after shaking for an hour using a HANNA pH/EC combo meter. Soil nitrate ($\text{NO}_3\text{-N}$) and ammonium ($\text{NH}_4\text{-N}$) concentrations were also measured on 1:1 soil and water mixture, after shaking for an hour, using Vernier ion-selective electrodes. At each time of measurement, the electrodes were calibrated using calibration solution and a calibration curve was established using set of solutions with known NO_3 and NH_4 concentrations.

2.6 Plant harvest and nutrient analyses

At harvest, the above ground biomass was dried to 70 °C for 72 h or until a constant weight was reached. Each plant biomass was finely ground, ashed at 500 °C for 4 h, then dissolved in 0.01 M HCl solution (0.25 g in 20 ml). The extract solution was analysed for P, Na, Mg, K, and Ca using an ICP. Total N was determined using the LECO analyzer. Total nutrient uptake per plant was calculated by multiplying concentration with dry biomass weight. Roots were shaken to remove most soil from both the 0–10 and 10–20 cm layers. Each root mass was air dried on paper, then the remaining attached dried soil was separated from the roots and just the roots visually ranked for biomass on a scale of 1–5 (small to large) for each soil and crop type as described by Walters and Wehner (1994).

2.7 Statistics

A two-way factorial analysis of variance (ANOVA) was conducted, using the STATISTIX V10, for each crop to compare the effects of amendment and soil type on each parameter. Tukey's mean separation was used at 5% probability for the significant parameters.

3 Results

3.1 Chinese cabbage

3.1.1 Soil

Both surface-applied (SBC) and incorporated (IBC) amendments significantly increased soil pH, total C, P, Ca, and Mg in the 0–10 cm soil layer at harvest, when both soil types were combined. In the 10–20 cm layer, both amendments only significantly increased Mg concentration. In addition, only IBC significantly increased total N and $\text{NO}_3\text{-N}$ concentrations in the 0–10 cm soil layer, and total C, pH, Ca in the 10–20 cm layer. The IBC also significantly reduced K concentration at 10–20 cm. Only SBC significantly increased K concentration in the 0–10 cm layer and P concentration in the 10–20 cm layer. In some cases, there were interactions with soil type, with the Andisol responding differently than the Oxisol.

In the Andisol, pH was significantly increased with both IBC and SBC in the 0–10 cm layer, but only IBC in the Oxisol. At harvest in trial 1, the Andisol's pH increased by 0.31 units for SBC and 0.77 units for IBC (Table 2). In the Oxisol, pH significantly increased by 0.39 units for IBC. Even though there were no amendments in the 10–20 cm layer, soil pH was significantly higher in this layer for the IBC amended Andisol soil. In trial 2, both IBC and SBC significantly increased pH in the 10–20 cm layer (Table 3).

Soil EC in trial 1 was not different to the unamended soil in the 0–10 cm layer (Table 2). In the 10–20 cm layer with the IBC and SBC, soil EC were 88% and 50% significantly higher than that in the unamended in the Oxisol, respectively. Just in the IBC, soil EC was significantly higher (2.3 times) than that in the unamended Andisol. In trial 2, soil EC was significantly higher in the IBC soils (64%) than that in the unamended for the 0–10 cm layer in the Andisol (Table 3).

Soil C was 47% significantly higher with the IBC amendment than that in the unamended Andisol soil in the 0–10 cm layer for trial 1 (Table 2). The Oxisol C content in the IBC was 87% significantly higher than that in the unamended Oxisol soil. The total C value of the SBC was not a comparable measure, however, due to the sampling process of removing the remaining surface amendment before soil analyses. In trial 2, however, SBC did significantly increase soil C content in the 0–10 cm layer for both soil types (Table 3). Total soil C had significantly increased in the 10–20 cm layer in the Andisol (22%) compared to the unamended, despite no amendment present initially, which was also seen in trial 1.

Total N was only significantly higher in the IBC than that in the unamended soil in the 0–10 cm layer of the

Table 2 Soil chemical properties at harvest of Chinese cabbage (trial 1 established in November 2017) for both 0–10 cm and 10–20 cm layers for the two soil types ($n=4$) and significance of treatment effect (different letters signify a statistical difference at $p<0.05$ along each row)

