Biochar: A Home Gardener's Primer

WASHINGTON STATE UNIVERSITY EXTENSION FACT SHEET • FS147E

Home gardeners may have heard about biochar, but may not understand exactly what it is and what it does. This fact sheet provides a quick overview of what biochar is, the science behind its manufacture and use, and how it affects soil, plants, and the environment.

What is biochar?

Biochar is a fine-grained charcoal left behind after **pyrolysis** of crop residues, livestock manures, and other organic material used in alternative fuel production (Figure 1). These alternative fuels, or biofuels, are produced by high temperature processing of organic materials in the absence of oxygen—a process known as pyrolysis. Biofuel researchers initially regarded biochar as nothing more than a waste product of pyrolysis. However, further investigation revealed some unique properties. For instance, biochar is so slow to decompose that scientists widely consider it to be a long-term repository for stored carbon.

From a global standpoint, biochar's ability to store rather than release carbon might be its single most important attribute. Properly "cooked" biochars do not release carbon dioxide into the atmosphere and their physical structure remains virtually intact. Their resistance to decomposition means that good biochars will not release carbon dioxide over the long term, either. Furthermore, biochars applied to wet soils like those found in rice paddies decrease methane and nitrous oxide production. Since, carbon dioxide, methane, and nitrous oxide are three of the most important greenhouse gases contributing to climate change, both biochar production and use may help slow this troubling phenomenon.

Researchers have identified some potential uses for biochar in addition to carbon storage. Biochar is similar to activated charcoal and has been used successfully to treat sewage and waste water. It is also exceptionally well suited for restoring degraded soils, such as those found near mining sites, because it tightly binds toxic heavy metals and neutralizes unnaturally acidic soils.

How is biochar made?

The best biochar consists of finely textured, porous particles made by using extremely high temperatures (at least

Figure 1. The material shown on the left is too coarse to be considered a high quality biochar, while the fine-textured material on the right is a high quality biochar.

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500°C) in the complete absence of oxygen (pyrolysis) as shown in Figure 2. During pyrolysis, organic matter breaks into fragments whose surfaces are covered with negatively charged chemical compounds. The hotter the temperature, the smaller and more porous the fragments become. These small, porous biochar particles have proportionally more surface area than large, solid particles. So slow-cooking at high temperatures (over 500°C) for several hours will produce a lightweight, fine-textured, negatively charged biochar.

Do not be tempted by the numerous websites that offer "home recipes" for making biochar from yard waste. Proper pyrolysis is impossible to achieve at home since oxygen is present and temperatures are too low. Improper cooking also generates carbon dioxide and other pollutants. You are better off using pruning debris and other home-garden wastes in your compost pile or on top of your soil as a natural and sustainable organic mulch layer. Ideally, biochar can be made commercially from excess crop residues, invasive plant species, such as kudzu and English ivy, and other organic materials that might otherwise end up in landfills.

Production techniques influence biochar's physical, chemical, and biological properties, which in turn affect how it works in the soil. The science behind biochar is complex: there are many variables associated with both making and using biochar. First, a finished biochar is specific to the material that was burned to produce it. A biochar made from straw is different than one made from coconut husks, yard waste, or wooden pallets. Second, the range of temperatures and times used for cooking biochar produces biochars that are chemically and physically different from one another. The highest quality biochars are cooked for several hours at temperatures from 350°C to 700°C. Finally, the effectiveness of biochar is highly dependent on soil characteristics, such as texture, organic content, and mineral nutrient levels.

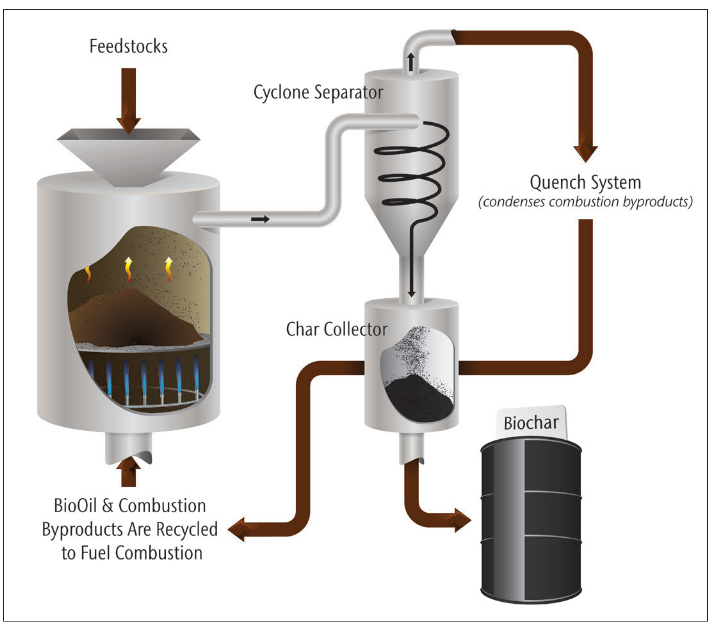

Figure 2. Production of biofuel and biochar by pyrolysis. Illustration by Andrew Mack, PREC.

How does biochar work?

Because biochar remains virtually intact for centuries, it can permanently change a soil's character. For example, this porous material improves aeration of poorly drained or compacted soils, while increasing the water-holding capacity of fast-draining, sandy soils. The porous nature of biochar also provides a physical home for bacteria and fungi, including beneficial mycorrhizal species.

Biochar's negatively charged surface binds to positively charged chemicals, including hydrogen ions and many plant nutrients in the soil (Figure 3). This phenomenon has two effects on soil characteristics. First, binding the hydrogen ions raises the pH of the soil, making it increasingly alkaline. Second, soil nutrition is enhanced because biochar binds and retains nutrients that otherwise might leach out of the soil. Biochar can improve urban soils by tightly binding lead, cadmium, and other heavy metals found in urban soils, preventing their uptake by plants and soil life. As biochar attaches to heavy metals, it sheds other bound ions, many of them plant nutrients. This process of ion exchange contributes to increased levels of available nutrients for plant uptake.

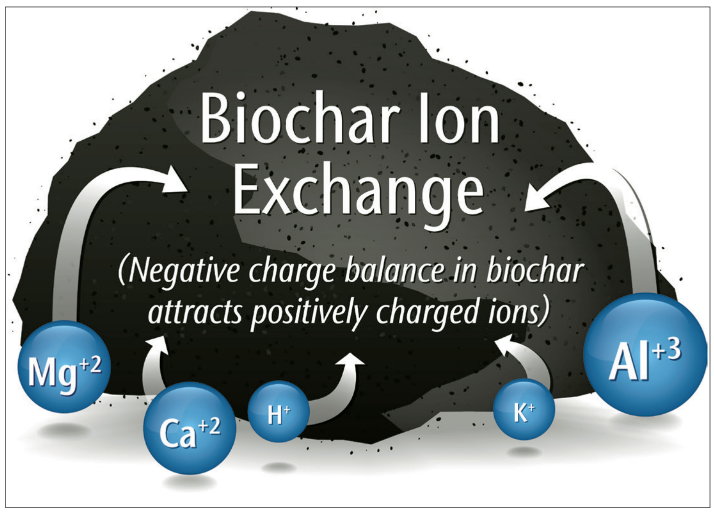

Figure 3. Biochar's negatively charged surface will bind positively charged elements. Illustration by Andrew Mack, PREC.

How are soil organisms affected by biochar?

Overall, biochar has a positive effect on beneficial soil microbes. The habitat it provides for fungi and bacteria also hides them from grazing protozoa, such as amoebas. Together with the biochar, these microscopic communities continue to change soil characteristics in positive ways. For instance, pathogenic bacterial populations decrease when biochar is added. This could be due to improved soil structure, or to competition from beneficial microbes housed in the biochar. Earthworm populations, however, often decline in biochar-amended soils, possibly due to pH changes or dehydration.

How is plant growth affected by biochar?

As you might expect, the beneficial effects biochar has on the soil environment also translate into plant benefits. Crops grown in biochar-amended soil consistently show increased growth. This may be due to improved nutrient and water availability and an increased number of beneficial microbes. Other biochar benefits include improved drought tolerance and greater resistance to root and leaf diseases. Gardeners should be cautious when using biochar, however. Application of too much biochar can injure plants, possibly by increasing soil alkalinity past the plant's tolerance level. Also, applying biochar to soils rich in organic matter can temporarily reduce nitrogen levels because increased microbial activity will compete with plants for this nutrient.

There are good reasons to be excited about the possible benefits of biochar in home gardens. A solid body of research is available that describes the benefits of adding biochar to crops, soils, and soil microorganisms.

Can we use biochars in our gardens?

Currently there are only a handful of studies on biochar with direct relevance to home gardens and landscapes. So far, biochar appears to benefit soils where turf grasses and trees are planted. Turf grasses perform better in more alkaline soil conditions like those that biochar can create. Lawns with compacted, poorly drained soil benefit from the increased aeration and drainage that biochar can provide. Both coniferous and broad-leaved trees have shown improved growth and disease resistance in soils amended with biochar. Biochar can also reduce the weight of planting mixes used for container plants and green roof gardens.

If you want to try biochar in your garden, be sure to use only a commercially produced biochar with well-defined characteristics. Be careful when applying biochar because improper application can create problems in your garden. For instance, adding too much biochar can injure beneficial soil organisms like earthworms, or reduce the effectiveness of soil-applied pesticides. You will also want to

Table 1. How biochar application affects soils and plants.

Benefits	Drawbacks	Best Use
Decreases soil bulk density	None	Compacted soils
Improves aeration	None	Heavy or compacted soils
Increases soil aggregation	None	Fine-textured soils
Improves water-holding capacity	Can cause waterlogging in heavy clay soils	Excessively drained, sandy soils
Increases soil sequestration of carbon	Can be washed out of saturated soils	All soils
Increases soil alkalinity	May injure acid-loving plants and earthworms	Soils used for alkaline-tolerant species, such as turf grasses
Increases cation exchange capacity (CEC)	None	Low nutrient and sandy soils
Binds salt	None	Soils contaminated with de-icing salts or exposed to tidal floods, or naturally salty soils
Binds nutrients, such as nitrogen and phosphorus, reducing their leaching	Not as effective on silty soils	Sandy and acidic soils
Binds organic material (OM)	None	Soils subjected to erosion or runoff
Binds and/or detoxifies heavy metals, such as lead, mercury, and chromium	None	Acidic soils
Binds and sequesters organic contaminants, such as polycyclic aromatic hydrocarbons	None	Application rates greater than 2% of soil volume
Binds and degrades pesticides	Soil-applied pesticides will be less effective	All soils
Reduces greenhouse gas emissions (CO_2, CH_4, and N_2O) from wet soils	None	Waterlogged soils, especially sandy types
Enhances fungal biodiversity, including mycorrhizal species	None	All soils
Increases availability of plant nutrients (N, P, K)	Levels of sodium can increase depending on biochar source	All soils
Decreases need for nitrogen fertilizers	None	All soils
Increases plant nutrient uptake and enhances plant growth	Less effective in OM-rich soils; use of excessive biochar in OM-rich soils can reduce growth	OM-poor soils and dry soils
Increases plant drought resistance	None when used appropriately	
Increases plant disease resistance	None when used appropriately	

monitor your plants in the first few months after applying biochar for signs of nitrogen deficiency. Overall leaf yellowing is an indicator of low nitrogen. Adding a nitrogen fertilizer can treat this temporary deficiency. Table 1 summarizes the benefits and drawbacks of biochar, along with optimal conditions for use. This information may help you decide whether your garden and landscape soils might benefit from biochar additions.

Further Reading

Arbestain, M.C., S. Saggar, and J. Leifeld. 2014. Environmental Benefits and Risks of Biochar Applications to Soil. *Agriculture, Ecosystems and Environment* 191:1–4.

Cogger, C. 2005. Home Gardener's Guide to Soils and Fertilizers. *Washington State University Extension Publication* EB1971E. http://cru.cahe.wsu.edu/CEPublications/eb1971e/eb1971e.pdf.

Cogger, C., and G. Stahnke. 2013. Organic Soil Amendments in Yards and Gardens: How Much Is Enough? *Washington State University Extension Publication* FS123E. http://cru.cahe.wsu.edu/CEPublications/FS123E/FS123E.pdf.

Miles, C., G. Sterrett, L. Hexnault, C. Benedict, and C. Daniels. 2013. Home Vegetable Gardening in Washington. *Washington State University Extension Publication* EM057E. http://cru.cahe.wsu.edu/CEPublications/EM057E/EM057E.pdf.

Weddell, B., L. Carpenter-Boggs, and S. Higgins. 2012. Global Climate Change. *Washington State University Extension Publication* FS069E. http://cru.cahe.wsu.edu/CEPublications/FS069E/FS069E.pdf.

WASHINGTON STATE UNIVERSITY EXTENSION

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FS147E

Biochar and Biosolids Increase Tree Growth and Improve Soil Quality for Urban Landscapes

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Urban soil quality is often degraded and a challenging substrate for trees. This study was conducted to assess the impacts of biochar (BC), biosolids (BS), wood chips (WC), compost (COM), aerated compost tea (ACT), and a nitrogen plus potassium fertilizer (NK) for improving three typical urban soils and tree sapling growth. Across the three soil types, the most significant changes in soil properties were observed with BS and BC. Biosolids decreased soil pH and increased available N, N mineralization, and microbial respiration. Biochar increased total organic C. Increases in microbial respiration were also observed with NK, COM, and WC in only the sand soil. Leachate concentrations of dissolved organic C were greater with BS and COM, but nitrate in leachates did not differ among the treatments. The greatest and most significant increases in *Acer saccharum* and *Gleditsia triacanthos* growth were found with BS and BC. Tree growth was modeled from plant-available N and microbial respiration. The N content in the treatments appeared to be a strong determinant of tree growth for all treatments except BC. Nitrogen fertilizer, COM, and WC are the most common urban soil amendments and mulches in use today. This study provides evidence that BS and BC are acceptable, and possibly preferred, alternatives for improving urban soil quality and tree growth.

Urban tree growth is affected by soil quality and many anthropogenic factors (e.g., pollution, management, disturbance) (Patterson, 1977; Scharenbroch and Catania, 2012). Compaction and topsoil removal associated with urban site development have immediate and dramatic negative impacts on soil quality (Jim, 1998; Craul, 1999). Specifically, these activities may strongly alter soil carbon (C) and nitrogen (N) pools (Beyer et al., 1996; Scharenbroch et al., 2005). Consequently, soil organic matter (SOM) dynamics should be at the forefront of concerns for stewards of urban trees.

