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ORIGINAL PAPER

Influence of biochar and compost on soil properties and tree growth in a tropical urban environment

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Abstract Research relating to the use of organic amendments on soils has focused largely on agricultural soils, and there is a lack of information worldwide on their efficacy as amendments for urban soil management, especially in tropical urban environments. A pot experiment was conducted to assess the influence of biochar and organic compost on urban soil properties and on tree growth performance in Singapore. Biochar and compost were mixed with topsoil in different proportions, and two urban tree species commonly grown in Singapore (*Samanea saman* and *Suregada multiflora*) were used. There were significant additional height increments for both the tree species following application of biochar. *S. saman* exhibited greater stem elongation compared with *S. multiflora* in response to organic amendments. A significantly higher foliar N content was found in both tree species in biochar-amended treatments along with significant increases in P and K. Increases in soil nutrient concentrations were also observed in combined biochar–compost treatments for both species. Combined compost and biochar had the strongest effects on soils and growth of the two urban tree species examined and applications containing biochar resulted in the most significant soil improvements.

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Introduction

Maintaining an appropriate level of soil organic matter (SOM) and biological cycling of nutrients is critical to the management of soils and plant growth but this is challenging in moist tropical environments due to the high rates of organic matter turnover compared with regions with lower rainfall (Tiessen et al. 1994; Zech et al. 1997). In the humid tropics, the use of organic composts to maintain SOM is widespread (Lasaridi and Stentiford 1998; French et al. 2006; Hartley et al. 2008), particularly in urban environments where conditions for plant growth are challenging. The benefits of applying organic composted materials to soils are widely acknowledged internationally (Amlinger et al. 2007; Lillenberg et al. 2010), and it has been found to facilitate increases in organic matter content, biological activity and nutrient supply to plants (Zhang and Selim 2008; Tandy et al. 2009). These effects, however, are typically short-lived in the tropics due to high rates of SOM decomposition and frequent compost application used to negate this effect. There are practical limits to the use of these materials because high rates of repeated compost application can result in plant toxicity (Soumare et al. 2003; Amlinger et al. 2007), increase in heavy metal content (Ayari et al. 2010) and potential ground and surface water pollution due to leaching and run off of nutrients (Soumare et al. 2003).

More recently, biochar has been promoted as a more stable organic soil amendment. Biochar is the product of thermal degradation of organic materials in the absence of oxygen (pyrolysis) (Elad et al. 2011; Ghosh 2012), which is an environmental friendly technology due to higher energy recovery efficiency (Zaman 2010). Biochar is believed to have the potential to enhance both physical and chemical fertility of soils and associated plant growth (Jones et al. 2012). Biochar amendment to soils has also been promoted for its capacity to sequester additional soil carbon, mitigating greenhouse gas emissions as part of our response to climate change (Gaunt and Cowie 2009; Roberts et al. 2010; Lehmann et al. 2011). The utilization of more stable biochar products, in combination with compost, might therefore offer the potential to alleviate some of the limitations associated with current compost amendments in the tropics and provide an additional, novel soil management option in these environments. There is, however, a current lack of information regarding the effects of biochar amendments on soils and plant response in tropical urban environments (Elad et al. 2011; Graber et al. 2010).

A small number of studies (e.g., Schulz and Glaser 2012; Fischer and Glaser 2012) have suggested synergies between biochar and compost resulting in enhanced plant growth. However, work on biochar to date has been predominantly focused on forestry and agricultural soils, and no studies to our knowledge have specifically examined the combined effects of biochar and conventional compost amendments on soil condition and plant growth in tropical urban environments.

The aim of this study was to investigate the effects of various application rates of biochar and compost (individually and in combination) to urban soils in Singapore on (1) soil quality as indicated by a selected range of indicators (aggregate stability, C, N, P, K, Ca, Mg), (2) the growth of two common urban tree species (*Samanea saman* and *Suregada multiflora*) as measured by plant height and girth size and (3) foliar nutrient (N, P, K) concentrations in these two tree species.