	Andisol			Oxisol		
	Control	Incorp	Surface	Control	Incorp	Surface
0–10 cm						
pH (water)	5.57 ^e	6.34 ^c	5.89 ^d	6.84 ^b	7.23 ^a	7.01 ^{ab}
EC (dS/m)	0.25 ^b	0.35 ^{ab}	0.26 ^{ab}	0.45 ^{ab}	0.46 ^a	0.41 ^{ab}
NO ₃ -N (mg/kg)	1.05 ^c	9.18 ^c	2.55 ^c	18.1 ^b	36.5 ^a	23.8 ^b
NH ₄ -N (mg/kg)	0.23 ^{ab}	0.13 ^b	0.30 ^{ab}	0.30 ^{ab}	0.33 ^{ab}	0.40 ^a
Total C (%)	2.16 ^{bc}	3.18 ^a	2.48 ^{ab}	1.33 ^c	2.50 ^{ab}	2.05 ^{bc}
Total N (%)	0.16 ^b	0.19 ^a	0.17 ^{ab}	0.15 ^b	0.18 ^{ab}	0.17 ^{ab}
P (mg/kg)	16.3 ^d	24.6 ^d	22.7 ^d	94.5 ^c	150.9 ^b	184.8 ^a
K (mg/kg)	71 ^d	120 ^d	116 ^d	604 ^b	481 ^c	764 ^a
Ca (mg/kg)	1227 ^d	3313 ^b	1836 ^c	2115 ^c	3763 ^a	3884 ^a
Mg (mg/kg)	654 ^{cd}	750 ^{ab}	705 ^{bc}	548 ^e	626 ^d	787 ^a
10–20 cm						
pH (water)	5.41 ^c	5.79 ^b	5.55 ^{bc}	6.52 ^a	6.57 ^a	6.45 ^a
EC (dS/m)	0.27 ^d	0.62 ^b	0.38 ^{cd}	0.42 ^c	0.79 ^a	0.63 ^b
NO ₃ -N (mg/kg)	1.10 ^b	2.15 ^b	3.79 ^b	22.9 ^{ab}	43.8 ^a	30.4 ^{ab}
NH ₄ -N (mg/kg)	3.11 ^{ab}	0.18 ^b	7.04 ^a	0.23 ^b	0.20 ^b	0.27 ^b
Total C (%)	2.09 ^b	2.56 ^a	1.97 ^b	1.32 ^c	1.39 ^c	1.41 ^c
Total N (%)	0.16 ^{ab}	0.18 ^a	0.16 ^{ab}	0.15 ^b	0.15 ^b	0.16 ^b
P (mg/kg)	16.0 ^c	18.4 ^c	17.6 ^c	93.9 ^b	99.7 ^b	128.5 ^a
K (mg/kg)	117 ^{bc}	58 ^c	176 ^b	321 ^a	191 ^b	332 ^a
Ca (mg/kg)	1195 ^c	2149 ^b	1299 ^c	2213 ^{ab}	2853 ^{ab}	2915 ^a
Mg (mg/kg)	632 ^{bc}	739 ^a	703 ^{ab}	520 ^d	543 ^{cd}	719 ^{ab}

Table 3 Soil chemical properties at harvest of Chinese cabbage (trial 2 established in May 2018) for the two soil types ($n=4$) and significance of treatment effect (different letters signify a statistical difference at $p<0.05$ along each row)

	Andisol			Oxisol		
	Control	Incorp	Surface	Control	Incorp	Surface
0–10 cm						
pH (water)	5.32 ^d	5.89 ^c	5.73 ^c	6.33 ^b	6.73 ^a	6.64 ^a
EC (dS/m)	0.14 ^c	0.23 ^b	0.17 ^c	0.29 ^a	0.28 ^{ab}	0.29 ^{ab}
NO ₃ -N (mg/kg)	4.57 ^b	6.64 ^{ab}	6.54 ^{ab}	4.50 ^b	8.67 ^a	8.15 ^a
NH ₄ -N (mg/kg)	0.1 ^c	0.1 ^c	0.1 ^c	0.33 ^a	0.25 ^b	0.2 ^b
Total C (%)	1.56 ^c	3.04 ^a	1.96 ^b	1.30 ^c	2.90 ^a	2.18 ^b
Total N (%)	0.10 ^{bc}	0.11 ^{bc}	0.08 ^c	0.09 ^c	0.13 ^b	0.17 ^a
P (mg/kg)	4.03 ^c	5.20 ^c	3.47 ^c	101 ^b	107 ^a	101 ^b
K (mg/kg)	102 ^c	57 ^c	115 ^c	504 ^a	361 ^b	392 ^b
Ca (mg/kg)	608 ^d	1939 ^b	1163 ^c	1726 ^b	2552 ^a	2312 ^a
Mg (mg/kg)	611 ^b	723 ^a	654 ^b	424 ^d	532 ^c	512 ^c
10–20 cm						
pH (water)	5.32 ^e	5.55 ^d	5.52 ^d	6.15 ^c	6.62 ^a	6.41 ^b
EC (dS/m)	0.24	0.30	0.29	0.30	0.26	0.23
NO ₃ -N (mg/kg)	15.21	6.23	19.33	4.26	4.46	3.06
NH ₄ -N (mg/kg)	2.38 ^a	0.1 ^b	0.58 ^{ab}	0.4 ^b	0.1 ^b	0.1 ^b
Total C (%)	1.54 ^{abc}	1.73 ^a	1.57 ^{ab}	1.29 ^d	1.45 ^{bcd}	1.31 ^{cd}
Total N (%)	0.11 ^{bc}	0.08 ^{cd}	0.07 ^d	0.10 ^{bcd}	0.13 ^{ab}	0.16 ^a
P (mg/kg)	4.34 ^b	4.05 ^b	4.30 ^b	103 ^a	99 ^a	96 ^a
K (mg/kg)	229 ^b	45 ^c	145 ^{bc}	491 ^a	242 ^b	225 ^b
Ca (mg/kg)	635	1057 ^b	931 ^b	1753 ^a	1875 ^a	1788 ^a
Mg (mg/kg)	639 ^a	644 ^a	681 ^a	376 ^b	400 ^b	384 ^b