Inorganic fertilizers have long been used to provide N to trees in urban landscapes (Chadwick, 1935, 1937). However, a number of concerns exist with the use of inorganic N fertilizers, including greenhouse gas emissions, eutrophication, acidification, salinization, and losses of soil C (Vitousek et al., 1997; Khan et al., 2007). Organic materials are considered slow-release nutrient sources, so the potential for exceeding tree nutrient demands and associated environmental contamination is likely reduced relative to synthetic fertilization (Smith and Hadley, 1989; Huntley et al., 1997). The use of organic materials is often more cost-effective and also promotes useful recycling (Finck, 1982).

Many studies have demonstrated the value of composts and wood chip mulches applied to urban landscapes for improving soil quality and tree growth (Chalker-Scott, 2007; Scharenbroch, 2009). Aerated compost teas (ACT), biochars (BC), and biosolids (BS) are three organic amendments that are increasing in popularity for managing soils for urban trees. However, the knowledge base for the effects of ACT, BC, and BS on urban soil quality and tree growth is limited.

Aerated compost tea is made by aerating compost and microbial food sources in water for approximately 24 h. Compost teas are applied directly to plants or to soils as drenches or liquid injections. The goal of an ACT program is to culture aerobic, beneficial microorganisms in the tea and then ultimately on the plants and in the soil in which they are applied. The effects of compost teas or extracts on plant growth and disease suppression have been the focus of much research (Yohalem et al., 1996;

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Abbreviations: ACT, aerated compost tea; BC, biochar; BS, biosolid; COM, compost; DOC, dissolved organic C; EC, electrical conductivity; HSD, honestly significant difference; LOI, loss-on-ignition; NK, NK fertilizer; Nmin, N mineralization; NUL, control; PAN, plant-available N; RES, microbial respiration; TOC, total organic C; WC, wood chips.

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Scheuerell and Mahaffee, 2002; Duffy et al., 2004; Scheuerell and Mahaffee, 2004; Welke, 2005; Scheuerell and Mahaffee, 2006; Al-Mughrabi, 2007; Hargreaves et al., 2008; Hendawy, 2008; Puglisi et al., 2008; Viator et al., 2008; Hargreaves et al., 2009a, 2009b; Pant et al., 2009; Segarra et al., 2009; Ezz El-Din and Hendawy, 2010; Pant et al., 2011). For the most part, mixed results have been reported for the effectiveness of compost teas to decrease disease and increase yield for a variety of agronomic and horticultural plants. Few of these studies focused on the specific impacts of ACT on soil quality (Hendawy, 2008; Larkin, 2008; Puglisi et al., 2008; Pant et al., 2009; Scharenbroch et al., 2011) and tree growth (Scharenbroch, 2013).

The increasing use of BC as a soil amendment was inspired by high fertility and organic C contents found in anthropic soils in the Amazon Basin, referred to as *Terra Preta de Indio* (Lehmann et al., 2003). Today, BC is most commonly produced through pyrolysis, burning at 350 to 800°C under partial exclusion of oxygen (Antal and Grønli, 2003). With ideal feedstock, such as woody biomass, the resulting material is highly aromatic with C concentrations of 70 to 80% and unique adsorption properties (high affinity for nutrients) and stability (high persistence) (Lehmann et al., 2006). A growing body of research is finding BC to increase soil quality and plant growth (Glaser et al., 2002; Lehmann and Rondon, 2006; Lehmann, 2007; Liang et al., 2010). Biochar is often found to increase soil surface area, water, and nutrient retention (Pietikäinen et al., 2000; Liang et al., 2006; Chan et al., 2008; Downie et al., 2009), and also increase microbial biomass and activity (Hockaday et al., 2006; Thies and Rillig, 2009; Lehmann et al., 2011). Potential negative impacts of BC on soil quality include increasing soil pH in alkaline soils (Novak et al., 2009) and potential N immobilization (Lehmann et al., 2003). Most research thus far has been in agronomy, and few studies have examined the impact of BC on woody plants (Wardle et al., 1998). Spokas et al. (2012) reviewed the effects of BC on plant growth, and of the 42 of the studies in the review, only 2 focused on trees.

Biosolids are the nutrient-rich organic materials from the treatment of sewage sludge. Biosolids have been used in reclamation of agricultural, forest, and disturbed lands since the 1960s (Sommers, 1977; Epstein, 2003). Studies have found increased soil fertility (Burton and Hook, 1979; Brockway, 1983), improved physical properties (Epstein, 1975), and increased microbial activity (Gilmour et al., 2003) with BS. Harrison et al. (1996) found that overapplication of BS (500 Mg ha^{-1}) decreased tree growth through soil acidification and cation leaching. In addition, increases in nitrification with BS have been reported to lead to increased nitrate leaching (Burton and Hook, 1979; Medalie et al., 1994); although this is not always the case (Dutch and Wolstenholme, 1994). Additional concerns associated with applying BS to soils include, but are not limited to, salinity (Epstein et al., 1976), heavy metals (Silviera and Sommers, 1977), organic contaminants (Harrison et al., 2006), and pathogens (Pepper et al., 2006), as well as a poor public perception (Beecher et al., 2005). Consequently, the USEPA requires that wastewater solids be stabilized to minimize odor generation, destroy pathogens, and reduce vector attraction potential (USEPA, 1995). In addition to stabilization, the USEPA sets ceiling and pollutant concentrations for nutrients and metals in BS. Some studies reported (Henry et al., 1994; Prescott and Blevins, 2005) and modeled (Luxmoore et al., 1999) increased tree and forest growth with BS applications, but the body of literature is limited compared with research on nonwoody plant responses.

The first objective of our experiment was to evaluate the impacts of four organic mulches (wood chips, compost, biosolids, and biochar), compost tea, and inorganic fertilization on tree growth, labile C and N in soil, and leaching of C and N. The second objective was to examine soil and leachate attributes for correlations with tree biomass. Three soil types were selected to represent a gradient of urban soil quality and potential limitations to tree growth. Noncompacted silt loam soils represent the highest-quality soils. A compacted clay soil was used to represent a dense, low organic matter soil typical of urban landscapes that have been compacted and scraped of topsoil. A sand soil was chosen to represent a low organic matter, well-drained, and relatively dry substrate often found in constructed soils in street tree cutouts. *Acer saccharum* (sugar maple) and *Gleditsia triacanthos* (honey locust) are commonly planted urban trees. Because of their faster growth response rates relative to mature trees, saplings of these species were used to study the trees and collect leachates in a controlled greenhouse setting.

Materials and Methods

Experimental Design

The experiment was a full factorial with two species, three soil types, six treatments plus control, and five replicates for a total of 210 experimental units. The two tree species were *A. saccharum* Marsh. and *G. triacanthos*. The trees were planted as 1- to 2-cm caliper bare root saplings in January 2011. Before planting, the main roots were pruned to a standardized 10-cm length, fine roots (≤2 mm in diameter) were removed, and stems were pruned to a 30-cm length. The three soil types were pure sand, silt loam, and compacted clay. The silt loam and clay soils were collected from a 3-m-deep pit on the grounds of The Morton Arboretum, Lisle, IL. The silt loam soil was from the Ap horizon (0 to 10 cm), and the clay soil from the Btg horizons (40 to 75 cm) of a fine, illitic, mesic Oxyaquic Hapludalf, Ozaukee series soil profile. The sand soil was playground sand purchased from a local retailer.

All soils were air-dried in the laboratory, passed through a 2-mm sieve, and thoroughly homogenized. The soils were placed in microcosms (cylindrical polyvinyl chloride containers, 15-cm diameter by 25-cm height) in six lifts (250 mL per lift). The silt loam and sands were lightly tamped down between each lift to a final bulk density of 1.12 and 1.41 Mg m^{-3}, respectively. The clay soils were placed and compacted to a bulk density of 1.65 Mg m^{-3} with a standard compaction drop hammer with 592.7 kJ m^{-3} effort (AASHTO, 2012). Before compaction, the Proctor test was used to determine the optimum moisture content (19 ± 0.5% gravimetric soil moisture) to maximize compaction effort for the clay soil. Characteristics of the silt loam, compact clay, and sand soils are given in Table 1.

Treatments

Four solid organic materials were included as treatments and applied at rates that are considered the current best practices for soil application (USEPA, 2000; US Composting Council, 2001; Major, 2010; USDA NRCS, 2011). Wood chips (WC), compost (COM), BC, and BS were applied annually as top-dressings to the soil surfaces at the rate of 25 Mg ha^{-1} yr^{-1} (100 mL of each treatment microcosm^{-1} yr^{-1}). Characteristics of WC, COM, BC, and BS are provided in Table 1.

Wood chips were from assorted hardwood trimmings at The Morton Arboretum. Tree trimmings were chipped in a wood-chipper, ground in a tub-grinder, and piled for a period of approximately 6 mo. The pile of wood chips was turned monthly during this period. Compost was the Organomix product (Midwest Organics, Inc.). The compost was tested by Soil Foodweb, Inc., and contained approximately 12,000 μg bacteria g^{-1}, 3500 μg fungi g^{-1} (mean hyphae diameter of 3 μm), 20,000 flagellates g^{-1}, 15,000 amoebae g^{-1}, 10,000 ciliates g^{-1}, and 1 nematode g^{-1}.

Biochar used in this experiment was produced from pine feedstock (*Pinus taeda*, *P. palustris*, *P. echinata*, *P. elliotti*). Feedstocks are known to influence BC characteristics (Spokas et al., 2012), and this feedstock was selected due to its availability and because it closely resembles urban forest and tree wood waste. Pyrolysis time of the BC was 1 h between temperatures of 550 and 600°C in a pyro-torrefaction style kiln. The BC contained (% dry wt.): 1.0% mobile C, 63.1% resident C, 0.1% mobile N, 0.3% resident N, 17% mobile hydrogen–oxygen (H-O), 6.8% resident H-O, 8.6% soluble ash, 3.7% nonsoluble ash (analyzed July 2011 by Control Laboratories Inc., Soil Control Laboratory, Watsonville, CA). The BC was obtained from New Earth Renewable Energy (a commercial producer no longer in operation). Biosolids contained (% dry wt.): 65.2% total solids, 0.65% mobile N, 0.97% P_2O_5, and 0.12% K_20. Metal contents of the BS meet the Illinois Environmental Protection Agency Class A standards for land application. The BS contained (mg kg^{-1} dry wt.): 1.5 Ar, 1.9 Cd, 20 Cr, 514 Cu, 25 Pb, 276 Mn, 1.8 Me, 9 Mo, 16 Ni, 4.9 Se, and 440 Zn (Downers Grove Sanitary District, Downers Grove, IL).

The NK fertilizer (30–0–12) contained 30% total N (15% water-insoluble N) from nitroform and urea. The NK fertilizer also contained 12% K from K_2SO_4, 0.10% Fe, 0.05% Mn, 0.05% Cu, and 0.05% Zn. The NK fertilizer was diluted with water and applied twice annually at a rate of 220 kg N ha^{-1} yr^{-1} (ANSI, 1998; Smiley et al., 2002).

Aerated compost tea was applied five times annually (35 mL microcosm^{-1} application^{-1}), May through September at a rate of 100 kL ha^{-1} yr^{-1} (Scharenbroch, 2013). Aerated compost tea was made with a KIS compost tea brewer (Keep It Simple, Inc.). A mesh bag was filled with 500 g of compost (Organomix, Midwest Organics, Inc.) and 500 g of a commercially produced compost tea package consisting of 80% organic nutrients, 20% natural minerals derived from feather meal, bone meal, cottonseed meal, sulfate of potash-magnesia, alfalfa meal, kelp, soymeal, and mycorrhizae (Keep It Simple, Inc.). The brewer was filled with 19 L of water. Humic acid (25 g) and soluble seaweed powder (25 g) were added to the water at the start of the brew (Keep It Simple, Inc.). During the 24-h brew cycle, dissolved oxygen, temperature, pH, and electrical conductivity (EC) were measured every hour. Dissolved oxygen remained above 6 mg kg^{-1}, with a mean value of 7 mg kg^{-1} throughout the brew cycle. Mean temperature, pH, and EC were 21°C, 5, and 2000 μS cm^{-1}, respectively. On average (10 brews), the ACT contained only a fraction of what was in the compost itself: 2000 μg bacteria g^{-1}, 5 μg fungi g^{-1} (mean hyphae diameter of 3 μm), 2000 flagellates g^{-1}, 1000 amoebae g^{-1}, 10 ciliates g^{-1}, and 0.1 nematodes g^{-1}. Characteristics of the water, the NK fertilizer, and ACT are given in Table 1.

Control (NUL) trees received no treatments. All trees received 35 mL of water at times when ACT and NK fertilizer was applied. During the growing seasons (March–November), 200 mL of water was added to each tree, three times per week. To accurately capture leachates, soil water-holding capacities were not exceeded during the watering. During the growing season, microcosms were maintained in a greenhouse at 20°C with light regime of 14 h light and 10 h dark. In the dormant season, November through February, tree in microcosms were moved to an outdoor Quonset hut. The experiment ran for 18 mo, and trees and soils were destructively sampled in June of 2012.

Tree Responses

In June 2012 (18 mo from beginning of experiment), trees were carefully separated from the soils. Trees were then washed with deionized water to remove all soil. Roots were photographed and scanned (WinRHIZO software, Regent Instruments, Inc.). Trees

Table 1. Characteristics (mean ± standard error of the mean) of three soils (silt loam, clay, and sand), and control or water (NUL), and six treatments: NK fertilizer (NK), aerated compost tea (ACT), compost (COM), wood chips (WC), biochar (BC), and biosolid (BS). Values are means of six replicate samples.

