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Impacts of Aerated Compost Tea on Containerized *Acer saccharum* and *Quercus macrocarpa* Saplings and Soil Properties in Sand, Uncompacted Loam, and Compacted Loam Soils

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Abstract. **Aerated compost teas (ACTs) are applied to soils with the intent of improving microbial properties and nutrient availability and stimulating plant growth. Anecdotal accounts of ACT for these purposes far outnumber controlled, replicated, and peer-viewed experiments that have examined the impacts of ACT on soil properties and plant growth responses. This research assessed the impacts of four rates of ACT compared with water on containerized *Acer saccharum* and *Quercus macrocarpa* saplings growing in loam, compacted loam, and sandy soils. No significant differences were found comparing water with ACT applied at rates of 2, 4, and 40 kL ACT/ha for any of the six tree responses and 21 soil responses. Microbial biomass nitrogen (N) and potassium (K) increased, and available N decreased, in soils treated with ACT at 400 kL·ha^{-1} compared with water. Shoot, root, total biomass, and the root/shoot ratio were significantly greater for *Quercus macrocarpa* trees growing in compact loam with the 400 kL ACT/ha treatment compared with water, but significant differences were not detected for this application rate compared with water in the other soil types and in no instances with *Acer saccharum* saplings. These results provide some support for claims of ACT being able to increase soil microbial biomass and K, but provide minimal support for ACT being able to increase tree growth across multiple species in a variety of soil types. An application rate of 400 kL ACT/ha may be attainable for trees in containers with limited soil volumes, but this application rate is likely cost-prohibitive, and not practical, in the landscape. At this application rate, ≈1000 L of ACT would be required to treat a typical, and relatively small, critical root zone of 25 m^2.**

Soil nutrient management is important for tree establishment, growth, and longevity. Nutrients are most often supplied to trees in the greenhouses, nurseries, and landscapes by inorganic fertilizers. Nutrient management with inorganic fertilizers poses some environmental risks such as eutrophication of fresh water from phosphorus (P) loading (Soldat et al., 2009), acidification of soils and surface waters, eutrophication of coastal water, and groundwater contamination from N (Vitousek et al., 1997), reductions in soil quality through salt accumulation (Finck, 1982; Follett et al., 1981), decreases soil carbon (C) and N with long-term synthetic fertilization (Khan et al., 2007), and greenhouse gas production during fertilizer synthesis and after applications through denitrification (Vitousek et al., 1997).

Given the potential risk associated with inorganic fertilizers, organic fertilization is becoming more common for supplying nutrients to trees. Organic fertilizers contain organic matter and encompass a diverse group of materials (e.g., animal or green manure, peat, bone meal, biosolids, compost) (Finck, 1982). The majority of the nutrients in these fertilizers is organically bound and slowly mineralized, so the potential for exceeding plant nutrient demands and associated environmental contamination is reduced relative to synthetic fertilization (Stratton et al., 1995). Because organic fertilizers have lower quantities of immediately available N compared with synthetic fertilizers, they may be less likely to speed up C losses from soil through N stimulation of microbial respiration (Follett et al., 1981; Triberti et al., 2008). The use of organic materials as fertilizer promotes useful recycling and removes potentially noxious waste products (Finck, 1982).

Aerated compost teas are one such organic fertilizer becoming more widely used with the hopes of improving soil quality and managing tree nutrition. Aerated compost tea is made by mixing compost with aerated water (National Organic Standards Board, 2004). Aeration during the brewing process distinguishes ACT from other compost extracts and is important considering the goal of increasing aerobic microorganisms. According to the National Organic Program (NOP), the predominant ACT production method in the United States involves one part compost in 10 to 50 parts water, constant aeration for 12 to 24 h, and immediate application (National Organic Standards Board, 2004). NOP standards specify that compost used to make ACT must be made from allowable feedstock materials and the entire pile must undergo an increase in temperature to at least 131 °F for at least 3 d (National Organic Standards Board, 2002). ACT additives such as molasses, yeast extract, and algal powders are used to encourage growth of beneficial microbes but can also have non-target negative effects by supporting the growth of bacterial human pathogens from undetectable levels in properly made compost to detectable in ACT. The National Organic Standards Board (2004) specifies that ACT made with additives can be applied to ornamental plants, not intended for human consumption, and is exempt from U.S. Environmental Protection Agency standards for a bacterial indicator of fecal contamination.