Andisol for trial 1, but both IBC and SBC significantly increased N in the Oxisol compared to the unamended soil in trial 2 (Tables 2 and 3). Nitrate N was only significantly higher in the IBC (50%) than that in the unamended in the 0–10 cm layer of the Oxisol for trial 1, but both IBC and SBC (48%, 45%) significantly increased Nitrate N than the unamended in trial 2.

Both IBC and SBC amendments significantly increased soil nutrients P, Ca, Mg in the 0–10 cm layer of the Oxisol, whereas in the Andisol only Ca was significantly higher than that in the unamended soil in trial 1 (Table 2). In the Oxisol, K significantly reduced in the IBC but significantly increased in the SBC compared to the unamended soil. Soil P was 96% significantly higher in the SBC and 60% significantly higher in the IBC than that in the unamended Oxisol soil in the 0–10 cm layer, and even 37% significantly higher in the SBC than that in the unamended in the 10–20 cm layer in trial 1. In trial 2, for soil nutrients P, Mg in the 0–10 cm layer of two soil types, only IBC was significantly higher than the unamended. Soil Ca was significantly higher in both IBC and SBC than that in the unamended.

3.1.2 Chinese cabbage biomass

Combining both soil types and dates, dry weight plant biomass was significantly higher in both IBC and SBC, than that in the unamended soil. The response in trial 1 to the amendments was smaller than the response in trial 2 despite the shorter growth period (Fig. 1). In trial 1, SBC produced 23% significantly larger plants than the unamended in the Andisol, yet there was no difference in the Oxisol. However, in trial 2, both SBC (54%) and IBC (54%) had significantly

higher biomass than the unamended in the Oxisol. The IBC had 92% significantly higher biomass than the unamended in the Andisol.

The soil amendments had only a small impact on the plant nutrient concentration at harvest (Supplementary material 1). Total N in the plants was significantly lower in the IBC than that in the unamended Andisol, in trial 1. In the Andisol soil, plant Ca was significantly higher in the IBC than that in the unamended in trial 1 and plant K was significantly higher in the SBC than that in the unamended in trial 2. In the Oxisol, there were no other differences for plant K, P and Mg.

Calculated total plant nutrient uptake, however, was significantly higher in the SBC for N, K, Ca, Mg, plus also in the IBC for Ca in trial 1 (Table 4) given the influence of plant size. In trial 2, plant uptake of N, P, K and Ca were all significantly higher in both IBC and SBC.

3.1.3 Chinese cabbage roots

The majority of the roots were in the 10–20 cm layer for the Oxisol and the Andisol had roots distributed through both layers. Overall, in the 0–10 cm layer, both SBC and IBC resulted in higher root biomass than the unamended (up to double) for both trial dates (Fig. 2). In the 10–20 cm soil layer, however, only the IBC resulted in significantly higher root biomass than the unamended for trial 1, but both IBC and SBC significantly increased root biomass in trial 2. The roots had a significantly greater biomass in the 0–10 cm layer in the Andisol compared to the Oxisol, but this was reversed for the 10–20 cm soil layer.