The experiment was carried out during December 2012 for 6 months at the research plot at Hort Park, Alexandra Road, Singapore.

Materials and methods

Experimental design and treatments

A factorial trial was undertaken in an open environment for 6 months at the research plot at Hort Park, Alexandra Road, Singapore. Average monthly day- and nighttime temperatures ranged between 30–34 and 24–28 °C, respectively, with average monthly rainfall of 195 mm during the experiment.

In the urban environment of Singapore, approved soil mix (ASM, 3:2:1 topsoil/compost/sand) from the National Parks Board (CUGE Standards 2009) is commonly used as a growing medium for urban tree plantations along with several other sand-based growing media. Biochar and compost were mixed gravimetrically with the loamy topsoil and ASM (Table 1) in different proportions and were placed in 0.02 m^3 pots with two common urban tree saplings (*S. saman* and *S. multiflora*) planted within. The experimental soil was sandy clay loam with a pH of 5.5 and bulk density was 1.6 g cm^{-3}. To ensure consistent access of water and nutrients for plant growth, water was added regularly to maintain the moisture level of the soil near 60 % field capacity. The treatments were laid out in a randomized block design and were replicated four times. The treatment details and plant information are given in Table 1. Prior to the experiment, the biochar and compost were analyzed for pH, total N, P, K, Ca, Mg, organic carbon and cation exchange capacity (CEC), and the results are presented in Table 2.

Table 1 Treatment details and general information on the tree species

Treatment	T1 = control (loam)	
	T2 = 3soil:2compost:1sand (ASM)	
	T3 = 3ASM:1biochar	
	T4 = 3soil:2compost:1biochar	
	T5 = 3soil:1compost:1biochar	
	T6 = 3soil:1biochar	
	T7 = 3soil:1compost	
Plant species		
*Samanea saman**	Botanical name	*Samanea saman*
	Common name	Rain Tree, Pukul Lima, Monkey-Pod Tree, East Indian Walnut
	Family	Fabaceae (Leguminosae)
	Origin	A tropical American tree, first introduced in Singapore in 1876
*Suregada multiflora**	Botanical name	*Surgeda multiflora*
	Common name	False Lime Merlimau
	Family	Euphorbiaceae
	Origin	India, Indochina and Malaysia

* NParks' Publication (2009)

Plant analyses

Treatment effects were assessed non-destructively by recording physiological data from trees (plant height and girth size) fortnightly for the first 2 months and then

Table 2 Characteristics of the biochar and compost used

	pH (1:5)	Total N (%)	Total P (%)	Total K (%)	Total Ca (%)	Total Mg (%)	OC (%)	C/N ratio	CEC (cmol kg^{-1})
Biochar	8.9	2.1	5.0	3.5	3.4	0.93	17.9	8.3	28.5
Compost	7.6	2.1	0.6	1.3	3.1	0.27	27.1	13	46.7

monthly for the rest of the experiment. After 6 months, the whole plants were harvested, and root/shoot ratio was measured as dry weight. Leaf samples were also collected and analyzed for foliar nutrient concentrations (total N, total P and total K) using the sealed chamber digestion method described by Anderson and Henderson (1986).

Soil analyses

Soil samples were collected from each treatment alongside destructive harvesting. The soil samples were air-dried and then passed through a 2-mm sieve, and the <2 mm fractions were analyzed for selected chemical and physical properties. All soil analyses are reported on an oven-dry basis. Air-dried soil samples were analyzed for pH_{water} (1:2.5 soil/water suspension), EC and essential macronutrients, total N (modified Kjeldahl method), extractable P (Bray II extraction), K, available Ca and Mg (ammonium acetate extraction method). Soil organic carbon (SOC) was determined by Walkley and Black (1934) wet oxidation method.