A growing body of research has been examining the effects of compost teas or extracts on plant growth and disease suppression (e.g., Al-Mughrabi, 2007; Duffy et al., 2004; Ezz El-Din and Hendawy, 2010; Hargreaves et al., 2008, 2009a, 2009b; Hendawy, 2008; Larkin, 2008; Pant et al., 2009, 2011; Puglisi et al., 2008; Scheuerell and Mahaffee, 2002, 2004, 2006; Segarra et al., 2009; Viator et al., 2008; Welke, 2005; Yohalem et al., 1996). These studies have examined ACTs, non-ACTs, teas applied as foliar sprays or soil drenches, and teas with and without additives. 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 have focused on the specific impacts of ACT on soil quality (e.g., Hendawy, 2008; Larkin, 2008; Pant et al., 2009; Puglisi et al., 2008; Scharenbroch et al., 2011) and none have examined the impacts of ACT on examined tree growth. These studies have rarely compared ACT with water, which is known to be a major limiting factor for tree growth (e.g., Scharenbroch et al., 2011). Furthermore, no standards exist for application rates of ACT to trees. Current ACT application rates for agricultural and horticultural plants range from 4 to 400 kL ACT/ha (personal communication with E. Ingham formerly of Soil Foodweb, Inc., July 2008), albeit these rates are not based on scientific evidence.

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This experiment was conducted to determine the impacts on tree and soil properties of varying rates of ACT. Treatment effects were examined for two tree species (*Acer saccharum* and *Quercus macrocarpa*) and three soil types (sand, uncompacted loam, and compacted loam) over 20 months. Varying rates of ACT were examined against water as a control toward identifying an appropriate ACT application rate for trees in containerized settings.

Materials and Methods

The experiment was a full factorial with two species, three soil types, five treatments, and six replicates for a total of 180 experimental units. The two tree species were *Acer saccharum* and *Quercus macrocarpa* (planted as 1- to 2-cm caliper bare root saplings). Before planting, the main roots were pruned to a standardized 10 cm length, fine roots removed, and stems were pruned to a 30 cm length.

The three soil types were: a pure sand, an uncompacted loam (1.20 $Mg \cdot m^{-3}$), and a compacted loam soil (1.65 $Mg \cdot m^{-3}$). The loam soil was collected from a 2-m wide × 3-m deep pit on the grounds of The Morton Arboretum, Lisle, IL. The soil was from the A horizon (0 to 10 cm) of a fine, illitic, mesic Oxyaquic Hapludalf, Ozaukee series soil profile. The sand soil was playground sand purchased from a local retailer. Biochemical characteristics of the loam and sand soil are given (Table 1). Soil was air-dried in the laboratory, passed through a 2-mm sieve, and thoroughly homogenized. Soils were placed in microcosms (cylindrical polyvinyl chloride containers, 15 cm diameter × 25 cm height) in six lifts and compacted with a standard compaction drop hammer with 592.7 $kJ \cdot m^{-3}$ effort (American Association of State Highway and Transportation Officials, T-99). 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 loam soil.

Microcosm bottoms had drainage wicks to collect soil leachates and the tops were equipped for static measurements of surface CO_2 efflux. During the growing season (March through November), microcosms were maintained in a greenhouse at 20 °C with light regime of 14 light and 10 h dark. During this period, soil moisture contents were maintained at 15% to 20% volumetric moisture. Trees were moved to an outdoor Quonset hut for Nov. 2009 through Mar. 2010.