Fig. 1 Chinese cabbage dry weight biomass (g/plant) in Andisol and Oxisol soils for control, incorporated and surface-applied treatments for **a** trial 1 (November 2017) and **b** trial 2 (May 2018), with standard

error ($n=4$), and significance of treatment effect (different letters signify a statistical difference at $p < 0.05$)

Table 4 Total nutrient uptake (mg/plant) at harvest of Chinese cabbage for trials established in November 2017 and May 2018, for the two soil types ($n=4$) and significance of treatment effect (different letters signify a statistical difference at $p<0.05$ along each row)

	Andisol			Oxisol		
	Control	Incorp	Surface	Control	Incorp	Surface
Trial 1						
N	267 ^{de}	219 ^e	297 ^{cd}	343 ^{bc}	406 ^a	397 ^{ab}
K	394 ^b	422 ^b	505 ^b	747 ^a	817 ^a	806 ^a
P	23 ^b	37 ^a	34 ^{ab}	38 ^a	39 ^a	39 ^a
Ca	86 ^d	183 ^a	123 ^c	141 ^{bc}	189 ^a	172 ^{ab}
Mg	54 ^{ab}	56 ^a	60 ^a	40 ^c	43 ^c	46 ^{bc}
Trial 2						
N	177 ^c	254 ^{abc}	241 ^{abc}	230 ^{bc}	305 ^{ab}	310 ^a
K	242 ^d	615 ^b	499 ^{bc}	383 ^{cd}	880 ^a	873 ^a
P	22 ^c	45 ^b	39 ^{bc}	51 ^b	80 ^a	87 ^a
Ca	105 ^c	197 ^b	171 ^{bc}	208 ^b	288 ^a	290 ^a
Mg	98 ^a	91 ^{ab}	94 ^a	38 ^c	55 ^{bc}	56 ^{bc}

Fig. 2 Root biomass rank of Chinese cabbage in Andisol and Oxisol soils for control, incorporated and surface-applied treatments for **a** trial 1 (November 2017) and **b** trial 2 (May 2018), with standard error ($n=4$) and significance of treatment effect (different letters signify a statistical difference at $p<0.05$ with lowercase letters comparing the 0–10 cm layer and uppercase letters comparing the 10–20 cm layer). Each plant's root biomass was visually ranked from 1 to 5, low to high, after drying and soil removed (Walters and Wehner 1994)

Table 5 Soil chemical properties at harvest of papaya (established May 2018) for the two soil types ($n=4$) and significance of treatment effect (different letters signify a statistical difference at $p < 0.05$ along each row)

	Andisol			Oxisol		
	Control	Incorp	Surface	Control	Incorp	Surface
0–10 cm						
pH (water)	5.38 ^d	6.43 ^b	5.84 ^c	6.44 ^b	6.89 ^a	6.88 ^a
EC (dS/m)	0.38 ^b	0.52 ^{ab}	0.48 ^{ab}	0.45 ^{ab}	0.61 ^a	0.63 ^a
NO ₃ -N (mg/kg)	1.5 ^b	9.3 ^{ab}	4.8 ^{ab}	13.3 ^{ab}	20.2 ^a	11.9 ^{ab}
NH ₄ -N (mg/kg)	0.15 ^c	0.10 ^c	0.18 ^c	0.53 ^b	0.48 ^b	0.74 ^a
Total C (%)	1.97 ^b	3.50 ^a	2.97 ^a	1.26 ^c	2.35 ^b	2.10 ^b
Total N (%)	0.17 ^c	0.21 ^a	0.20 ^{ab}	0.17 ^{bc}	0.21 ^a	0.21 ^a
P (mg/kg)	9.7 ^c	15.0 ^c	16.8 ^c	190 ^b	253 ^a	258 ^a
K (mg/kg)	128 ^d	222 ^c	249 ^c	657 ^{ab}	587 ^b	716 ^a
Ca (mg/kg)	1360 ^d	4330 ^a	2974 ^c	2649 ^c	4029 ^a	3576 ^b
Mg (mg/kg)	590 ^c	738 ^a	693 ^{ab}	661 ^b	674 ^b	733 ^a
10–20 cm						
pH (water)	5.12 ^c	5.48 ^b	5.08 ^c	6.15 ^a	6.29 ^a	6.25 ^a
EC (dS/m)	0.72 ^c	1.30 ^{ab}	1.07 ^{abc}	0.95 ^{bc}	1.28 ^{ab}	1.33 ^a
NO ₃ -N (mg/kg)	9.1 ^b	62.2 ^{ab}	85.9 ^a	12.8 ^b	23.9 ^b	10.6 ^b
NH ₄ -N (mg/kg)	0.63 ^{bc}	0.40 ^c	0.53 ^{bc}	1.25 ^{ab}	1.09 ^{abc}	1.67 ^a
Total C (%)	1.93 ^b	2.40 ^a	2.03 ^b	1.30 ^c	1.40 ^c	1.45 ^c
Total N (%)	0.17 ^b	0.19 ^a	0.17 ^{ab}	0.18 ^{ab}	0.18 ^{ab}	0.18 ^{ab}
P (mg/kg)	9.8 ^c	11.7 ^c	10.9 ^c	200 ^b	207 ^{ab}	214 ^a
K (mg/kg)	212 ^b	273 ^b	244 ^b	678 ^a	555 ^a	565 ^a
Ca (mg/kg)	1447 ^d	2541 ^c	1590 ^d	2660 ^{bc}	3096 ^a	2856 ^{ab}
Mg (mg/kg)	593 ^b	611 ^b	688 ^a	472 ^d	486 ^{cd}	546 ^{bc}