Response†	Loam	Clay	Sand	NUL	NK	ACT	COM	WC	BC	BS
F gravel (5–2 mm) (%)	0.0 ± 0.0	0.0 ± 0.0	0.3 ± 0.0	n/a	n/a	n/a	12.2 ± 0.3	71.4 ± 0.6	1.0 ± 0.1	18.7 ± 0.3
VC sand (2–1 mm) (%)	2.1 ± 0.1	0.2 ± 0.1	0.4 ± 0.1	n/a	n/a	n/a	19.2 ± 0.2	11.3 ± 0.2	5.6 ± 0.1	21.2 ± 0.2
C sand (1–0.5 mm) (%)	3.1 ± 0.1	2.2 ± 0.1	1.1 ± 0.1	n/a	n/a	n/a	24.8 ± 0.2	6.5 ± 0.1	21.5 ± 0.2	25.1 ± 0.1
M sand (0.5–0.25 mm) (%)	3.8 ± 0.2	7.6 ± 0.2	8.9 ± 0.1	n/a	n/a	n/a	21.9 ± 0.1	4.6 ± 0.1	30.9 ± 0.2	20.9 ± 0.1
F sand (0.25–0.05 mm) (%)	4.5 ± 0.2	20.3 ± 0.2	72.3 ± 0.1	n/a	n/a	n/a	15.6 ± 0.1	5.4 ± 0.1	22.9 ± 0.1	9.9 ± 0.1
Silt (0.05–0.002 mm) (%)	57.7 ± 0.4	27.2 ± 0.1	16.9 ± 0.1	n/a	n/a	n/a	5.9 ± 0.1	0.6 ± 0.1	12.6 ± 0.2	3.0 ± 0.1
Clay (<0.002 mm) (%)	28.8 ± 0.3	42.5 ± 0.2	0.1 ± 0.1	n/a	n/a	n/a	0.4 ± 0.1	0.2 ± 0.1	5.5 ± 0.2	1.2 ± 0.1
Bulk density (Mg m^{-3})	1.12 ± 0.1	1.65 ± 0.3	1.41 ± 0.2	n/a	n/a	n/a	0.52 ± 0.01	0.27 ± 0.03	0.26 ± 0.02	0.62 ± 0.01
pH	6.27 ± 0.1	7.85 ± 0.2	8.89 ± 0.1	7.52 ± 0.2	5.03 ± 0.1	7.52 ± 0.1	7.74 ± 0.1	5.07 ± 0.2	9.18 ± 0.1	5.50 ± 0.1
EC (dS m^{-1})	47 ± 5	112 ± 7	32 ± 3	322 ± 21	10 ± 2	770 ± 23	366 ± 16	33 ± 6	99 ± 9	279 ± 12
C (%) or (Mg ha^{-1} yr^{-1})	2.61 ± 0.1	1.85 ± 0.1	0.11 ± 0.1	<0.01 ± 0.0	0.2 ± 0.1	0.4 ± 0.1	4.8 ± 0.2	11.2 ± 0.5	16.0 ± 0.7	4.1 ± 0.3
N (%) or (kg ha^{-1} yr^{-1})	0.24 ± 0.02	0.07 ± 0.01	<0.01 ± 0.0	<0.01 ± 0.0	140 ± 5	38 ± 3	215 ± 12	125 ± 12	100 ± 10	428 ± 11
C/N ratio	11 ± 1	27 ± 2	100 ± 2	n/a	1 ± 0.1	10 ± 1	22 ± 1	92 ± 2	160 ± 3	10 ± 1
Nmin (g N m^{-2} yr^{-1})	1.74 ± 0.02	0.88 ± 0.05	0.01 ± 0.01	0.05 ± 0.01	2.49 ± 0.01	2.73 ± 0.01	4.39 ± 0.01	1.66 ± 0.01	1.85 ± 0.01	11.23 ± 0.2
RES (kg C m^{-2} yr^{-1})	1.09 ± 0.01	0.49 ± 0.01	0.32 ± 0.02	0.04 ± 0.01	0.18 ± 0.01	0.19 ± 0.01	0.36 ± 0.02	0.06 ± 0.01	0.08 ± 0.01	1.12 ± 0.02

† F, fine; C, coarse; VC, very coarse; M, medium; EC, electrical conductivity; Nmin, N mineralization; RES, microbial respiration.

were partitioned into leaf, stem, fine root (≤2 mm diam.), and coarse root fractions (>2 mm diam.). All fractions were dried at 60°C for 5 d and weighed to determine biomass in those fractions.

Soil Responses

At the conclusion of the experiment, soils were carefully removed from each microcosm and separated from tree roots. Soils were passed through a 6-mm screen and homogenized for further characterization. Soil pH and EC in dS m^{-1} were measured in 1:1 and 1:5 (soil:deionized water) pastes, respectively (Model Orion 5-Star, Thermo Fisher Scientific Inc.). Soil EC was used as proxy for plant-available N (PAN). Soil EC correlates to the presence of the major dissolved inorganic salts (Na^+, Mg^{2+}, Ca^{2+}, K^+, NH_4^+, Cl^-, SO_4^{2-}, HCO_3^-, NO_3^-, and CO_3^{2-}) (Rhoades et al., 1999). In a similar soil microcosm study with identical soils, EC was significantly correlated with the combined pools of NH_4^+, NO_3^-, and dissolved organic N (PAN = 1.83 + 0.39×EC; $R^2 = 0.29$; $P < 0.0001$; $N = 180$) (Scharenbroch, 2013). The correlations with EC and PAN were stronger than any correlations with EC and Na^+, Mg^{2+}, Ca^{2+}, K^+, or Bray P. Soil organic matter was determined by loss on ignition (LOI) at 400°C for 6 h to a stable mass (Nelson and Sommers, 1996). Total organic C (TOC) was predicted from LOI using an equation (TOC = 0.55 + 0.54×LOI; $R^2 = 0.63$; $P < 0.0001$; $N = 205$) derived from these soils relating LOI with TOC via dry combustion in a CN analyzer (Vario ELIII, elementar Analysensysteme). Potential N mineralization (Nmin) was measured as the net increase or decrease in extractable NH_4^+ in a dark, anaerobic, 10-d incubation at 25°C at 100% water-filled pore spaces. Base and incubated soils were extracted with 2.0 M KCl and extractable NH_4^+ measured with a modified indophenol blue method and read at 650 nm on a microplate reader (Biotek ELx800) (Sims et al., 1995). Microbial respiration (RES) was the CO_2 evolution measured during the 10-d aerobic incubations (sans roots), sequestered in NaOH traps, and titrated to a phenophalthein endpoint with 0.25 M standardized HCl (Parkin et al., 1996).

Leachate Responses

Microcosm bottoms contained 3 cm of coarse sand plus gravel and drainage wicks. During the period 14 to 21 May 2012 (17 mo from the beginning of experiment), all microcosms were placed under a vacuum of 35 kPA and soil leachates were collected in side-arm flasks. Before the leachate collection, no water was allowed to drain from the microcosms. The collection of leachate at this time was to represent potential nutrient loss after the tree seedlings are relatively well established. The leachates were analyzed for dissolved organic C (DOC) and nitrate (NO_3^-). Leachate DOC was analyzed on a total organic C analyzer (Model 1010, OI Analytical). Leachate NO_3^- was analyzed by reduction to NH_4^+ using a Devarda's alloy and 0.1 M H_2SO_4, and then read colorimetrically at 650 nm (Model ELx500 microplate reader, BioTek) (Sims et al., 1995).

Statistical Analyses

The effects of treatment (NUL, NK, ACT, COM, WC, BC, and BS) on soil, leachate, and tree properties were individually tested using standard least squares and ANOVA, with treatment as the main effect and species and soil type as blocking variables. Differences among treatments for each of the tested variables were compared using Tukey-Kramer honestly significant difference (HSD) test, $\alpha = 0.05$. Assumptions of normality were tested using a Shapiro-Wilk test ($P > 0.05$) and homogeneity of variance tested using a Levene's test ($P > 0.05$). When necessary, soil, leachate, and tree properties were transformed using natural log, square, square root, exponential, and reciprocal functions before analyses to address ANOVA violations. A sequential Bonferroni inequality was applied to the critical P values to control for false positives (Type I error) associated with multiple testing (Rice, 1989).

Relationships among soil, leachate, and tree variables were assessed using least squares linear regression and multivariate modeling ($P < 0.05$). Combinations of different predictors for tree biomass were tested in a stepwise procedure to find the combination of predictors that maximized R^2. To balance the trade-off between model fit and model complexity, a predictor was added to the model only if it improved the model R^2 by more than 0.05. Nonparametric multiplicative regression (NPMR) was also used to suggest the best predictors for tree biomass (McCune, 2006). Significance of the final selected model was determined as the percentage of 100 Monte Carlo trials with R^2 greater than or equal to the R^2 of the final selected model, when observed predictor values were randomly reassigned among the microcosms during each trial. Statistical analyses were conducted using SAS JMP 7.0 software (SAS Inc.), as well as PC-ORD 6.0 HyperNiche Version 2 software (MjM Software Design).

Results

Tree Responses

Significant treatment effects were detected for all tree responses (Table 2). Effects of soil type and species were also significant, but no treatment × soil or treatment × species interactions were detected for tree responses. Leaf biomass was greater with BS compared with compost tea (ACT), compost (COM), WC, and NUL. Leaf biomass was greater with NK fertilizer compared with WC, ACT, and NUL. Leaf biomass was also greater with BC compared with NUL. Stem biomass was greater with BS compared with NUL. Coarse root biomass was greater with BS and BC compared with ACT and NUL. Total tree biomass was greater with BS compared with ACT and NUL. Total tree biomass was also greater with BC compared with NUL.

More significant differences were detected for *G. tricanthos* compared with *A. saccharum* when treatment effects were assessed on individual species (Fig. 1). Total tree biomass for *A. saccharum* was greater for BS and BC compared with NUL. *Acer saccharum* leaf biomass was greater with BS compared with WC, COM, ACT, and NUL. *Acer saccharum* leaf biomass was greater with BC compared with WC and NUL. *Acer saccharum* leaf biomass was greater with NK compared with ACT, WC, and NUL. Significant differences were not detected for coarse and fine roots and stem biomass of *Acer saccharum*. Total tree biomass for *G. triacanthos* was greater for BS compared with WC, ACT, and NUL. Total tree biomass for *Gleditsia triacanthos* was greater for BC and NK compared with WC and NUL and BC compared with NUL. *Gleditsia triacanthos* leaf biomass was greater for BS and NK compared with WC, ACT, and NUL. *Gleditsia triacanthos* leaf biomass was greater for BC compared *Gleditsia* *triacanthos* NUL. Stem biomass of *G. triacanthos* was greater for BS compared *Gleditsia triacanthos* WC, ACT, and NUL. Coarse root biomass for *G. triacanthos* was greater for BS compared with WC and NUL. Fine root biomass for *G. triacanthos* was greater for BS and BC compared with WC and NUL.

Significant soil type and species effects were detected for all tree parameters (Table 2). Biomass in all components was greater with *A. saccharum* compared with *G. triacanthos*. Individual tree biomass components and total tree biomass was greater in silt loam compared with compact clay and sand soils. Leaf fluorescence was greater in silt loam, followed by compact loam and lastly, sand soils.

Soil Responses

Significant treatment, soil, and treatment × soil type effects were detected for all soil properties, except treatment × soil for soil PAN (Table 2; Fig. 2). In all three soils, soil PAN was greater with BS compared with NUL, ACT, NK, WC, and BC. Soil pH did not differ with treatment for the silt loam soils. Soil pH was significantly higher for ACT compared with BS with the compact clay soils. In sand soils, pH was lower with BS compared with all other treatments. Soil pH was greater for ACT compared with BS and BC in the sand soils. Total organic C was greater with BC compared with all other treatments in all soil types. Total organic C was greater with BS, WC, and COM compared with NK, ACT, and NUL in all three soil types (sans silt loam and WC). In both silt loam and compact clay, Nmin was greater with BS compared with all other treatments, but no differences were detected in sand for Nmin. Microbial respiration was greater with BS compared with NUL and ACT in all soils. In compact clay, RES was greater with NK compared with NUL and ACT. In sand soils, RES was greater with BS compared with BC, WC, and COM. In sand soils, RES was greater with BC, NK, WC, and COM compared with ACT and NUL.

All soil responses differed by soil type. Soil pH increased from silt loam to compact clay to sand soils. Plant-available N was greatest in compact clay, followed by silt loam and then sand soils. Soil TOC decreased from silt loam to compact clay to sand soils. Nitrogen mineralization was greater in silt loam and compact clay compared with sand soils. Microbial respiration decreased from silt loam to sand to compact clay. Microbial respiration and PAN were greater with *A. saccharum* compared with *G. triacanthos*.

Leachate Responses

Significant treatment differences were detected for DOC but not for NO_3^- in leachates (Table 2). Leachate DOC was greater with COM compared with BC, WC, ACT, NK, and

Table 2. Mean ± standard error of the mean of tree, soil, and leachate properties from control (NUL) and six treatments: NK fertilizer (NK), aerated compost tea (ACT), compost (COM), wood chips (WC), biochar (BC), and biosolid (BS). Each mean is 18-mo response from 30 microcosms across two tree species (*Acer saccharum* and *Gleditsia triacanthos*), and three soil types (silt loam, compact clay, and sand).

Response†	NUL	NK	ACT	COM	WC	BC	BS	Tr‡§	So§	Sp§	Tr × So	Tr × Sp	So × Sp	Tr × Sp × So
Leaf biomass (g)	3.0 ± 0.3d¶	5.5 ± 0.9ab	3.6 ± 0.4cd	4.1 ± 0.4bcd	3.4 ± 0.4cd	5.2 ± 0.5abc	6.6 ± 0.6a	***	***	***	ns#	ns	ns	ns
Stem biomass (g)	9.2 ± 0.9b	12.3 ± 1.2ab	9.9 ± 1.0b	11.3 ± 0.8ab	11.0 ± 1.2ab	12.5 ± 1.0ab	13.5 ± 1.0a	***	***	***	ns	ns	ns	ns
F root biomass (g)	6.2 ± 0.3	7.1 ± 0.3	6.5 ± 0.3	7.1 ± 0.3	6.6 ± 0.3	6.8 ± 0.3	7.5 ± 0.4	**	***	***	ns	ns	ns	ns
C root biomass (g)	9.4 ± 0.6b	12.0 ± 0.9ab	10.2 ± 0.8b	12.0 ± 0.9ab	10.7 ± 0.9ab	13.7 ± 1.1a	14.4 ± 1.2a	***	***	***	ns	ns	ns	ns
Total biomass (g)	24.9 ± 2.1c	33.8 ± 2.6abc	27.5 ± 2.6bc	30.9 ± 2.3abc	29.0 ± 3.0abc	35.8 ± 2.7ab	38.3 ± 2.9a	***	***	***	ns	ns	ns	ns
pH	7.99 ± 0.1ab	8.00 ± 0.1ab	8.08 ± 0.1a	8.02 ± 0.1ab	7.95 ± 0.1ab	7.92 ± 0.1ab	7.73 ± 0.1b	***	***	ns	***	ns	ns	ns
PAN (g N m^{-2})	0.101 ± 0.01b	0.115 ± 0.02b	0.104 ± 0.01b	0.119 ± 0.01ab	0.104 ± 0.01b	0.116 ± 0.01b	0.181 ± 0.02a	***	***	**	ns	ns	***	ns
TOC (kg C m^{-2})	2.99 ± 0.4c	3.02 ± 0.4bc	2.98 ± 0.4c	3.79 ± 0.4abc	3.58 ± 0.4abc	5.22 ± 0.5a	3.93 ± 0.4ab	***	***	ns	***	ns	ns	ns
Nmin (g N m^{-2} yr^{-1})	0.83 ± 0.2b	1.22 ± 0.3b	0.86 ± 0.2b	1.38 ± 0.2b	0.92 ± 0.2b	0.96 ± 0.2b	2.85 ± 0.5a	***	***	ns	***	ns	ns	ns
RES (kg C m^{-2} yr^{-1})	0.87 ± 0.1b	1.15 ± 0.1ab	0.89 ± 0.1b	1.10 ± 0.1ab	1.10 ± 0.1ab	1.10 ± 0.1ab	1.26 ± 0.1a	***	***	***	***	ns	***	ns
Leach DOC (mg kg^{-1})	14.0 ± 1.1cde	11.2 ± 1.0cd	10.2 ± 0.8d	21.8 ± 1.6a	14.7 ± 0.9cd	16.2 ± 1.8bc	19.4 ± 2.8ab	***	***	**	ns	ns	ns	ns
Leach NO_3^- (mg kg^{-1})	2.08 ± 0.4	1.72 ± 0.4	1.08 ± 0.3	1.49 ± 0.3	1.58 ± 0.4	1.26 ± 0.2	1.85 ± 0.3	ns	**	ns	ns	ns	ns	ns

** $P < 0.01$.

*** $P < 0.0001$.

† F, fine; C, coarse; PAN, plant-available N; TOC, total organic C; Nmin, N mineralization; RES, microbial respiration; Leach, leachate.