Aggregate stability of the samples was measured by determining their mean weight diameters (MWD) by dry sieving. The air-dried split samples (approximately 100 g) were placed in a stack of sieves from >2 mm down to <0.125 mm. The soil aggregates retained by the individual sieves were then weighed, and MWD were computed (van Bevel 1949) using the following equation:

$$\mathrm{MWD} = \sum_{i=1}^{n} x_i w_i$$

where x_i is the mean diameter of any particular size range of aggregates separated by sieving, and w_i is the weight of the aggregates in that size range as a fraction of the total dry weight of the sample analyzed.

Statistical analysis

Results were analyzed in R 2.5.0 (R Development Core Team 2006) using analysis of variance (ANOVA) with "treatment" (rate and type of application) and "tree species" as factors, and P values ≤ 0.05 were considered significant. Variances were checked by plotting residual versus fitted values to confirm the homogeneity of the data. No transformations were necessary. Means for significant treatment effects were separated based on least significant difference (LSD) values. Tabulated values are reported where main terms were significant. In the event where the interaction was significant, results are provided in the text.

Results and discussion

Plant responses to compost and biochar addition

Our results suggest that plant growth and foliar nutrient concentrations were enhanced by organic amendments, and the largest responses were observed with combined application of biochar and compost.

There were significant treatment effects on height and girth increments for the two tree species studied (Table 3). However, a significant interaction between treatment and tree species ($P < 0.05$) was also observed indicating that the treatment effect on height and girth size increments differed between the two trees (Table 3). Overall, *S. saman* had a consistently greater stem and girth elongation compared with *S. multiflora* across all treatments (Table 3). The largest proportional increases in height and girth increments were identified in T3 (3ASM:1biochar) for *S. saman* and for *S. multiflora*, those were identified in T6 (3soil:1biochar) and T4 (3soil:2compost:1biochar), respectively.

Application of biochar alone had some effect on the elongation of stems as well as girth increments in both tree species examined. Although some studies have reported only a limited effect of biochar and other organic amendments on plant growth (Moore et al. 2005; Lehmann et al. 2011; Jones et al. 2012), a number of others, using a range of plant species, have reported similar results to ours following additions of biochar (Lehmann 2007; Husk and Major 2011; Elad et al. 2011). This might suggest that these positive effects are specific to particular locations, environments, or plant species. Our findings, however, suggest that compost played only a minor role in stem elongation, but had a more significant effect on lateral expansion. Biochar and compost had mixed effects on root/shoot ratio. Largest root/shoot ratio was found in those treatments where organic amendments were either absent or in low proportions (T1 and T7) for both the tree species (Table 3). This suggested that the trees under these treatments had to allocate more resources into root development presumably to satisfy their nutrient

Table 3 Effect of biochar and compost on plant chemical and physiological parameters [significance level and LSD (least significant difference) refers only to treatment effect for individual tree species]

Treatment	Plant 1						Plant 2					
	Total N (%)	Total P (%)	Total K (%)	Ht incr (%)	Gir incr (%)	R/S ratio	Total N (%)	Total P (%)	Total K (%)	Ht incr (%)	Gir incr (%)	R/S ratio
T1	1.37	0.11	0.82	26.5	18.7	1.25	1.34	0.12	1.08	8.8	5.5	1.19
T2	1.74	0.98	1.52	30.7	9.8	0.87	1.38	0.51	1.57	12.3	14.0	1.04
T3	3.08	0.29	1.39	46.7	47.6	0.99	1.85	0.82	2.26	12.8	11.6	1.20
T4	2.69	0.25	1.24	23.0	13.7	0.71	1.88	0.93	2.65	18.2	15.8	0.45
T5	2.74	0.19	0.87	30.2	24.1	0.84	1.73	0.96	2.48	12.8	8.2	1.06
T6	3.64	0.22	1.08	26.3	26.0	0.94	2.02	0.75	2.18	18.9	10.0	1.02
T7	3.17	0.15	0.84	38.0	23.8	1.12	1.17	0.27	1.94	16.6	8.5	1.48
LSD	0.572	0.043	0.430	13.06	12.02	0.645	0.638	0.391	1.318	3.99	7.33	0.369
Significance	***	***	*	*	***	ns	*	**	ns	***	ns	**