3.2 Papaya

3.2.1 Soil

Overall, both surface (SBC) and incorporated (IBC) applications of amendments significantly increased soil pH, EC, total C, total N, P, Ca, and Mg in the 0–10 cm soil layer at harvest (Table 5). In the 10–20 cm layer, both SBC and IBC significantly increased EC, NO₃-N, and Ca. In addition, only IBC significantly increased pH and total C in the 10–20 cm layer, and only SBC significantly increased NH₄-N, K, in the 0–10 cm and P, Mg in the 10–20 cm layer.

Soil pH was significantly increased by both IBC and SBC in both soil types in the 0–10 cm layer. In the Andisol, pH had significantly increased by 0.45 units for SBC and by 1.05 units for IBC. In the Oxisol, soil pH was significantly increased by 0.44 units for SBC and 0.45 units for IBC. As found in the Chinese cabbage data, soil pH was significantly higher in the 10–20 cm layer for the IBC amended Andisol. For soil EC in the 10–20 cm layer, it was significantly higher just with SBC than the unamended Oxisol and was significantly higher just with IBC than the unamended Andisol.

Soil C was 78% significantly higher with IBC amendment and 51% significantly higher with SBC than that in the unamended Andisol in the 0–10 cm layer (Table 5). The

Oxisol soil C was 87% significantly higher with IBC and 67% significantly higher with SBC than that the unamended Oxisol. The SBC increased soil C to the same extent that IBC did, even though the remaining surface amendments were removed before soil analyses. As was found with the Chinese cabbage trial, total soil C had significantly increased in the 10–20 cm layer of the IBC amendment in the Andisol (24%) compared to the unamended soil.

Total N was significantly higher in both the IBC and SBC than that in the unamended soil in the 0–10 cm layer of the Andisol, and significantly higher in both amendments to the same extent in the Oxisol (Table 5). There was no difference in NO₃-N concentrations, except for in the 10–20 cm layer in the Andisol, where SBC significantly increased NO₃-N ten times compared to the unamended. The only difference in NH₄-N concentration was a significant increase from the SBC amendment compared to the control in the 0–10 cm layer of the Oxisol.

Both IBC and SBC amendments significantly increased soil nutrient concentrations of extractable P, and Ca in the 0–10 cm layer of the Oxisol, whereas in the Andisol, K, Ca, and Mg concentrations were significantly higher than that the unamended control (Table 5). The nutrient concentration patterns in the 10–20 cm were mixed for both soil types. In the Oxisol, P was 36% significantly higher in the SBC and

Fig. 3 Plant dry weight biomass (g/plant) of papaya (established November 2017) at 3 months old in Andisol and Oxisol soils for control, incorporated and surface-applied treatments with standard error ($n=4$) and significance of treatment effect (different letters signify a statistical difference at $p<0.05$). When soil data were combined, there was significantly higher plant biomass in the surface-applied amendments than control

34% significantly higher in the IBC than that the unamended Oxisol in the 0–10 cm layer, and 7% significantly higher in the SBC than that the unamended in the 10–20 cm layer. Soil K concentration was significantly higher only in the Andisol 0–10 cm soil layer, by both IBC and SBC. Soil Ca was significantly higher in both IBC and SBC than that the unamended in the Andisol. Only the IBC amendment significantly increased Ca in the 10–20 cm soil layer in both soil types.

3.2.2 Papaya biomass

Overall, with both soils combined, plant dry biomass was 24% significantly higher in SBC than that in the unamended soil, but IBC was not statistically different. Plants grown in the Oxisol had 34% more biomass than those grown in the Andisol. The effects of IBC and SBC were not statistically significant, however, when compared separately for each soil type (Fig. 3).