‡ Tr, treatment; So, soil; Sp, species.

§ P values are given for ANOVA F-test results of main and interaction effects.

¶ Unique letters indicate significantly different means using Tukey-Kramer honestly significant difference test ($\alpha = 0.05$).

ns, nonsignificant ($\alpha = 0.05$).

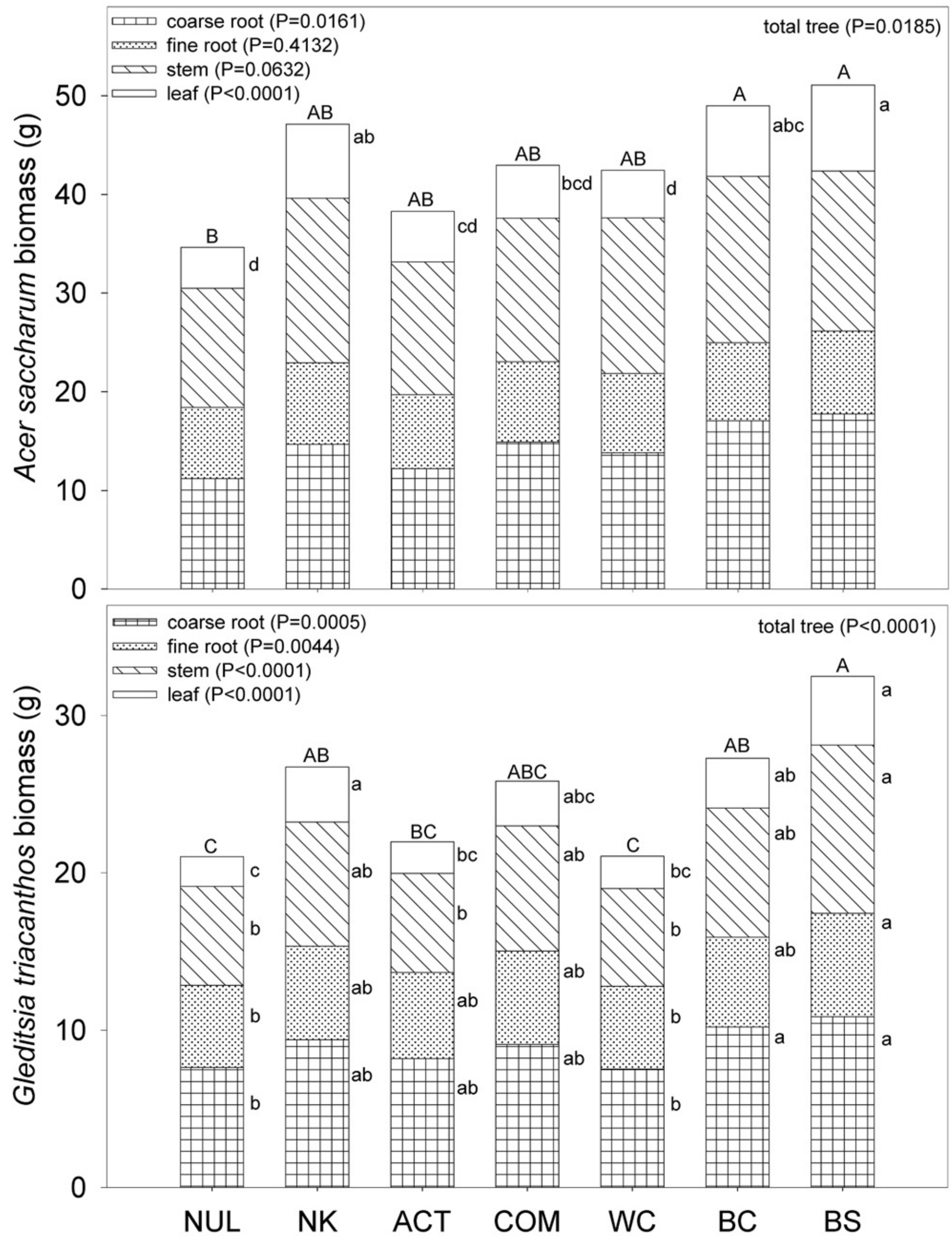

Fig. 1. Leaf (open), stem (diagonal), fine root (stipuled), coarse root (hatched), and total tree biomass (total bar) for *Acer saccharum* and *Gleditsia triacanthos* saplings with a control (NUL) and six treatments applied as top-dressings over 18 mo: NK fertilizer (NK), aerated compost tea (ACT), compost (COM), wood chips (WC), biochar (BC), and biosolid (BS). Values are means of 15 trees in microcosms across three soil types (silt loam, compact clay, and sand). *P* values are given for ANOVA F-test results, and unique letters indicate significantly different means using Tukey-Kramer HSD test (α = 0.05).

NUL. Leachate DOC was greater with BS compared with BC, WC, ACT, NK, and NUL. Leachate DOC was greater with BC compared with ACT. Significant differences in leachate DOC and NO_3^- were detected among the three soil types. Sandy soils had greater leachate NO_3^- compared with compact clay. Leachate DOC was greater in silt loam and compact clay compared with sand. Leachate DOC was greater with *A. saccharum* compared to *G. triacanthos*.

Modeling Tree Biomass

All tree attributes were positively and significantly correlated with each other (R^2 > 0.05; P < 0.0001). Soil pH was negatively correlated with all tree biomass measures (Fig. 3). Total organic C, Nmin, and RES were positively and significantly correlated with all tree biomass measures. Soil PAN was positively correlated with leaf, stem, and total tree biomass. Correlations between tree biomass and leachate DOC and NO_3^- were nonsignificant.

Combinations of the soil properties were tested in a stepwise procedure to maximize R^2 and minimize model complexity. A two-factor model (Tree biomass = 6.96 + 14.0×RES + 0.0742×PAN, R^2 = 0.34; P < 0.0001) was an improvement over the single-factor model (Tree biomass = 19.8 + 11.1×RES, R^2 = 0.16; P < 0.0001); but adding additional factors could not improve on the two-factor model. In addition to the stepwise procedure, a nonparametric multiplicative regression was used to evaluate the six predictors on tree biomass. This procedure also yielded a two-factor model with RES and PAN (xR^2 = 0.28), where, xR^2 is the cross-validated R^2 = 1 – (residual sum of squares/

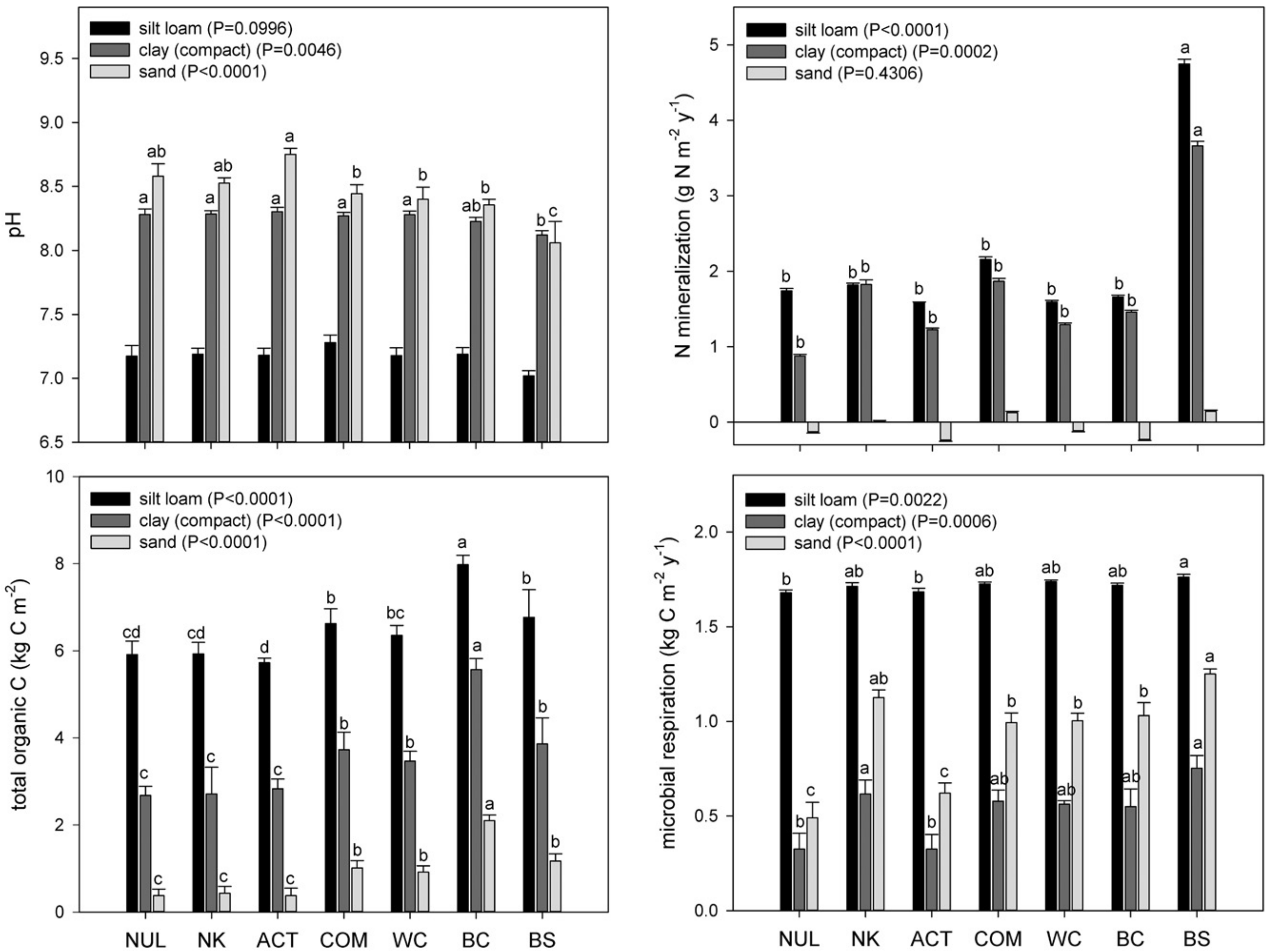

Fig. 2. Soil pH, total organic C, N mineralization, and microbial respiration in silt loam, compact clay, and sand soil tree microcosms with *Acer saccharum* and *Gleditsia triacanthos* saplings. Treatments were applied as top-dressings over 18 mo in a greenhouse setting: control (NUL), NK fertilizer (NK), aerated compost tea (ACT), compost (COM), wood chips (WC), biochar (BC), and biosolids (BS). *P* values are given for ANOVA F-test results, and unique letters indicate significantly different means using Tukey-Kramer HSD test (α = 0.05).

total sum of squares). The Monte Carlo analysis of the two-factor model (Fig. 4) yielded a $p = 0.0099$, where p is the proportion of randomized runs with fits greater than or equal to the observed fit. Sensitivity analysis of the two-factor model revealed values of 0.19 (PAN) and 0.24 (RES) for the mean absolute differences resulting from 397 nudgings of the predictors, expressed as a proportion of the range of the response variable.

The amount of N applied in the treatments was significantly correlated with all tree and soil responses, and all correlations were positive except for soil pH. The strongest correlations were observed among treatment N and PAN ($R^2 = 0.83$; $P = 0.0043$), RES ($R^2 = 0.78$; $P = 0.0081$), and total tree biomass ($R^2 = 0.65$; $P = 0.0281$) (Fig. 5). The relationship between tree biomass and N added in treatment was substantially improved ($R^2 = 0.97$; $P = 0.0004$) when the BC microcosms were removed. No significant correlations were detected between N in treatments and leachate DOC or NO_3^-.

Discussion

Tree Growth

The greatest increases in tree growth were observed with BS treatment. Across both species and three soil types, total tree biomass increased with BS compared to the control. Our findings confirm other reports of increased tree growth with BS. Henry et al. (1994) found height increases in young *Pseudotsuga menziesii* (Douglas fir) stands of up to 72% with BS applied at 47 Mg ha^{-1}. McDonald et al. (1994) reported a 24% increase in diameter of *Thuga plicata* (western red cedar) 2 yr following BS applied at 69 Mg ha^{-1}; however, growth rates were greater with an inorganic fertilizer at 225 kg N and 75 kg P ha^{-1}. Our findings contrast Fuentes et al. (2007), who found BS to have a negative effect on *Quercus ilex* seedling growth at the rate of 12 Mg ha^{-1}, but this difference may be due to impact of incorporated BS as backfill, whereas we applied BS as a soil mulch. Harrison et al. (1996) also found BS to decrease tree growth at high rates (500 Mg ha^{-1}) due to soil acidification and cation leaching.

Increases in tree biomass were also observed with the BC treatments. Across both species and three soil types, total tree biomass increased 44% with BC compared with the control. Our findings of increased tree biomass are in general agreement with the body of research examining BC effects on tree growth. Robertson et al. (2012) found BC to increase seedling growth in *Pinus contorta* (lodgepole pine) and *Alnus viridis* (sitka alder). Sovu et al. (2012) found rice hull BC at 4 Mg ha^{-1} to increase diameter and height growth of some slow-growing tree species (*Dipterocarpus alatus*, *Pterocarpus macrocarpus*, and *D. cochichinensis*) after 4 yr on a degraded restoration site.