T1 = Control (loam), T2 = ASM (3 soil:2 compost:1 sand), T3 = 3ASM:1biochar, T4 = 3soil:2compost:1biochar, T5 = 3soil:1compost:1biochar, T6 = 3soil:1biochar, T7 = 3soil:1compost; Plant 1 = *Samanea saman*, Plant 2 = *Suregada multiflora*

Sample size = 56 (28 for each plant species)

ns not significant, *Ht incr* height increase, *Gir incr* girth increase; *R/S ratio* root/shoot ratio

*** $P < 0.001$; ** $P < 0.01$; * $P < 0.05$

requirements. The girth and foliar N appeared to increase where compost was added alone but in combination with biochar both girth and height increments and a range of foliar nutrient increases were observed although differences in plant performance (e.g., stem elongation, girth enhancement) between *S. saman* and *S. multiflora* observed here may simply be the result of *S. saman* being a faster growing tree species as opposed to *S. multiflora.*

There was a significant interaction (treatment × tree species) effect on foliar nutrient concentrations. Higher foliar N concentrations were observed in both the species in the treatments with only soil + biochar (T6) (Table 3). For *S. multiflora*, all treatments that had the addition of biochar, exhibited significantly higher ($P < 0.05$) levels of foliar N. Although these differences were similar in magnitude for *S. saman*, they were nevertheless significant ($P < 0.001$). Foliar P concentrations in *S. saman* were found to be relatively low with the highest concentrations found in ASM (T2). The highest foliar P concentrations were found in treatments T4 and T5, which consisted of combined biochar and compost applications. The lowest foliar P concentrations in both species were found in control treatment (T1) where both compost and biochar were absent. Pattern in the levels of foliar potassium (K) were similar to those observed for nitrogen. As with phosphorus, the lowest concentrations of K were found to be in the control treatment (T1) for both species, while the highest concentrations were found in T2 and T4 for *S. saman* and *S. multiflora*, respectively.

Supplementing the nutrient requirement of plants in agricultural, forestry and urban environments is critical to ensure healthy and sustainable plant growth (Novak et al. 2009). As for plant growth responses, increases in foliar nutrient concentrations seen with *S. saman* and *S. multiflora* are both supported and refuted by the literature (Liang et al. 2006; Blackwell et al. 2010; Lehmann et al. 2011). This present study indicated that although there was no clear increase in foliar N levels with the addition of compost, levels of foliar P and K were both found to have increased following this treatment. However, treatments 3–5 illustrate the synergistic effects of combined application of biochar and compost to plant growth and nutritional quality. Combined amendments boosted foliar nutrient concentrations, and this effect was most pronounced when the amendments were at its greatest proportions in this trial.

Regardless, our findings indicate a significant enhancement of tree growth in this tropical environment as a result of the addition of organic amendments, particularly where compost and biochar were combined. It is beyond the scope our work to identify the optimum proportions and application rates of these additions. It is possible that insufficient application may result in below optimal plant performance while excessive application may result in toxicity (Craul 1999; Rhodes et al. 2008). Both short- and long-term studies spanning a range of species will therefore be necessary to facilitate a fuller understanding of these relationships.

Effects on soils

It has been proposed elsewhere that organic amendments particularly biochar have considerable potential for soil

Table 4 Effect of biochar and compost on soil properties [significance level and LSD (least significant difference) refers only to treatment effect for individual tree species]