The soil amendments had only a small impact on the plant nutrient concentration at harvest (Supplementary material 2). Nitrogen in the plants was significantly lower in the IBC than that the unamended in the Andisol. IBC significantly increased plant concentrations of Ca, Fe and K compared to the unamended soil, but P and Mg concentrations were

Table 6 Total plant nutrient uptake (mg/plant) at harvest of papaya for the two soil types ($n=4$) and significance of treatment effect (different letters signify a statistical difference at $p<0.05$ along each row)

	Andisol			Oxisol		
	Control	Incorp	Surface	Control	Incorp	Surface
N	201 ^b	243 ^{ab}	271 ^{ab}	262 ^{ab}	298 ^{ab}	318 ^a
K	181 ^c	308 ^b	256 ^{bc}	422 ^a	486 ^a	499 ^a
P	15 ^c	23 ^b	18 ^{bc}	31 ^a	37 ^a	35 ^a
Ca	110 ^c	190 ^{ab}	145 ^{bc}	208 ^a	244 ^a	239 ^a
Mg	101 ^{ab}	144 ^a	146 ^a	98 ^b	106 ^{ab}	123 ^{ab}

Fig. 4 Root biomass rank of papaya at harvest, in Andisol and Oxisol soils for control, incorporated and surface-applied treatments with standard error ($n=4$) and significance of treatment effect (different letters signify a statistical difference at $p<0.05$ with lowercase letters comparing the 0–10 cm layer and uppercase letters comparing the 10–20 cm layer). Each plant's root biomass was visually ranked from 1 to 5, low to high, after drying and soil removed (Walters and Wehner 1994)

unaffected. Total nutrient uptake, however, was significantly higher in both IBC and SBC for K, Ca, and Mg, with IBC significantly increasing plant P content, but not affecting N (Table 6).

3.2.3 Papaya roots

The root distribution of the papayas was very different to that found for the Chinese cabbage in response to the amendments as the majority of the roots were in the 0–10 cm layer. Overall, in the 0–10 cm layer, only SBC resulted in significantly higher root biomass than the unamended soil (Fig. 4). In the 10–20 cm layer, both the IBC and SBC resulted in significantly higher root biomass than the unamended soil. The roots had a greater biomass in the 0–10 cm layer in the Oxisol compared to the Andisol, but there was no difference between the soil types in 10–20 cm layer.

4 Discussion

4.1 Impact of biochar and compost on soil and plants

Regardless of whether the amendments were incorporated or on the surface, the combination of the wood biochar and chicken manure compost significantly increased soil fertility, and plant and root biomass. Plant biomass yield increases of 14–70% compared to the mineral fertilised soils were of similar scale to other studies using combined biochar and compost (Agegnehu et al. 2015; Berek et al. 2018; Cao et al. 2018; Liu et al. 2019; Schulz and Glaser 2012). Plants grown in biochar and compost amended soils were deemed more effective at accessing and using nutrients than that the controls (Agegnehu et al. 2016a; Berek et al. 2018; Manolikaki and Diamadopoulos 2019; Schulz and Glaser 2012). This is likely due to the additional nutrients supplied by the amendments, improved nutrient availability from the increased soil pH, increased soil organic matter content, water-holding capacity and reduced nutrient leaching (Agegnehu et al. 2015, 2016b,c; Cao et al. 2018; Ghosh et al. 2015; Liu et al. 2012; Radin et al. 2018). It is suggested that these Hawaiian soil properties improved (and plant biomass increased) due to their initial low fertility, acidic pH and coarse texture, as the amendments addressed these specific limitations (Jeffery et al. 2017).

Chinese cabbage and papaya biomass increases may be explained by increased nutrient supply and/or retention. The amendments provided 1.7 times (Oxisol) to 2 times (Andisol) the N more than the mineral fertiliser. They also provided more P (0.75 times) and K (0.79 times) than the fertiliser for the Andisol. The compost component of the combination was more likely to contribute the most available

nutrients (Liu et al. 2019; Radin et al. 2018). At harvest, the soil N was higher in the amended 0–10 cm soil for the papaya trials, but was not consistent for the Chinese cabbage trials. This may be explained by the longer growing period for the papayas, and the variability experienced in the cabbage trials.

The NO_3^- -N concentrations were double in the amended Oxisol soils for the Chinese cabbage, which may be due to the ability of biochar to reduce nitrate leaching by retaining N within the biochar pore structure (Agegnehu et al. 2015; Borchard et al. 2019; Nguyen et al. 2017). The amendments had no effect, however, on NO_3^- -N concentrations in the Andisol soil, which may be due to its low-nutrient retention capacity. Borchard et al. (2019) also found that NO_3^- -N concentration was unaffected by biochar addition to coarse or medium textured soil, yet increased in fine soil. They attributed biochar's ability to both reversibly take up and release NO_3^- , the key to understanding the complexity of NO_3^- stabilisation and retention pathways.