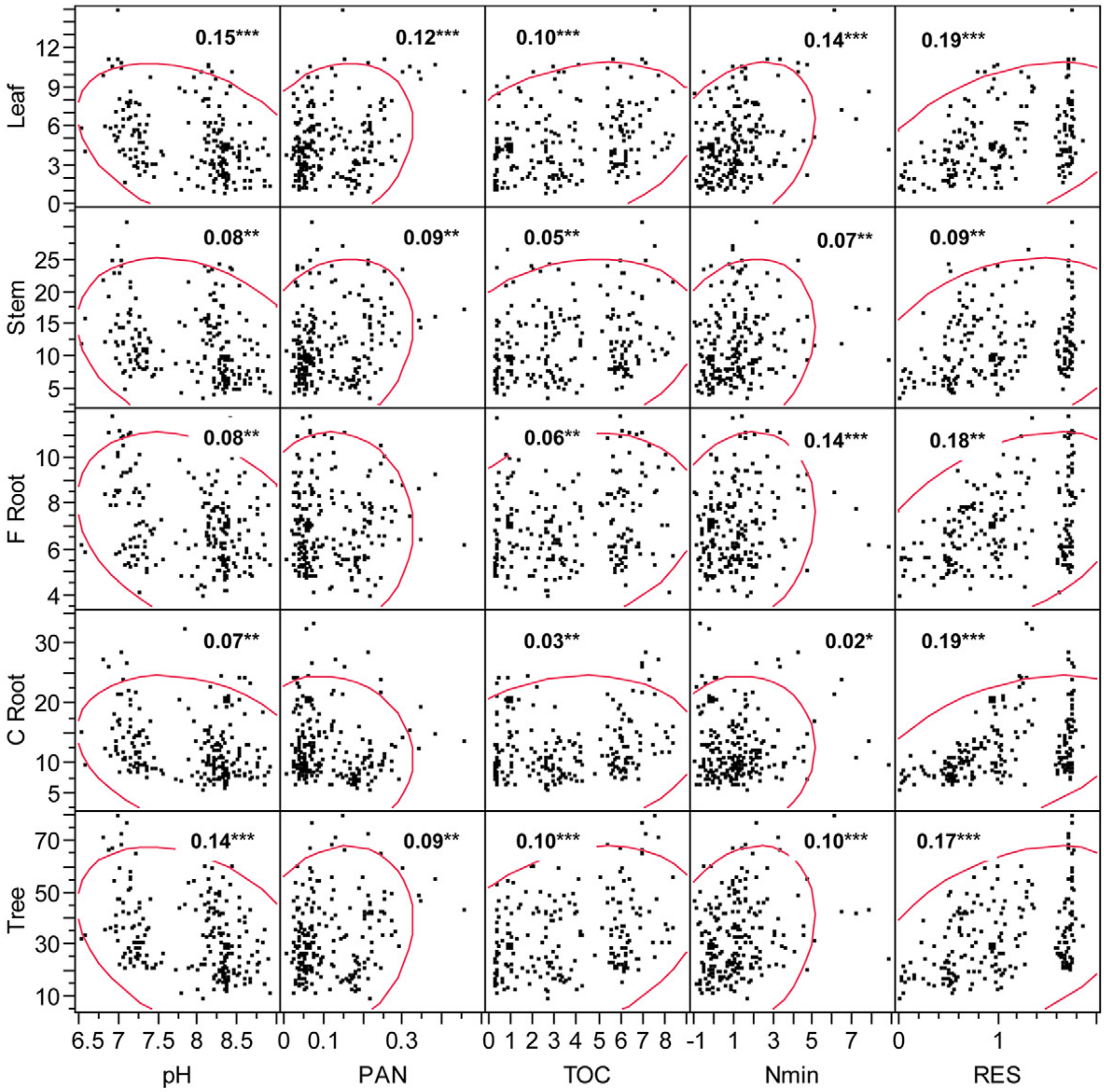

Fig. 3. Correlation matrix and R^2 values among leaf biomass, stem biomass, fine and coarse root biomass, total tree biomass, soil pH, plant-available N (PAN), total organic C (TOC), N mineralization (Nmin), and microbial respiration (RES). Data from 210 tree microcosms with *Acer saccharum* and *Gleditsia triacanthos* in silt loam, compact clay, and sand, treated with control (NUL) and six treatments: NK fertilizer (NK), aerated compost tea (ACT), compost (COM), wood chips (WC), biochar (BC), and biosolids (BS) applied as top-dressings over 18 mo in a greenhouse setting. Significance values: *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.0001$.

Chidumayo, (1994) reported 13% greater biomass production among seven woody plants growing in soils under charcoal kilns compared with undisturbed Alfisols and Ultisols.

Surprisingly, increases in tree biomass with COM and WC were not observed. Total tree biomass for *G. triacanthos* was 34% greater with COM compared with NUL, but this difference was not significantly different at $\alpha = 0.05$. Our findings of no change in tree biomass contrast with studies that found increased tree growth with surface applications of COM (Watson, 1988; Sæbø and Ferrini, 2006) and WC (Fraedrich and Ham, 1982; Litzow and Pellett, 1983; Hensley et al., 1988; Watson and Kupkowski, 1991; Gilman and Grabosky, 2004; Montague et al., 2007; Ferrini et al., 2008). Unlike our study, most of these experiments were field based (often in nurseries), with larger-sized trees, and were of longer duration. In addition, these studies examined tree growth responses to COM and WC in higher-quality soils, whereas our study examined degraded soils to mimic typical urban soil conditions (compacted clay and sand soils). Others reported COM (Erhart and Hartl, 2003; Rumberger et al., 2004; Yao et al., 2006) and WC (Arnold et al., 2005; Roberts, 2006) to have no or even negative effects on tree growth. Erhart and Hartl, (2003) found decreases in the first year, increases in the second year, and no changes after the second year for *Picea pungens* (blue spruce) growth with COM applied as mulch. Both Rumberger et al. (2004) and Yao et al. (2006) found no improvements in tree growth of *Malus* spp. (apple) with preplant COM treatments in an orchard. Negative tree growth responses with COM and WC have been attributed to negative impacts on soil water associated with these materials being incorporated as backfill (Roberts, 2006) or with thick mulch applications, often exceeding 25 cm (Arnold et al., 2005).

Some increases (total tree and leaf for *G. triacanthos* and leaf for *A. saccharum*) in tree biomass were observed with the NK fertilizer relative to the control. This finding was expected given that inorganic fertilizers have long been used to supply nutrients for urban landscape trees (Chadwick, 1935, 1937; Himelick et

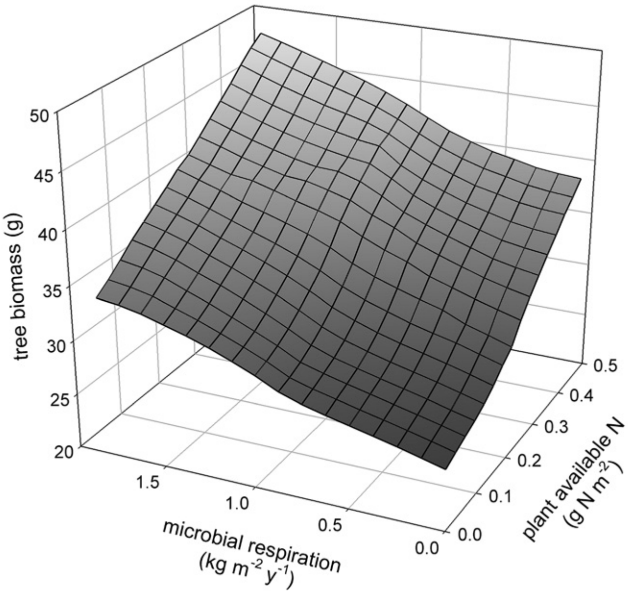

Fig. 4. Tree biomass by plant-available N and microbial respiration. Data from 210 tree microcosms with *Acer saccharum* and *Gleditsia triacanthos* in silt loam, compact clay, and sand, treated with control (NUL) and six treatments: NK fertilizer (NK), aerated compost tea (ACT), compost (COM), wood chips (WC), biochar (BC), and biosolids (BS) applied as top-dressings over 18 mo in a greenhouse setting. Biomass is projected using a running average local smoothing technique and a 1.0 sampling proportion (tree biomass = 6.96 + 14.0×RES + 0.0742×PAN, R^2 = 0.34; P < 0.0001).

al., 1965). Reviews of shade tree fertilization by Rose (1999) and Struve (2002) summarize the general consensus of increased tree growth with fertilization at 50 to 300 kg N ha^{-1} yr^{-1} (Smiley et al., 2002) and are in agreement with our findings of increase in tree growth with the NK fertilizer.

We found no significant differences in tree biomass for ACT compared with the control. This finding confirms Scharenbroch (2013), who found no increases in tree growth with ACT applications at 2, 4, and 40 kL ha^{-1} yr^{-1} to *A. saccharum* and *Quercus macrocarpa* (bur oak) saplings in sand, uncompacted loam, and compacted loam soils. Scharenbroch (2013) did find root, shoot, and total biomass to increase for *Q. macrocarpa* trees growing in compact loam at an application rate of 400 kL ACT ha^{-1} compared with a water control, but significant differences were not detected for this application rate compared with water in the other soil types and in no instances with *A. saccharum* saplings. We are not aware of other studies that have examined the effects of ACT on tree growth.

Soil Properties

We found BS to increase PAN, Nmin, and RES, confirming studies reporting BS to increase N availability (Burton and Hook, 1979; Brockway, 1983) and microbial activity (Terry et al., 1979; Lerch et al., 1992; Sikora and Yakovchenko, 1996). The BS used in this research were 1.7% N and had relatively low C/N ratios of 10/1 and so were likely to stimulate N mineralization and microbial activity (McGill and Cole, 1981). Like others, we found BS to decrease soil pH (Harrison et al., 1994), which in these alkaline soils may be beneficial for nutrient availability and tree growth. We suspect the decrease in pH with BS was in part derived from H^+ transfer processes associated with N mineralization and microbial respiration (Van Breemen et al., 1983).

Almost no information is currently available concerning how BC affects existing soil C and N stocks, microbial activity, and N mineralization (Wardle et al., 2008; Ippolito et al., 2012). We found significant increases in TOC in all soils with BC, but we did not differentiate whether this increase was from the C in BC or an increase in soil C. Biochar additions have been found to have a priming effect and accelerate decomposition of SOM (Liang et al., 2010; Cross and Sohi, 2011). We found a significant increase in RES with BC compared with the NUL control in the sand soils; this increase may have been from a priming effect. Compared with the silt loam (2.6%) and compact clay soils (1.85%), baseline C contents in these sand soils were low (0.11%), but SOM in the sand soils was likely minimally protected by physical and chemical processes (Six et al., 1998, 2002). In contrast to our findings for TOC and RES, we did not find PAN or Nmin to be affected by BC. Berglund et al. (2004) found increased nitrification with activated C in laboratory trials but not in field soils. They also found activated C plus glycine (a simple amino acid that is readily mineralized to NH_4^+) to further stimulate N mineralization. Likewise, Gundale and DeLuca (2007) found increased Nmin with ponderosa pine- and Douglas fir-derived BC, but only when it was combined with glycine. Nitrogen immobilization is a commonly raised concern with BC due to its relatively high C/N ratio (Amonette et al., 2009; Chan and Xu, 2009). The BC in this research had low N content (0.4%) and high C/N ratio (160/1), which may be responsible for the nonresponses observed in PAN and Nmin with BC. It should be noted that BC is relatively recalcitrant, and thus the total C and N content may not accurately reflect what is actually available for microbial metabolism (Gundale and DeLuca, 2007). Biochar has been found to have a liming effect and increase soil pH (Verheijen et al., 2010). We did not observe changes in soil pH with BC. Starting soil pH values were high and rose during the experiment across all treatments, likely due to the alkaline nature of the irrigation water. We suspect that inherently high soil pH and buffering capacities were sufficient to mask any differences in pH that may have been induced from BC, which had a pH of 9.18.

Many researchers have reported beneficial effects of COM mulches on soil properties related to nutrient retention, SOM quality, and microbial activity (Tiquia et al., 2002; Rivero et al., 2004; Mulumba and Lal, 2008). Few studies have examined the effects of WC mulches on soil properties, but those that have report increases in soil nutrients and microbial activity with WC mulch (Litzow and Pellett, 1983; Arthur and Wang, 1999). As expected, both COM and WC increased total organic C in all soils (except WC in silt loam). The silt loam soils had the highest TOC contents, so a dampened response for TOC in these soils was reasonable. Similar to the effects of BC, we observed increased RES in only the sand soils with COM and WC. We suspect a similar mechanism of increased RES with COM and WC associated with priming of unprotected SOM. Soil pH, PAN, and Nmin were not significantly different with COM and WC compared with NUL in these soils. We suspect soil pH did not differ with COM and WC due to the already-discussed high pH values and soil buffering. Similar to BC, both COM and WC had comparatively higher C/N ratios (22/1 and

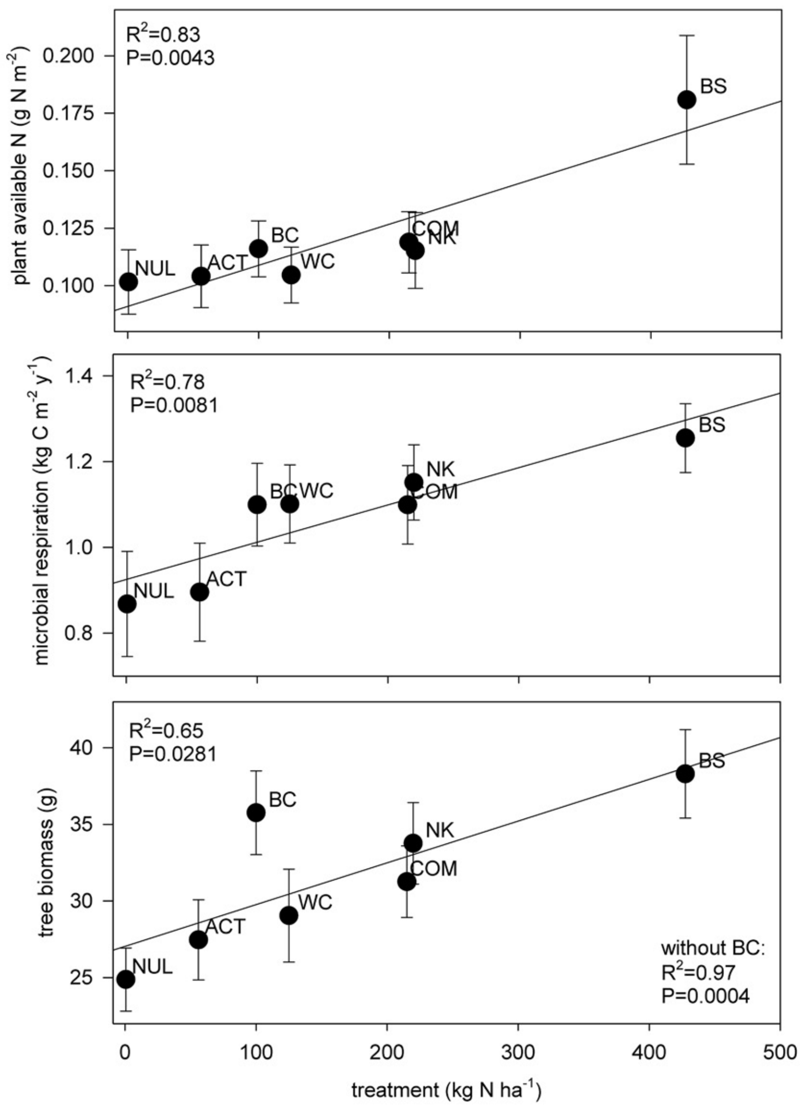

Fig. 5. Plant-available N, microbial respiration, and total tree biomass by N applied in seven treatments: control (NUL), NK fertilizer (NK), aerated compost tea (ACT), compost (COM), wood chips (WC), biochar (BC), and biosolids (BS). Means across three soil types (silt loam, compact clay, and sand) and two species (*Acer saccharum* and *Gleditsia triacanthos*). R^2 and *P* values are given.