Treatments were applied monthly May through Oct. 2009 and 2010 for a total of 10 applications. ACT was diluted to the appropriate concentration and all microcosms received a total of 100 mL of ACT plus water solution for each treatment application. The total ACT applied for each treatment throughout the experiment was 0, 3.5, 7, 70, and 700 mL of ACT per tree. These rates equated to ≈0, 2, 4, 40, and 400 $kL \cdot ha^{-1}$ (0, 211, 423, 4,237, and 42,368 gal ACT/ac).

Aerated compost tea was made with a KIS compost tea brewer, 18.9 L (5 gal) (Keep It Simple, Inc., Redmond, WA). Deionized water (18.9 L) was combined with one commercially available package of compost (≈500 g) containing wood chips, sawdust, rock, minerals, fungal ingredients, humus, and vermicompost (KIS 5-gal compost tea brewing kit from Keep It Simple, Inc.). The compost contained 11,648 µg bacteria/g, 3,547 µg fungi/g (mean hyphae diameter of 2.8 µm), 18,883 flagellates/g, 14,596 amoebae/g, 11,338 ciliates/g, and 1.2 nematodes/g (analyses performed by Soil Foodweb, Inc., Corvallis, OR). A package (500 g) of microbial food 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 was added at the start of brew (Keep It Simple, Inc.). Humic acid (25 g) and soluble seaweed powder (25 g) were also added 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 $mg \cdot kg^{-1}$ with a mean value of 7.3 $mg \cdot kg^{-1}$ throughout the brew cycle. Mean temperature, pH, and EC were 21 °C, 4.9, and 2169 $\mu S \cdot cm^{-1}$, respectively. On average (10 brews), the ACT contained only a fraction of what was in the compost itself: 1972 µg bacteria/g, 4.9 µg fungi/g (mean hyphae diameter of 2.6 µm), 1920 flagellates/g, 1392 amoebae/g, 7.7 ciliates/g, and 0.1 nematodes/g. Biochemical characteristics of the water and ACT are given (Table 1).

Microcosms were flushed on 13 Apr. 2010, 27 May 2010, 29 June 2010, and 23 Aug. 2010 with 300 mL of deionized and the first 100 mL of leachates were collected, filtered, and analyzed for nitrate (NO_3^-) using ion chromatography (Metrohm 732/733 Detector and Separation Center, Riverview, FL). Surface CO_2 efflux was measured on 9 June 2009, 15 July 2009, 31 July 2009, 4 Sept. 2009, 13 Oct. 2009, 19 May 2010, 20 June 2010, and 21 July 2010 using static NaOH traps. CO_2 concentrations in the NaOH traps were determined by acid-base titration with HCl to a phenophalthein end point (Parkin et al., 1996).

Leaf color was assessed with a chlorophyll meter (Konica Minolta SPAD 502 Plus Chlorophyll Spectrum Technologies, Inc., Plainfield, IL) on 5 Aug. 2009, 2 June 2010, 29 June 2010, and 18 Aug. 2010. Five leaves per tree were measured and a mean of the five measurements was calculated. Stem calipers were measured at four cardinal directions at the start and end of the experiment at painted locations on the tree stems to compute diameter growth rates of each tree. In November of 2010, trees were carefully separated from the soils. Trees were washed with deionized water to remove all soil and all leaves were removed. Trees were cut at the root and shoot interface. Shoots and roots were dried at 60 °C for 5 d and then weighed to express shoot, root, total biomass, and the root to shoot ratio (R/S ratio).

At the conclusion of the experiment, soils were sampled from each microcosm. Soil penetration resistance was measured on the soil surface four directions at the midpoint of stem and edge of the microcosm using a pocket penetrometer (Model 29-3729; ELE International, Loveland, CO). Soil was then carefully removed from each microcosm and separated from tree roots. Soil ped size was measured on five random intact soil peds from each microcosm (mm). Soils were then passed through a 6-mm screen and homogenized for further characterization.