The increase in soil pH, which was associated with improved nutrient availability, may have contributed to increased plant biomass (Berek et al. 2018; Slavich et al. 2013; Van Zwieten et al. 2015). The increase of 0.4–1.1 pH units found for IBC in the 0–10 cm layer was anticipated due to the liming effects of biochars (Bass et al. 2016; Berek et al. 2018; Doan et al. 2015; Liu et al. 2012; Radin et al. 2018). The increase in soil pH after application of an alkaline biochar is thought to be attributed to the biochar's high base cation content, alkalinity and its capacity to decrease exchangeable Al and H (Brassard et al. 2019).

It is possible that the higher plant biomass response in the Andisol soil was due to the larger increase in soil pH [from 5.6 to 6.3 (IBC) and 5.9 (SBC) for cabbage for example], compared with the Oxisol, being closer to 7 (Berek et al. 2018). The acidic Andisol soil was improved by the amendments, which transferred it into the preferred pH range of the Chinese cabbage (Berek et al. 2018). The soil pH change found in this study is consistent with the significant association between increased soil pH and plant productivity in the acidic to neutral range by Jeffrey et al. (2011) and especially in the tropical climate (Jeffery et al. 2017).

Most studies have shown that biochar and compost application increased available soil K due to the addition of K in an available form (Agegnehu et al. 2015; Radin et al. 2018; Sadegh-Zadeh et al. 2018), however, responses in this study were variable. The papaya trial supported these findings with significant increases in soil K, but only in the Andisol soil. The Chinese cabbage trial, however, had lower soil K for both treatments and soil layers. This also corresponded to significantly higher plant uptake of K (2–2.5 times) in these treatments than the unamended. It is, therefore, suggested that the reduction in soil K is due to increased uptake of K by these plants (Agegnehu et al. 2015; Manolikaki and

Diamadopoulos 2019). Further to this, the soil layers with reduced K correspond to higher root biomass in both soil types, and there is also potential for some K to be held in the roots. Chinese cabbage has a high requirement for K (Berek et al. 2018; van Averbeke et al. 2007) and it was determined that at harvest, the control plants had insufficient K concentrations (Jones et al. 1991). The outlier of higher soil K in the 0–10 cm for the SBC than the control, in the Oxisol, could not be explained by plant response, and is another example of inconsistent K to biochar (Hossain et al. 2020).

The higher P in the amended soil increased P availability and subsequent plant uptake, which was supported by other similar studies (Agegnehu et al. 2016c; Bass et al. 2016; Manolikaki and Diamadopoulos 2019; Van Zwieten et al. 2019). Greater plant P uptake from amended soil was particularly evident in the Andisol, a soil inherently deficient in P (Uehara and Ikawa 2000). As wood-derived biochars (such as the one in this study) have shown little effect on P availability in soils (Glaser and Lehr 2019), it is likely that the compost has supplied the majority of the available P. The addition of both mineral and organic P forms in the compost may have allowed microbial mineralisation of organic P over time to supply plant needs, especially for the papaya plant (da Silva et al. 2019).

The combination of biochar and compost has often proved superior to separate amendments in increasing plant biomass (Al-Omran et al. 2019; Berek et al. 2018; Ghosh et al. 2015; Khorram et al. 2019; Liu et al. 2019; Pandit et al. 2019), which may be influenced by the additive nature of the complementary properties. A mechanism proposed to explain this suggests the formation of nutrient-rich organic coatings that cover the pore surfaces (inner and outer) of biochar particles improves nutrient retention and availability (Hagemann et al. 2017). In addition, evidence of compost adsorption to biochar exists, creating soil–biochar–compost aggregates, which may provide protection from microbial decomposition, and slowing mineralisation (Jien et al. 2018).

4.2 Surface vs. incorporated amendment application

The plant biomass in the surface-applied amendment in this study was as great as that found in the incorporated amendment, despite the surface-applied amendments having little contact with the bulk soil. When the soil data were combined, papaya biomass was larger than the control, only in the surface-applied amendment. This was unexpected given that several studies using surface application of biochar with organic matter in perennial subtropical crops reported no or negative effects (Bass et al. 2016; Galanti et al. 2019). The yield response to surface

application of biochar alone has also shown to be negligible (Sarauer et al. 2018; Schnell et al. 2012), though there are fewer studies examining this application method. Incorporated compost has performed better than surface applied, with higher yield, higher soil C and N, and lower bulk density (Cogger et al. 2008; Whatmuff et al. 2018), however, surface application improved water infiltration, and therefore, lowered runoff (Agassi et al. 1998).