Treatment	Plant 1					Plant 2				
	Organic C (%)	Total N (mg kg^{-1})	Ext P (mg kg^{-1})	Ext K (mg kg^{-1})	MWD (mm)	Organic C (%)	Total N (mg kg^{-1})	Ext P (mg kg^{-1})	Ext K (mg kg^{-1})	MWD (mm)
T1	1.18a	350.0a	1.0a	10.8a	2.06a	0.83a	466.7a	0.8a	7.9a	2.23
T2	2.30bc	1,236.7b	18.5a	32.9a	2.77c	2.15bc	1,376.7b	14.9a	27.1a	2.49
T3	3.80d	3,813.3e	521.7c	241.3c	2.59bc	3.63d	3,570.0e	510.7d	265.0c	2.35
T4	3.05cd	2,426.7d	361.0b	99.8b	2.33ab	3.00cd	2,683.3d	317.0b	129.6b	2.60
T5	2.88c	2,123.3cd	476.3c	168.0c	2.77c	2.59c	2,753.3d	410.7c	142.7b	2.16
T6	2.14b	1,656.7bc	491.3c	166.0c	2.40b	2.36bc	2,146.7c	407.0c	148.3b	2.02
T7	1.87ab	1,096.7b	7.47a	36.2a	2.46bc	1.80b	1,143.3b	7.97a	36.3a	2.12
LSD	0.792	577.75	74.34	49.21	0.320	0.748	472.50	51.76	59.04	0.707
Significance	***	***	***	***	**	***	***	***	***	ns

T1 = Control (loam), T2 = ASM (3soil:2compost:1sand), T3 = 3ASM:1biochar, T4 = 3soil:2compost:1biochar, T5 = 3soil:1compost:1biochar, T6 = 3soil:1biochar, T7 = 3soil:1compost; Plant 1 = *Samanea saman*, Plant 2 = *Suregada multiflora*

Sample size = 56 (28 for each plant species)

Values with same letters are not significantly different at the 5 % level

ns not significant, *Ext P* extractable P, *Ext K* extractable K, *MWD* mean weight diameter

*** $P < 0.001$; ** $P < 0.01$; * $P < 0.05$

improvement because of its unique physical, chemical, and biological properties and their interactions with soil and plant communities (Lehmann et al. 2006; Amlinger et al. 2007; Elad et al. 2011). All the organic amendments were applied significantly ($P < 0.001$) increased SOC, and this effect was most pronounced where compost and biochar were combined and added at their highest proportional concentrations to the growth medium (Table 4). This increase in SOC concentration might be important from the perspective of carbon storage and greenhouse gas abatement. If we assume a bulk density of 1.2 Mg ha^{-1} for the soils studied (adjusted following amendment application), the increased SOC concentration would equate to an additional carbon storage in the order of up to 31.4 Mg ha^{-1} (T3; Plant 1 = *S. saman*) and 33.6 Mg ha^{-1} (T3; Plant 2 = *S. multiflora*) in the top 10 cm of the soil. If this result was repeated through the extensive urban landscape, this figure could potentially make a significant contribution to our response to climate change. The organic carbon concentration in the remaining treatments was found to be in the order T4 > T5 > T2 > T6 > T7 > T1. This additional organic carbon might therefore have the potential to store additional carbon as a response to climate change, but its residence and turnover times in the soil, optimum combinations and application rates will require further work to determine the effectiveness of these amendments for long-term carbon storage. Soil carbon is, however, widely acknowledged to be a key indicator of soil condition (Karlen et al. 2001), and the addition of these amendments and the organic matter they contained had generated a range of other beneficial effects in the soils studied.

Figure 1 shows the treatment differences following application of amendments. Significant increases ($P < 0.001$) in soil pH and EC were found in association with all compost and biochar treatments compared with the control (T1). Initial soil pH was 5.38, which increased significantly following the addition of organic amendments up to a maximum of 7.10 (T3). However, the various treatments did not differ significantly in their effect on pH, except for T4 (3soil:2compost:1biochar), which had a less marked pH increase compared with control soil (Fig. 1). Significant increases soil pH probably resulted from the mineral ash content of the various organic materials and resulted in a liming effect raising the soil pH (Matsubara et al. 2002; Lehmann et al. 2003).