92/1, respectively) than the BS (10/1), likely responsible for the no effects we observed in PAN and Nmin with these materials.

Increased RES was observed with the NK fertilizer compared with NUL control for the compact clay and sand soils. Increases in RES with inorganic N fertilization have been reported (Dick, 1992). Short-term increases in RES with N fertilization have been attributed to increases in growth, litter inputs, and rhizodeposition (Bowden et al., 2004). We did not observe an increase in RES with NK in our silt loam soils. The higher background levels of RES in the silt loam soils may have masked any observable NK treatment response and/or microbial activity may have been limited by N supply in the sand and compact clay soils. Van Cleve and Moore (1978) found increased RES with NPK fertilization and attributed those increases to increased N, P, and also SOM levels in the soil. An important and commonly cited effect of N fertilization is soil acidification (Bünemann et al., 2006). However, we did not observe any changes in soil pH with this NK fertilizer compared with the NUL treatment. Likewise, we were surprised that the NK fertilizer did not affect PAN or Nmin. Because we did not observe changes in PAN or Nmin with the NK fertilizer, we suspect the added N in inorganic fertilizer was taken up by the trees, immobilized by microbes, or lost via volatilization (Bouwman et al., 2002). It could also be that the N was lost via leaching, but we did not observe any significant differences in NO_3^- leaching among these treatments.

The ACT did not affect any soil properties. Few studies are available for comparison for the effects of ACT on soil properties. Those studies that have been performed on the effects of ACT on soil properties have found minimal impacts. Hargreaves et al. (2008) found no differences in soil nutrients (Ca^{2+}, Mg^{2+}, and K^+) after applying nonaerated compost teas made from municipal waste and ruminant compost. Scharenbroch et al. (2011) found no changes in soil pH, available nutrients (Ca^{2+}, Mg^{2+}, K^+, NH_4^+, NO_3^-, dissolved organic N), total C and N, microbial biomass N, microbial respiration, and N mineralization with 22.4 kL ACT ha^{-1} compared with a water control in A and Bt horizon soils. Scharenbroch, (2013) found increases in soil K^+ and microbial biomass N, and decreases in plant available N at application rates of 400 kL ACT ha^{-1} but no changes in 17 other soil properties at this or lesser application rates of ACT. The application of ACT in this experiment was 100 kL ACT ha^{-1}, and our results are in agreement with these other studies, finding minimal impacts of ACT on soil properties.

Nutrient Leaching

Nutrient leaching losses are a concern with both inorganic and organic fertilizers (Eghball et al., 1996; Bergström and Kirchmann, 1999). Inorganic fertilizer salts are soluble, thus nutrients are immediately available for uptake, and also thought to be more prone to leaching losses (Smith and Hadley, 1989). However, nutrients may be released from organic materials at times when plant uptake is low (Havlin et al., 2005). Biosolids are nutrient-rich and many studies have reported significant increases in nutrient leaching with their applications (Medalie et al., 1994). Studies often report decreases in nutrient leaching with additions of BC due to its high adsorption capacity (Lehmann et al., 2003; Laird et al., 2010; Singh et al., 2010). Altland and Locke, (2012) found BC amendments to be effective at moderating extreme levels of nitrate in container substrates over time. We are aware of only one study that has examined nutrient leaching with ACT. Scharenbroch, (2013) found no differences in NO_3^- leaching with five ACT application rates (0, 2, 4, 40, and 400 kL ACT ha^{-1}).

We found low concentrations of NO_3^- in leachates and no significant differences among the five organic treatments, inorganic fertilizer, and control. The N applied in these treatments (38–428 kg N ha^{-1} yr^{-1}) was within the range of specifications for N demands for urban trees (Smiley et al., 2002), so it is reasonable to expect that the majority of the added N was taken up by trees. Nitrogen not taken up by trees may have been immobilization by microbes, retained on the soil exchange sites, or possibly lost through volatilization. Moderate rates of dentrification may have occurred in these alkaline soils; however, the moisture contents were maintained below saturation, which is ideal for dentrification (Bremner and Shaw, 1958).

We observed increased DOC in leachates with BS and COM. Kaschl et al. (2002) found increases in water-soluble organic matter with municipal solid waste compost below the rooting zone in sandy soils but also found significantly reduced mobility of dissolved organic matter in loamy soils. They found that the vertical displacement of trace metals (Cu, Ni, and Zn) in calcareous soils resulted primarily from the presence of mobile metal–organic complexes in the soil solution after compost addition. The increases in DOC we observed with BS and COM may be important considering others have reported increases in metal mobility with municipal solid waste compost (Zhou and Wong, 2001; Madrid et al., 2007). We did not specifically measure metal concentrations in leachates, and further studies are needed to examine the risk of metal leaching with DOC in urban soils treated with these materials.

Management Implications

Our tree biomass models suggest increases in tree growth are coupled with increases in soil N and microbial activity. Positive feedbacks among tree growth, soil nutrients, and microbial activity are well established in the research literature (Grayston et al., 1997; Binkley and Giardina, 1998). Furthermore, we found the N added in treatments explained positive responses in soil and tree properties. Tree growth is known to be limited by N supply, especially on poorly developed soils with low fertility (Vitousek and Farrington, 1997). Future research should quantify in more detail the uptake and movement of N in the trees, specific pools of soil N, and potential N loss pathways to better identify mechanisms for increased tree and microbial growth with these treatments.

In this research, two organic mulches, BS and BC, appeared to have greatest impact on tree growth and soil properties. As discussed above, organic mulches have broad impacts on soil physical, chemical, and biological properties. In this study, urban tree growth appeared to be limited by N supply. This was particularly evident with the BS treatment, in which we observed the greatest increases in tree growth and also the greatest amount of N supplied. However, other factors not measured in this study (e.g., aggregation, porosity, water and air distribution and flow, other macro- and micronutrients, and potential contaminants) may have been impacted by these treatments with subsequent effects on tree growth. In particular, it did not appear that the N applied in the BC was a strong predictor of tree biomass. We suspect increases in tree growth with BC may have been derived from a combination of many of these effects. Spokas et al. (2012) pointed out that nutrient supply alone is not sufficient to explain all plant responses after BC amendments. Future research should assess the effects of these organic mulches on these additional soil properties in field-based and longer-term research.

Tree biomass with both BS and BC exceeded or was equal to what was observed with the NK fertilizer at the standard application rate of 220 kg N ha^{-1} yr^{-1} (Smiley et al., 2002). The N applied in this experiment with BS and BC was 427 and 193 kg N ha^{-1} yr^{-1}, respectively. No standards currently exist for either BS and BC application to urban trees, but these findings and those of others suggest BS and BC be applied as top-dressings or mulches at moderate rates (<75 Mg ha^{-1}) (Spokas et al., 2012). As a starting point, application rates for these products could be computed based by matching the N content of the material with the tree demand. Assuming the tree demand of 220 kg N ha^{-1} yr^{-1}, appropriate application rates for BS and BC may be 13 and 55 Mg ha^{-1} yr^{-1}, respectively.

The use of BS and BC for urban tree and soil management is attractive given the many potential environment benefits. Both are generated from waste products, and land applications would divert materials that may otherwise end up in landfills. MacFarlane, (2009) estimated that 54% of annual yields from urban trees and yard trimmings in the United States may be going to landfills. In the United States, more than 180 million Mg of municipal solid waste is generated per year, with about 21 million Mg from wood waste and 12 million Mg from urban trees and yard wastes (McKeever, 1999; McKeever and Skog, 2003).

Biochar has additional potential benefits of bioenergy production and C sequestration. Urban forestry and arboriculture might be well suited for mobile fast-pyrolysis systems that could convert urban wood waste into bio-oil, syngas, and BC (Bridgewater, 2004). Units could be strategically located at or near biomass removal locations to convert low-value urban wood waste into easily stored and transportable fuel to be used for heat, power, and chemical production (Garcia-Perez et al., 2007). The BC produced could then be returned to the site as a means for improving urban soil quality and storing C in soil (Lehmann, 2007). Research is still in its infancy on the economic feasibility of bioenergy production systems and BC application using residual woody biomass from forest management activities (McElligott et al., 2011), but these efforts may be useful for adaption to the urban forest wood utilization.

Questions remain pertaining to the potential environmental contamination with BS (e.g., various organic compounds, pharmaceuticals, trace metals) (Clarke and Smith, 2011; Lu et al., 2012). Similar concerns have been identified with BC (e.g., polycyclic aromatic hydrocarbons, trace metals), but some recent findings report BC to enhance sorption of these contaminants, essentially reducing their bioavailability (Beesley et al., 2010; Chen and Yuan, 2011; Gomez-Eyles et al., 2011). More research is required regarding the persistence and toxicity of these potential contaminants before implementing a BS or BC program for managing urban soils for trees.

Conclusions

This study found that BC and BS are acceptable, and possibly preferable, soil improvement mulching materials compared with more commonly applied materials (N fertilizer, COM, WC, and ACT). Biosolids decreased soil pH and increased tree growth, available N, N mineralization, and microbial respiration. Increased tree growth and total organic C were found with BC. Nitrate losses in leachates were minimal with all treatments, but we did observe increases in leachate dissolved organic C with BS and COM. Tree growth was best modeled with soil N availability and microbial respiration. The N content in the treatments appeared to be an important predictor for tree growth for all treatments except BC, suggesting the effects of BC for soil quality improvement are not limited to N supply. Biosolids and BC applied to urban landscapes would divert materials from landfills. This research provides support that these materials would also improve soil quality and tree growth.

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References

Al-Mughrabi, K.I. 2007. Suppression of phytophthora infestans in potatoes by foliar application of food nutrients and compost tea. Aust. J. Basic Appl. Sci. 1:785–792.

Altland, J.E., and J.C. Locke. 2012. Biochar affects macronutrient leaching from a soilless substrate. HortScience 47:1136–1140.

American Association of State Highway and Transportation Officials. 2012. Moisture-density relations of soils using a 2.5-kg (5.5-lb) rammer and a 305-mm (12-in.) drop. Standard specifications for transportation materials and methods of sampling and testing. Vol. 2A. 32nd ed. T-99-10. AASHTO, Washington, DC.

American National Standards Institute. 1998. Tree care operations—Tree, shrub, and other woody plant maintenance—Standard practices (fertilization). A300 (Part 2) 1998. ANSI, New York. p. 1–14.

Amonette, J.E., and S. Joseph. 2009. Characteristics of biochar: Microchemical properties. In: J. Lehmann and S. Joseph editors, Biochar for environmental management: Science and technology. Earthscan, London. p. 33–52.

Antal, M.J., and M. Grønli. 2003. The art, science, and technology of charcoal production. Ind. Eng. Chem. Res. 42:1619–1640. doi:10.1021/ie0207919

Arnold, M.A., G.V. McDonald, and D.L. Bryan. 2005. Planting depth and mulch thickness affect establishment of green ash (*Fraxinus pennsylvanica*) and bougainvillea goldenraintree (*Koelreuteria bipinnata*). J. Arboric. 31:168–170.

Arthur, M.A., and Y. Wang. 1999. Soil nutrients and microbial biomass following weed-control treatments in a Christmas tree plantation. Soil Sci. Soc. Am. J. 63:629–637. doi:10.2136/sssaj1999.03615995006300030028x

Beecher, N., E. Harrison, N. Goldstein, M. McDaniel, P. Field, and L. Susskind. 2005. Risk perception, risk communication, and stakeholder involvement for biosolids management and research. J. Environ. Qual. 34:122–128.

Beesley, L., E. Moreno-Jiménez, and J.L. Gomez-Eyles. 2010. Effects of biochar and greenwaste compost amendments on mobility, bioavailability, and toxicity of inorganic and organic contaminants in a multi-element polluted soil. Environ. Pollut. 158:2282–2287. doi:10.1016/j.envpol.2010.02.003

Berglund, L., T. DeLuca, and O. Zackrisson. 2004. Activated carbon amendments to soil alters nitrification rates in scots pine forests. Soil Biol. Biochem. 36:2067–2073. doi:10.1016/j.soilbio.2004.06.005

Bergström, L.F., and H. Kirchmann. 1999. Leaching of total nitrogen from nitrogen-15-labeled poultry manure and inorganic nitrogen fertilizer. J. Environ. Qual. 28:1283–1290. doi:10.2134/jeq1999.00472425002800040032x

Beyer, L., E. Cordsen, H.-P. Blume, U. Schleuss, B. Vogt, and Q. Wu. 1996. Soil organic matter composition in urbic anthrosols in the city of Kiel, NW-Germany, as revealed by wet chemistry and CPMAS 13C-NMR spectroscopy of whole soil samples. Soil Technol. 9:121–132. doi:10.1016/S0933-3630(96)00007-4

Binkley, D., and C. Giardina. 1998. Why do tree species affect soils? The warp and woof of tree–soil interactions. Biogeochemistry 42:89–106. doi:10.1023/A:1005948126251

Bouwman, A.F., L.J.M. Boumans, and N.H. Batjes. 2002. Emissions of N_2O and NO from fertilized fields: Summary of available measurement data. Global Biogeochem. Cycles 16:1058–1071.

Bowden, R.D., E. Davidson, K. Savage, C. Arabia, and P. Steudler. 2004. Chronic nitrogen additions reduce total soil respiration and microbial respiration in temperate forest soils at the harvard forest. For. Ecol. Manage. 196:43–56. doi:10.1016/j.foreco.2004.03.011

Bremner, J.M., and K. Shaw. 1958. Denitrification in soil: II. Factors affecting denitrification. J. Agric. Sci. 51:40–52. doi:10.1017/S0021859600032779

Bridgewater, A.V. 2004. Biomass fast pyrolysis. Thermal Sci. 8:21–50. doi:10.2298/TSCI0402021B

Brockway, D.G. 1983. Forest floor, soil, and vegetation responses to sludge fertilization in red and white pine plantations. Soil Sci. Soc. Am. J. 47:776–784. doi:10.2136/sssaj1983.03615995004700040033x

Bünemann, E.K., G.D. Schwenke, and L. Van Zwieten. 2006. Impact of agricultural inputs on soil organisms: A review. Soil Res. 44:379–406. doi:10.1071/SR05125

Burton, T.M., and J.E. Hook. 1979. A mass balance study of application of municipal waste water to forests in Michigan. J. Environ. Qual. 8:589–596. doi:10.2134/jeq1979.00472425000800040030x

Chadwick, L.C. 1935. The fertilization of shade trees in the nursery. Proc. Am. Soc. Hortic. Sci. 32:357–360.