The positive response to surface application implies that during the watering process and plant growth, soluble nutrients moved down the profile, and also potentially particles of biochar and/or compost, which were accessible by the roots (Beesley and Dickinson 2011; Cogger et al. 2008; Major et al. 2010; Singh et al. 2015). Some evidence to support this is the 29–57% increase in total C in the 0–10 cm layer for the SBC compared to the unamended, and a corresponding increase in EC. There was also 12–18% higher total soil carbon in the 10–20 cm layer, below where the incorporated amendments were positioned, indicating a movement of soil C down the profile, as corroborated by others (Haefele et al. 2011; Singh et al. 2015). Given the short time frame of this study, the C is more likely to predominantly be in the dissolved (DOC) than particulate (POC) form (Major et al. 2010). The increase in C could also be attributed to both an increase in DOC released mainly from the compost and the retention of this DOC by the biochar (Lei et al. 2018).

While both IBC and SBC increased soil pH compared to the unamended soil in the 0–10 cm layer, IBC also increased soil pH in the 10–20 cm layer. It is inferred, therefore, that the alkaline substances of the biochar were released and moved through the soil profile, increasing exchangeable base cations of the soil (Yuan and Xu 2011). This result may be influenced by the soil type, inherent porosity and charge, used in this pot trial.

The increased root biomass in the surface applied amended soil indicates that an adequate release of surface nutrients into the soil layers occurred, where the root system took advantage of the decomposition of the surface amendments and mineralisation of nutrients from the compost over time (Agassi et al. 1998; Ahmad et al. 2014b; Cogger et al. 2008; Jien et al. 2018). The increased root biomass in the 10–20 cm layer, below the incorporated amendments, also supports the trend found for soil C, soil nutrient and pH with depth. The increased root growth in soil incorporated with biochar and compost may be due to increased soil porosity and water-holding capacity (Agegnehu et al. 2015; Manolikaki and Diamadopoulos 2019), which would, therefore, allow retention of soluble nutrients in the root zone for longer. Liu et al. (2012) showed that this combination of amendments doubled plant-available water-holding capacity, with biochar the main contributor. A limitation of the current study

is the lack of soil moisture information over time which may have shed further light on the mechanisms involved. Future work, including field trials in different soil types, should include this factor.

4.3 Andisol vs. Oxisol

The two soil types responded differently to the amendments, and the increases in plant and root biomass were higher in the Andisol than in the Oxisol. This may be due to the Andisol's lower initial pH, P, K, water-holding capacity and bulk density. The Andisol's high infiltration rate, likely due to the pumice content, may have been reduced and retained more moisture than the Oxisol, as biochar and composts have been particularly effective at improving soil properties and crop yield in these coarser soil types (Somerville et al. 2019; Wang et al. 2019). The Andisol pH increase due to the amendments may have also overcome some nutrient availability limitations in the acidic range of the unamended soil (Van Zwieten et al. 2015). The Oxisol, while containing more clay, was highly aggregated, and therefore, also had a high infiltration rate. The presence of increased cations in this amended soil at depth indicated movement over time with irrigation (Radin et al. 2018). The 6–10% higher water requirement over the growing seasons compared to Andisol emphasises the difference in physical structure, and water retention. The responsiveness to biochar amendment of coarser-textured soils through improved soil aggregate stability and increased plant-available water (Burrell et al. 2016) has helped prioritise the soil types more likely to benefit from this soil amendment.

5 Conclusion

The results of this study indicate that the combination of biochar and compost is an effective amendment to increase Chinese cabbage and papaya biomass and improve soil chemical properties, and that surface application is an option for perennial horticulture. There is evidence of downward movement of the amendments possibly in soluble or particulate form, with increased soil pH, total C, extractable P and Ca in the layer below application. These changes were found in the 10–20 cm layer below the incorporated amendment and also in the 0–10 cm layer below the surface-applied amendment. This is supported by the root distribution patterns in the 0–10 and 10–20 cm layers. The results suggest the amendments provided extra nutrients, improved nutrient availability and plant uptake, potentially due to improved soil pH and increased C. However, this was more apparent in the acidic Andisol than the Oxisol that had a pH of 6.9. The rate of nutrient addition with these amendments was high, as they provided 1.5–2 times the N more than the mineral fertilised

soil. They also provided extra P (0.75 times) and K (0.79 times) than the fertiliser for the Andisol. Further work to control for nutrient addition from amendments would enable exploration of the physical and biological impacts of these inputs. These pot trial results need to be examined with perennials in field trials over a longer time frame to determine the effectiveness of surface application, given the potential risks of losses due to erosion and other farming practices. Biochar and compost in combination can provide an effective input to both increase crop yield and reduce leaching of land-applied fertilisers to the environment.

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Compliance with ethical standards

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