We also observed significant ($P < 0.001$) increases in soil nutrients (N, P, K, Ca and Mg) resulting from the organic amendments but these increases were again most significant where biochar was a component of the amendment (Table 4; Fig. 1). Soil N concentrations in other treatments were then found in the order T4 > T5 > T6 > T2 > T7 > T1 for *S. saman* and T5 > T4 > T6 > T2 > T7 > T1 for *S. multiflora* (Table 4). Larger increases in soil P and K concentrations were recorded when biochar was applied in combination with ASM (T3). However, soil application with compost alone (T2 and T7) did not have any significant effect on soil extractable P and K content (Table 4). These increases in soil nutrient content might be primarily associated with the nutrient content of the

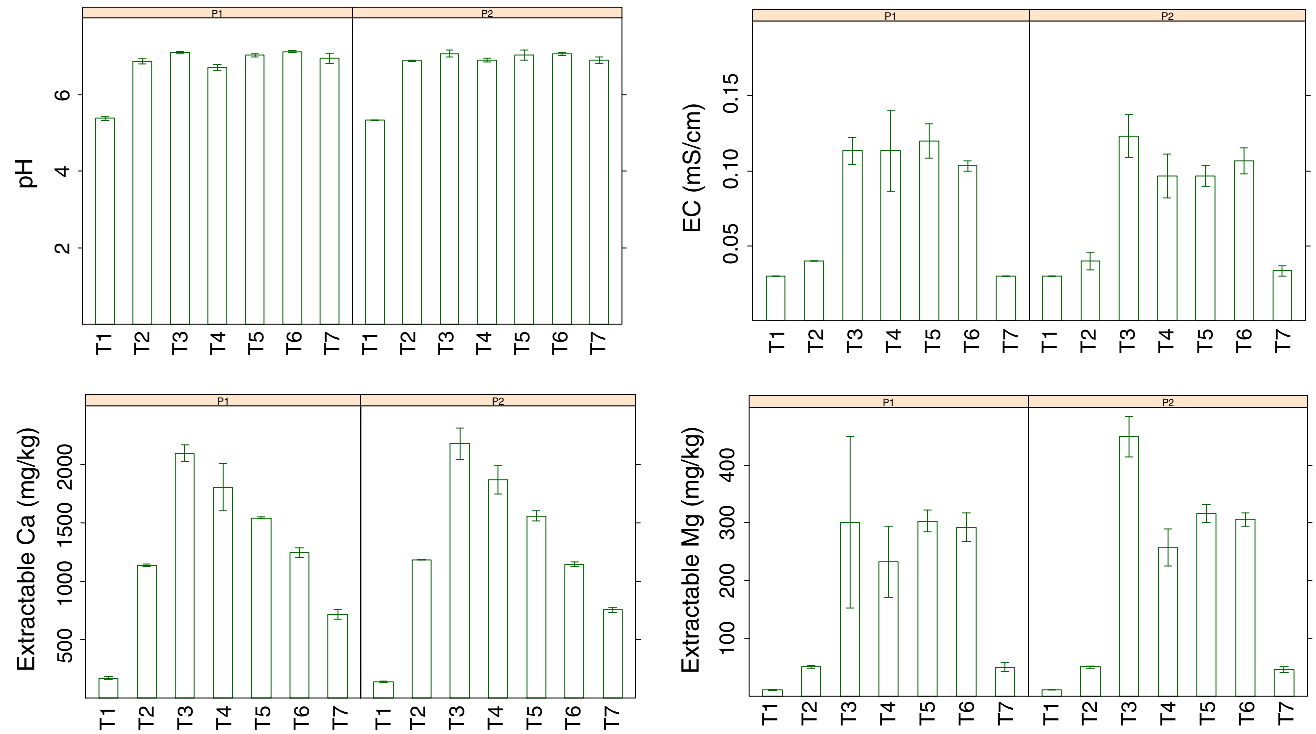

Fig. 1 Changes in soil properties following the application of organic amendments. T1 = Control (loam), T2 = ASM (3soil:2compost:1sand), T3 = 3ASM:1biochar, T4 = 3soil:2compost:1biochar, T5 = 3soil:1compost:1biochar, T6 = 3soil:1biochar, T7 = 3soil:1compost; P1 = *Samanea saman*, P2 = *Suregada multiflora*. Sample size = 56 (28 for each plant species)