Chadwick, L.C. 1937. Fertilizer trials with shade trees in the nursery. Proc. Am. Soc. Hortic. Sci. 34:664–668.

Chalker-Scott, L. 2007. Impact of mulches on landscape plants and the environment: A review. J. Environ. Hortic. 25:239–249.

Chan, K., L. Van Zwieten, I. Meszaros, A. Downie, and S. Joseph. 2008. Agronomic values of greenwaste biochar as a soil amendment. Soil Res. 45:629–634.

Chan, K.Y., and Z. Xu. 2009. Biochar: Nutrient properties and their enhancement. In: J. Lehmann and S. Joseph, editors, Biochar for environmental management: Science and technology. Earthscan, London. p. 67–84.

Chen, B., and M. Yuan. 2011. Enhanced sorption of polycyclic aromatic hydrocarbons by soil amended with biochar. J. Soils Sediments 11:62–71. doi:10.1007/s11368-010-0266-7

Chidumayo, E. 1994. Effects of wood carbonization on soil and initial development of seedlings in Miombo woodland, Zambia. For. Ecol. Manage. 70:353–357. doi:10.1016/0378-1127(94)90101-5

Clarke, B.O., and S.R. Smith. 2011. Review of "emerging" organic contaminants in biosolids and assessment of international research priorities for the agricultural use of biosolids. Environ. Int. 37:226–247. doi:10.1016/j.envint.2010.06.004

Craul, P.J. 1999. Urban soils: Applications and practices. John Wiley & Sons, New York.

Cross, A., and S.P. Sohi. 2011. The priming potential of biochar products in relation to labile carbon contents and soil organic matter status. Soil Biol. Biochem. 43:2127–2134. doi:10.1016/j.soilbio.2011.06.016

Dick, R.P. 1992. A review: Long-term effects of agricultural systems on soil biochemical and microbial parameters. Agric. Ecosyst. Environ. 40:25–36. doi:10.1016/0167-8809(92)90081-L

Downie, A., A. Crosky, and P. Munroe. 2009. Physical properties of biochar. In: J. Lehmann and S. Joseph, editors, Biochar for environmental management: Science and technology. Earthscan, London. p. 13–32.

Duffy, B., C. Sarreal, S. Ravva, and L. Stanker. 2004. Effect of molasses on regrowth of *E. coli* o157:H7 and *Salmonella* in compost teas. Compost Sci. Util. 12:93–96.

Dutch, J., and R. Wolstenholme. 1994. The effects of sewage sludge application to a heathland site prior to planting with sitka spruce. For. Ecol. Manage. 66:151–163. doi:10.1016/0378-1127(94)90154-6

Eghball, B., G.D. Binford, and D.D. Baltensperger. 1996. Phosphorus movement and adsorption in a soil receiving long-term manure and fertilizer application. J. Environ. Qual. 25:1339–1343. doi:10.2134/jeq1996.00472425002500060024x

Epstein, E. 1975. Effect of sewage sludge on some soil physical properties. J. Environ. Qual. 4:139–142. doi:10.2134/jeq1975.00472425000400010033x

Epstein, E. 2003. Land application of sewage sludge and biosolids. CRC Press, Boca Raton, FL.

Epstein, E., J. Taylor, and R. Chancy. 1976. Effects of sewage sludge and sludge compost applied to soil on some soil physical and chemical properties. J. Environ. Qual. 5:422–426. doi:10.2134/jeq1976.00472425000500040021x

Erhart, E., and W. Hartl. 2003. Mulching with compost improves growth of blue spruce in Christmas tree plantations. Eur. J. Soil Biol. 39:149–156. doi:10.1016/S1164-5563(03)00030-X

Ezz El-Din, A.A., and S.F. Hendawy. 2010. Effect of dry yeast and compost tea on growth and oil content of *Borago officinalis* plant. Res. J. Agric. Biol. Sci. 6:424–430.

Ferrini, F., A. Fini, P. Frangi, and G. Amoroso. 2008. Mulching of ornamental trees: Effects on growth and physiology. Arboric. Urb. For. 34:157–162.

Finck, A. 1982. Fertilizers and fertilization: Introduction and practical guide to crop fertilization. Verlag Chemie, Deerfield Beach, FL.

Fraedrich, S.W., and D.L. Ham. 1982. Wood chip mulching around maples: Effect on tree growth and soil characteristics. J. Arboric. 8:85–89.

Fuentes, D., A. Valdecantos, J. Cortina, and V. Vallejo. 2007. Seedling performance in sewage sludge-amended degraded mediterranean woodlands. Ecol. Eng. 31:281–291. doi:10.1016/j.ecoleng.2007.09.001

Garcia-Perez, M., A. Chaala, H. Pakdel, D. Kretschmer, and C. Roy. 2007. Characterization of bio-oils in chemical families. Biomass Bioenergy 31:222–242. doi:10.1016/j.biombioe.2006.02.006

Gilman, E.F., and J. Grabosky. 2004. Mulch and planting depth affect live oak (*Quercus virginiana* Mill.) establishment. J. Arboric. 30:311–317.

Gilmour, J.T., C.G. Cogger, L.W. Jacobs, G.K. Evanylo, and D.M. Sullivan. 2003. Decomposition and plant-available nitrogen in biosolids. J. Environ. Qual. 32:1498–1507. doi:10.2134/jeq2003.1498

Glaser, B., J. Lehmann, and W. Zech. 2002. Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal: A review. Biol. Fertil. Soils 35:219–230. doi:10.1007/s00374-002-0466-4

Gomez-Eyles, J.L., T. Sizmur, C.D. Collins, and M.E. Hodson. 2011. Effects of biochar and the earthworm *Eisenia fetida* on the bioavailability of polycyclic aromatic hydrocarbons and potentially toxic elements. Environ. Pollut. 159:616–622. doi:10.1016/j.envpol.2010.09.037

Grayston, S.J., D. Vaughan, and D. Jones. 1997. Rhizosphere carbon flow in trees, in comparison with annual plants: The importance of root exudation and its impact on microbial activity and nutrient availability. Appl. Soil Ecol. 5:29–56. doi:10.1016/S0929-1393(96)00126-6

Gundale, M.J., and T.H. DeLuca. 2007. Charcoal effects on soil solution chemistry and growth of *Koeleria macrantha* in the ponderosa pine/Douglas-fir ecosystem. Biol. Fertil. Soils 43:303–311. doi:10.1007/s00374-006-0106-5

Hargreaves, J.C., M. Sina Adl, and P.R. Warman. 2009a. Are compost teas an effective nutrient amendment in the cultivation of strawberries? Soil and plant tissue effects. J. Sci. Food Agric. 89:390–397. doi:10.1002/jsfa.3456

Hargreaves, J.C., M. Sina Adl, and P.R. Warman. 2009b. The effects of municipal solid waste compost and compost tea on mineral element uptake and fruit quality of strawberries. Compost Sci. Util. 17:85–94.

Hargreaves, J.C., M. Sina Adl, P.R. Warman, and H.P. Vasantha Rupasinghe. 2008. The effects of organic amendments on mineral element uptake and fruit quality of raspberries. Plant Soil 308:213–226. doi:10.1007/s11104-008-9621-5

Harrison, E.Z., S.R. Oakes, M. Hysell, and A. Hay. 2006. Organic chemicals in sewage sludges. Sci. Total Environ. 367:481–497. doi:10.1016/j.scitotenv.2006.04.002

Harrison, R.B., S.P. Gessel, D. Zabowski, C.L. Henry, D. Xue, and D.W. Cole. 1996. Mechanisms of negative impacts of three forest treatments on nutrient availability. Soil Sci. Soc. Am. J. 60:1622–1628. doi:10.2136/sssaj1996.03615995006000060005x

Harrison, R.B., C.L. Henry, and D. Xue. 1994. Magnesium deficiency in Douglas-fir and grand fir growing on a sandy outwash soil amended with sewage sludge. Water Air Soil Pollut. 75:37–50. doi:10.1007/BF01100397

Havlin, J.L., J.D. Beaton, S.L. Tisdale, and W.L. Nelson. 2005. Soil fertility and fertilizers: An introduction to nutrient management. Pearson Prentice Hall, Upper Saddle River, NJ.

Hendawy, S.F. 2008. Comparative study of organic and mineral fertilization of *Plantago arenaria* plant. J. Appl. Sci. Res. 4:500–506.

Henry, C.L., D.W. Cole, and R.B. Harrison. 1994. Use of municipal sludge to restore and improve site productivity in forestry: The pack forest sludge research program. For. Ecol. Manage. 66:137–149. doi:10.1016/0378-1127(94)90153-8

Hensley, D.L., R.E. McNiel, and R. Sundheim. 1988. Management influences on growth of transplanted *Magnolia grandiflora*. J. Arboric. 14:204–207.

Himelick, E.B., D. Neely, and W.R. Crowley. 1965. Experimental field studies on shade tree fertilization. Illinois Natural History Survey. Biological Notes 53. Univ. of Illinois, Champaign.

Hockaday, W.C., A.M. Grannas, S. Kim, and P.G. Hatcher. 2006. Direct molecular evidence for the degradation and mobility of black carbon in soils from ultrahigh-resolution mass spectral analysis of dissolved organic matter from a fire-impacted forest soil. Org. Geochem. 37:501–510. doi:10.1016/j.orggeochem.2005.11.003

Huntley, E.E., V. Barker Allen, and M.L. Stratton. 1997. Composition and uses of organic fertilizers. In: J.E. Rechicigl, and H.C. MacKinnon, editors, Agricultural uses of by-products and wastes. American Chemical Society, Washington, DC. p. 120–139.

Ippolito, J.A., D.A. Laird, and W.J. Busscher. 2012. Environmental benefits of biochar. J. Environ. Qual. 41:967–972. doi:10.2134/jeq2012.0151

Jim, C.Y. 1998. Physical and chemical properties of a Hong Kong roadside soil in relation to urban tree growth. Urban Ecosyst. 2:171–181. doi:10.1023/A:1009585700191

Kaschl, A., V. Römheld, and Y. Chen. 2002. The influence of soluble organic matter from municipal solid waste compost on trace metal leaching in calcareous soils. Sci. Total Environ. 291:45–57. doi:10.1016/S0048-9697(01)01091-9

Khan, S.K., R.L. Mulvaney, T.R. Ellsworth, and C.W. Boast. 2007. The myth of nitrogen fertilization for soil carbon sequestration. J. Environ. Qual. 36:1821–1832. doi:10.2134/jeq2007.0099

Laird, D., P. Fleming, B. Wang, R. Horton, and D. Karlen. 2010. Biochar impact on nutrient leaching from a midwestern agricultural soil. Geoderma 158:436–442. doi:10.1016/j.geoderma.2010.05.012

Larkin, R.P. 2008. Relative effects of biological amendments and crop rotations on soil microbial communities and soilborne diseases of potato. Soil Biol. Biochem. 40:1341–1351. doi:10.1016/j.soilbio.2007.03.005

Lehmann, J. 2007. A handful of carbon. Nature 447:143–144. doi:10.1038/447143a

Lehmann, J., J.P. da Silva, Jr., C. Steiner, T. Nehls, W. Zech, and B. Glaser. 2003. Nutrient availability and leaching in an archaeological anthrosol and a ferralsol of the central Amazon basin: Fertilizer, manure and charcoal amendments. Plant Soil 249:343–357. doi:10.1023/A:1022833116184

Lehmann, J., J. Gaunt, and M. Rondon. 2006. Bio-char sequestration in terrestrial ecosystems: A review. Mitig. Adapt. Strategies Glob. Change 11:395–419. doi:10.1007/s11027-005-9006-5

Lehmann, J., M.C. Rillig, J. Thies, C.A. Masiello, W.C. Hockaday, and D. Crowley. 2011. Biochar effects on soil biota: A review. Soil Biol. Biochem. 43:1812–1836. doi:10.1016/j.soilbio.2011.04.022

Lehmann, J., and M. Rondon. 2006. Bio-char soil management on highly weathered soils in the humid tropics. CRC Press, Boca Raton, FL.

Lerch, R., K. Barbarick, L. Sommers, and D. Westfall. 1992. Sewage sludge proteins as labile carbon and nitrogen sources. Soil Sci. Soc. Am. J. 56:1470–1476. doi:10.2136/sssaj1992.03615995005600050022x

Liang, B., J. Lehmann, S.P. Sohi, J.E. Thies, B. O'Neill, and L. Trujillo. 2010. Black carbon affects the cycling of non-black carbon in soil. Org. Geochem. 41(2):206–213. doi:10.1016/j.orggeochem.2009.09.007

Liang, B., J. Lehmann, D. Solomon, J. Kinyangi, J. Grossman, and B. O'Neill. 2006. Black carbon increases cation exchange capacity in soils. Soil Sci. Soc. Am. J. 70:1719–1730. doi:10.2136/sssaj2005.0383

Litzow, M., and H. Pellett. 1983. Influence of mulch materials on growth of green ash. J. Arboric. 9:7–12.

Lu, Q., Z.L. He, and P.J. Stoffella. 2012. Land application of biosolids in the USA: A review. Appl. Environ. Soil Sci. 11: 10.1155/2012/201462.

Luxmoore, R., M. Tharp, and R. Efroymson. 1999. Comparison of simulated forest responses to biosolids applications. J. Environ. Qual. 28:1996–2007. doi:10.2134/jeq1999.00472425002800060041x

MacFarlane, D.W. 2009. Potential availability of urban wood biomass in Michigan: Implications for energy production, carbon sequestration, and sustainable forest management in the U.S.A. Biomass Bioenergy 33:628–634. doi:10.1016/j.biombioe.2008.10.004

Madrid, F., R. López, and F. Cabrera. 2007. Metal accumulation in soil after application of municipal solid waste compost under intensive farming conditions. Agric. Ecosyst. Environ. 119:249–256. doi:10.1016/j.agee.2006.07.006

Major, J. 2010. Guidelines on practical aspects of biochar application to field soil in various soil management systems. Version 1.0. International Biochar Initiative, Westerville, OH.

McCune, B. 2006. Non-parametric habitat models with automatic interactions. J. Veg. Sci. 17:819–830. doi:10.1111/j.1654-1103.2006.tb02505.x

McDonald, M., B. Hawkins, C. Prescott, and J. Kimmins. 1994. Growth and foliar nutrition of western red cedar fertilized with sewage sludge, pulp sludge, fish silage, and wood ash on northern Vancouver Island. Can. J. For. Res. 24:297–301. doi:10.1139/x94-042

McElligott, K.M., D.S. Page-Dumroese, M. Coleman, and K. McElligott. 2011. Bioenergy production systems and biochar application in forests: Potential for renewable energy, soil enhancement, and carbon sequestration. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO.