amendments (Table 2), which of course depends on the source and nature of the feedstock (Gaskin et al. 2008) and, for biochar, the pyrolysis process (such as temperature, heating rate, duration) (Tsai et al. 2007). However, the soil nutrients we examined were either extractable (P) or available (Ca, Mg, K) and depend upon soil chemistry and exchange behavior for their availability to plants (Schneider 2012). Modification of soil pH, in addition to the gross addition of these elements (Glaser et al. 2002; Ghosh et al. 2012), from the organic amendments might therefore have enhanced available nutrient concentrations in the soil.

Organic amendments and particularly biochar have also been demonstrated to modify exchange behavior in soils (e.g., (Glaser et al. 2000, 2001). The higher surface area of biochar has particularly been demonstrated to enhance the soil's capacity to provide plant nutrients (N, P, K) (Nigussie et al. 2012), all of which we observed in the soil and was reflected in the higher foliar concentrations reported earlier. The individual effects of the various organic amendments would also seem have been enhanced where they were combined, and in our study, compost and biochar together (T3, T4 and T5) showed increased nutrient availability compared with their application individually (T2, T6 and T7). Other studies have, however, reported that increase in soil nutrient concentrations due to biochar addition may be short-lived and may decline with plant uptake and leaching (Gaskin et al. 2010; Steiner et al. 2007). Longer-term studies will therefore be required to evaluate these trends.

Increase in N content in soils amended with compost and biochar suggests the ability of these amendments to supply N because of their fairly high N content (Table 2). The results also suggest increased mineralization of native soil N was due to the priming effect after application of these amendments as a result of enhanced growth of soil microorganisms (Hamer et al. 2004). The adsorption of phosphorus in soil is pH dependent. With the increase in soil pH, solubility of P will also increase when biochar is added (Schneider 2012). Similar to our observation (Fig. 1), other studies have confirmed increase in the amount of extractable Ca in the soil due to addition of biochar (Rondon et al. 2006; Chan et al. 2008), which also help increased uptakes of Ca by the plants (Rondon et al. 2006).

Differential responses were observed on MWD following addition of biochar (Table 4). Increase in MWD compared with control might be attributed to large organic C content of the amendments (Table 2) and could also be due to their high Ca and Mg contents (Table 2) that might help produce stronger physical bonds between particles (Ghosh et al. 2012). Similar to our results, Busscher et al. (2010) also did not observe any increase in MWD after addition of biochar in the loamy sands after 70-day incubation. Therefore, further work is needed to modify biochar application methods to increase soil stability, especially in the tropical urban soils. Sand is commonly used as one of the components in ASM, and results suggest the potentiality of biochar to replace sand in ASM (T2). However, future longer-term field trials are needed to strengthen this conclusion. Because of their high organic C content, compost and biochar are predominantly applied to improve the C sequestration of soils as urban soils are often deficient in carbon, available nutrients and biological activity.

Conclusion

Combined use of organic amendments had exerted a positive effect on soil condition and the growth and nutritional quality of the two urban tree species examined. A significant growth response was found in both plant species studied particularly where combined compost/biochar amendments were applied. Increased soil N, P and K concentrations under organic amendments were reflected in higher foliar N, P and K concentrations in the plants. There is therefore a clear value in the use of both compost and biochar to improve plant and soil quality in this tropical urban environment. Further work is required to identify better the optimum combinations and application rates best suited for tropical urban soils given the potential this may have on negating the benefits these amendments have on plant and soil quality. Future research will also need to investigate the longer-term effects of biochar on growth and nutrition of plants and potential negative effects of high and repeat applications on a wider range of tropical, urban plant species. The addition of these soil amendments might also make a significant contribution to climate change mitigation storing as much as 36 Mg ha^{-1} additional soil carbon. Across extensive urban landscapes, this additional carbon storage might provide significant opportunities in our response to climate change although the rate of cycling of these materials in the soil system requires further investigation to improve confidence in the long-term nature of these changes.

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