McGill, W., and C. Cole. 1981. Comparative aspects of cycling of organic C, N, S, and P through soil organic matter. Geoderma 26:267–286. doi:10.1016/0016-7061(81)90024-0

McKeever, D.B. 1999. How woody residuals are recycled in the United States. BioCycle 40:33–44.

McKeever, D.B., and K. Skog. 2003. Urban tree and woody yard residues: Another wood resource. USDA Forest Service, Forest Products Laboratory, Madison, WI.

Medalie, L., W.B. Bowden, and C.T. Smith. 1994. Nutrient leaching following land application of aerobically digested municipal sewage sludge in a northern hardwood forest. J. Environ. Qual. 23:130–138. doi:10.2134/jeq1994.00472425002300010021x

Montague, T., C. McKenney, M. Maurer, and B. Winn. 2007. Influence of irrigation volume and mulch on establishment of select shrub species. Arboric. Urb. For. 33:202–209.

Mulumba, L.N., and R. Lal. 2008. Mulching effects on selected soil physical properties. Soil Tillage Res. 98:106–111. doi:10.1016/j.still.2007.10.011

Nelson, D.W., and L.E. Sommers. 1996. Total carbon, organic carbon, and organic matter. In: D.L. Sparks, editor, Methods of soil analysis. Part 2. SSSA, Madison, WI. p. 961–1010.

Novak, J.M., W.J. Busscher, D.L. Laird, M. Ahmedna, D.W. Watts, and M.A. Niandou. 2009. Impact of biochar amendment on fertility of a southeastern coastal plain soil. Soil Sci. 174:105–112. doi:10.1097/SS.0b013e3181981d9a

Pant, A.P., T.J.K. Radovich, N.V. Hue, and N.Q. Arancon. 2011. Effects of vermicompost tea (aqueous extract) on pak choi yield, quality, and soil biological properties. Compost Sci. Util. 19:279–292.

Pant, A.P., T.J.K. Radovich, N.V. Hue, S.T. Talcott, and K.A. Krenek. 2009. Vermicompost extracts influence growth, mineral nutrients, phytonutrients and antioxidant activity in pak choi (*Brassica rapa* cv. Bonsai, *Chinensis* group) grown under vermicompost and chemical feriliser. J. Sci. Food Agric. 89:2383–2392. doi:10.1002/jsfa.3732

Parkin, T.B., J.W. Doran, and E. Franco-Vizcaino. 1996. Field and laboratory tests of soil respiration. In: J.W. Doran and A.J. Jones, editors, Methods for assessing soil q. SSSA, Madison, WI. p. 231–245.

Patterson, J.C. 1977. Soil compaction: Effects on urban vegetation. J. Arboric. 3:161–167.

Pepper, I.L., J.P. Brooks, and C.P. Gerba. 2006. Pathogens in biosolids. Adv. Agron. 90:1–41. doi:10.1016/S0065-2113(06)90001-7

Pietikäinen, J., O. Kiikkilä, and H. Fritze. 2000. Charcoal as a habitat for microbes and its effect on the microbial community of the underlying humus. Oikos 89:231–242. doi:10.1034/j.1600-0706.2000.890203.x

Prescott, C.E., and L.L. Blevins. 2005. Eleven-year growth response of young conifers to biosolids or nitrogen and phosphorus fertilizer on northern Vancouver island. Can. J. For. Res. 35:211–214. doi:10.1139/x04-146

Puglisi, E., G. Fragoulis, A.A.M. Del Re, R. Spaccini, A. Piccolo, and G. Gigliotti. 2008. Carbon deposition in soil rhizosphere following amendments with compost and its soluble fractions, as evaluated by combined soil-plant rhizobox and reporter gene systems. Chemosphere 73:1292–1299. doi:10.1016/j.chemosphere.2008.07.008

Rhoades, J., F. Chanduvi, and S. Lesch. 1999. Soil salinity assessment: Methods and interpretation of electrical conductivity measurements. Irrigation and Drainage Paper 57. FAO, Rome.

Rice, W.R. 1989. Analyzing tables of statistical tests. Evolution 43:223–225. doi:10.2307/2409177

Rivero, C., T. Chirenje, L.Q. Ma, and G. Martinez. 2004. Influence of compost on soil organic matter quality under tropical conditions. Geoderma 123:355–361. doi:10.1016/j.geoderma.2004.03.002

Roberts, B.R. 2006. Compost-containing substrates and their effect on posttransplant growth of containerized tree seedlings. Arboric. Urb. For. 32:289–296.

Robertson, S.J., P.M. Rutherford, J.C. López-Gutiérrez, and H.B. Massicotte. 2012. Biochar enhances seedling growth and alters root symbioses and properties of sub-boreal forest soils. Can. J. Soil Sci. 92:329–340. doi:10.4141/cjss2011-066

Rose, M.A. 1999. Nutrient use patterns in woody perennials: Implications for increasing fertilizer efficiency in field-grown and landscape ornamentals. HortTechnology 9:613–617.

Rumberger, A., S. Yao, I.A. Merwin, E.B. Nelson, and J.E. Thies. 2004. Rootstock genotype and orchard replant position rather than soil fumigation or compost amendment determine tree growth and rhizosphere bacterial community composition in an apple replant soil. Plant Soil 264:247–260. doi:10.1023/B:PLSO.0000047760.13004.94

Sæbø, A., and F. Ferrini. 2006. The use of compost in urban green areas–a review for practical application. Urban For. Urban Green. 4:159–169. doi:10.1016/j.ufug.2006.01.003

Scharenbroch, B.C. 2009. A meta-analysis of studies published in Arboriculture & Urban Forestry relating to organic materials and impacts on soil, tree, and environmental properties. Arboric. Urb. For. 35:221–231.

Scharenbroch, B.C. 2013. Impacts of aerated compost tea on containerized *Acer saccharum* and *Quercus macrocarpa* saplings and soil properties in sand, uncompacted loam, and compacted loam soils. HortScience 48:625–632.

Scharenbroch, B.C., and M. Catania. 2012. Soil quality attributes as indicators of urban tree performance. Arboric. Urb. For. 38:214–228.

Scharenbroch, B.C., J.E. Lloyd, and J.L. Johnson-Maynard. 2005. Distinguishing urban soils with physical, chemical, and biological properties. Pedobiologia 49:283–296. doi:10.1016/j.pedobi.2004.12.002

Scharenbroch, B.C., W. Treasurer, M. Catania, and V. Brand. 2011. Laboratory assays on the effects of aerated compost tea and fertilization on biochemical properties and denitrification in a silt loam and Bt clay loam soils. Arboric. Urb. For. 37:269–277.

Scheuerell, S.J., and W.F. Mahaffee. 2002. Compost tea: Principles and practices. Compost Sci. Util. 10:313–338.

Scheuerell, S.J., and W.F. Mahaffee. 2004. Compost tea as a container medium drench for suppressing seedling damping-off caused by *Pythium ultimum*. Phytopathology 94:1156–1163. doi:10.1094/PHYTO.2004.94.11.1156

Scheuerell, S.J., and W.F. Mahaffee. 2006. Variability associated with suppression of gray mold (*Botrytis cinerea*) on geranium by foliar applications of nonaerated and aerated compost teas. Plant Dis. 90:1201–1208. doi:10.1094/PD-90-1201

Segarra, G., M. Reis, E. Casanova, and M.I. Trillas. 2009. Control of powdery mildew (*Erysiphe polygoni*) in tomato by foliar applications of compost tea. J. Plant Pathol. 91:683–689.

Sikora, L.J., and V. Yakovchenko. 1996. Soil organic matter mineralization after compost amendment. Soil Sci. Soc. Am. J. 60:1401–1404. doi:10.2136/sssaj1996.03615995006000050015x

Silviera, D., and L. Sommers. 1977. Extractability of copper, zinc, cadmium, and lead in soils incubated with sewage sludge. J. Environ. Qual. 6:47–52. doi:10.2134/jeq1977.00472425000600010012x

Sims, G.K., T.R. Ellsworth, and R.L. Mulvaney. 1995. Microscale determination of inorganic nitrogen in water and soil extracts. Commun. Soil Sci. Plant Anal. 26:303–316. doi:10.1080/00103629509369298

Singh, B.P., B.J. Hatton, B. Singh, A.L. Cowie, and A. Kathuria. 2010. Influence of biochars on nitrous oxide emission and nitrogen leaching from two contrasting soils all rights reserved. J. Environ. Qual. 39:1224–1235. doi:10.2134/jeq2009.0138

Six, J., R.T. Conant, and K. Paustian. 2002. Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. Plant Soil 241:155–176. doi:10.1023/A:1016125726789

Six, J., E. Elliott, K. Paustian, and J. Doran. 1998. Aggregation and soil organic matter accumulation in cultivated and native grassland soils. Soil Sci. Soc. Am. J. 62:1367–1377. doi:10.2136/sssaj1998.03615995006200050032x

Smiley, E.T., S. Lilly, and P. Kelsey. 2002. Tree and shrub fertilization. International Society of Arboriculture, Champaign, IL.

Smith, S., and P. Hadley. 1989. A comparison of organic and inorganic nitrogen fertilizers: Their nitrate-N and ammonium-N release characteristics and effects on the growth response of lettuce (*Lactuca sativa* L. cv. Fortune). Plant Soil 115:135–144. doi:10.1007/BF02220704

Sommers, L. 1977. Chemical composition of sewage sludges and analysis of their potential use as fertilizers. J. Environ. Qual. 6:225–232. doi:10.2134/jeq1977.00472425000600020026x

Sovu, M.T., P. Savadogo, and P.C. Odén. 2012. Facilitation of forest landscape restoration on abandoned swidden fallows in Laos using mixed-species planting and biochar application. Silva Fennica 46:39–51.

Spokas, K.A., K.B. Cantrell, J.M. Novak, D.W. Archer, J.A. Ippolito, and H.P. Collins. 2012. Biochar: A synthesis of its agronomic impact beyond carbon sequestration. J. Environ. Qual. 41:973–989. doi:10.2134/jeq2011.0069

Struve, D.K. 2002. A review of shade tree nitrogen fertilization research in the United States. J. Arboric. 28:252–263.

Terry, R., D. Nelson, and L. Sommers. 1979. Carbon cycling during sewage sludge decomposition in soils. Soil Sci. Soc. Am. J. 43:494–499. doi:10.2136/sssaj1979.03615995004300030013x

Thies, J., and M.C. Rillig. 2009. Characteristics of biochar: Biological properties. In: J. Lehmann and S. Joseph, editors, Biochar for environmental management: Science and technology. Earthscan, London. p. 85–105.

Tiquia, S.M., J. Lloyd, D.A. Herms, H.A. Hoitink, and F.C. Michel. 2002. Effects of mulching and fertilization on soil nutrients, microbial activity and rhizosphere bacterial community structure determined by analysis of TRFLPs of PCR-amplified 16s rRNA genes. Appl. Soil Ecol. 21:31–48. doi:10.1016/S0929-1393(02)00040-9

US Composting Council. 2001. Field guide to compost use. US Composting Council, Bethesda, MD.

U.S. Department of Agriculture Natural Resources Conservation Service. 2011. Mulching. Code 484. NRCS NHCP, Washington, DC.

U.S. Environmental Protection Agency. 1995. A guide to the biosolids risk assessment for the EPA Part 503 rule. EPA/823/B-93/005. USEPA, Washington, D.C.

U.S. Environmental Protection Agency. 2000. Biosolids technology fact sheet: Land application of biosolids. EPA 832-F-00-064. USEPA, Washington, DC.

Van Breemen, N., J. Mulder, and C. Driscoll. 1983. Acidification and alkalinization of soils. Plant Soil 75:283–308. doi:10.1007/BF02369968

Van Cleve, K., and T.A. Moore. 1978. Cumulative effects of nitrogen, phosphorus, and potassium fertilizer additions on soil respiration, pH, and organic matter content. Soil Sci. Soc. Am. J. 42:121–124. doi:10.2136/sssaj1978.03615995004200010026x

Verheijen, F., S. Jeffery, A.C. Bastos, M.V.D. Velde, and I. Diafas. 2010. Biochar application to soils: A critical scientific review of effects on soil properties, processes and functions. Office for the Official Publications of the European Communities, Luxembourg. p. 1–166.

Viator, H.P., J. Flanagan, L. Gaston, S. Hall, J. Hoy, and T. Hymel. 2008. The influence of post-harvest residue management on water quality and sugarcane yield in Louisiana. J. Am. Soc. Sugar Cane Technol. 28:76–85.

Vitousek, P.M., J.D. Aber, W.R. Howarth, G.E. Likens, P.A. Matson, and D.W. Schindler. 1997. Human alteration of the global nitrogen cycle: Sources and consequences. Ecol. Appl. 7:737–750.

Vitousek, P.M., and H. Farrington. 1997. Nutrient limitation and soil development: Experimental test of a biogeochemical theory. Biogeochemistry 37:63–75. doi:10.1023/A:1005757218475

Wardle, D.A., M.-C. Nilsson, and O. Zackrisson. 2008. Fire-derived charcoal causes loss of forest humus. Science 320:629. doi:10.1126/science.1154960

Wardle, D., O. Zackrisson, and M.-C. Nilsson. 1998. The charcoal effect in boreal forests: Mechanisms and ecological consequences. Oecologia 115:419–426. doi:10.1007/s004420050536

Watson, G.W. 1988. Organic mulch and grass competition influence tree root development. J. Arboric. 14:200–203.

Watson, G.W., and G. Kupkowski. 1991. Effects of a deep layer of mulch on the soil environment and tree root growth. J. Arboric. 17:242–245.

Welke, S. 2005. The effect of compost extract on yield of strawberries and severity of *Botrytis cinerea*. J. Sustain. Agric. 25:57–68. doi:10.1300/J064v25n01_06

Yao, S., I.A. Merwin, G.S. Abawi, and J.E. Thies. 2006. Soil fumigation and compost amendment alter soil microbial community composition but do not improve tree growth or yield in an apple replant site. Soil Biol. Biochem. 38:587–599. doi:10.1016/j.soilbio.2005.06.026

Yohalem, D.S., E.V. Nordheim, and J.H. Andrews. 1996. The effect of water extracts on spend mushroom compost on apple scab in the field. Phytopathology 86:914–922. doi:10.1094/Phyto-86-914

Zhou, L.X., and J.W.C. Wong. 2001. Effect of dissolved organic matter from sludge and sludge compost on soil copper sorption. J. Environ. Qual. 30:878–883. doi:10.2134/jeq2001.303878x