Gravimetric soil moisture content was determined by the mass loss after drying soil subsamples at 105 °C for 48 h (Black, 1965). Soil subsamples were extracted with 1 M NH_4OAc (pH 7.0) and $mg \cdot kg^{-1}$ of Ca^{2+}, Mg^{2+}, K^+, and Na^+ were determined with atomic adsorption spectroscopy (Model A5000; Perkin Elmer Inc., Waltham, MA) (Schollenberger and Simon, 1945). Soil P was determined with the Bray P-1 or Olsen extraction methods and analyzed colorimetrically at 882 nm on a spectrophotometer (Model ultraviolet mini 1240; Shidmadzu Inc., Kyoto, Japan) (Olsen and Sommers, 1982). Soil pH and EC in $\mu s \cdot cm^{-1}$ were measured in 1:1 (soil:deionized water) pastes (Model Orion 5-Star; Thermo Fisher Scientific Inc., Waltham, MA). Total organic matter was determined by loss-on-ignition at

Table 1. Biochemical characteristics of loam, sand, water, and aerated compost tea (ACT).

Response	Loam soil	Sand soil	Water	ACT
pH	7.09 (0.1)[z]	8.89 (0.2)	7.52 (0.4)	4.88 (0.1)
EC ($dS \cdot m^{-1}$)	46.7 (5.0)	44.3 (2.2)	4.80 (0.5)	738 (44)
Ca ($mg \cdot kg^{-1}$)	936 (32)	508 (10)	1153 (13)	1893 (9.0)
Mg ($mg \cdot kg^{-1}$)	399 (8.0)	297 (5.5)	225 (9.0)	534 (3.0)
K ($mg \cdot kg^{-1}$)	69.4 (4.0)	70.7 (2.3)	126 (22)	164 (42)
Na ($mg \cdot kg^{-1}$)	37.6 (6.0)	4.20 (4.2)	48.1 (2.0)	42.2 (5.0)
P ($mg \cdot kg^{-1}$)	0.947 (1.0)	0.002 (0.0)	0.601 (0.0)	4.83 (2.1)
NO_3^- ($mg \cdot kg^{-1}$)	10.0 (0.7)	2.12 (0.6)	0.501 (0.0)	8.32 (0.2)
NH_4^+ ($mg \cdot kg^{-1}$)	1.19 (0.8)	0.063 (0.8)	1.21 (0.1)	7.20 (0.2)
Dissolved organic N ($mg \cdot kg^{-1}$)	16.4 (0.2)	6.31 (0.2)	1.22 (0.0)	5.21 (0.1)
Total organic matter (%)	6.42 (0.6)	0.123 (0.7)	N/A	N/A
Microbial biomass N ($mg \cdot kg^{-1}$)	13.6 (3.0)	0.943 (1.5)	0.002 (0.0)	132 (4.0)
N minimum (mg NH_4^+/NO_3^- $kg^{-1} \cdot d^{-1}$)	0.284 (0.1)	0.002 (0.0)	5.280 (0.3)	21.7 (2.0)
Microbial respiration (mg CO_2 $kg^{-1} \cdot d^{-1}$)	57.8 (1.0)	2.58 (0.5)	0.103 (0.0)	5.31 (1.1)

[z]SEM in parentheses with means from six replicate samples. Data not available (N/A) for soil organic matter for water and ACT.

EC = electrical conductivity; Ca = calcium; Mg = magnesium; K = potassium; Na = sodium; P = phosphorus.

360 °C for 6 h (Nelson and Sommers, 1996). Particulate organic matter (POM), which is relatively labile, physically uncomplexed OM, was determined by particle size fractionation following methods of Gregorich et al. (2006). The soil fumigation–extraction method (Brookes et al., 1985) was used to determine microbial biomass N (MBN) in mg·kg^{-1}. Soil subsamples were fumigated with ethanol-free chloroform for 5 d, extracted with 0.5 M K_2SO_4, and total extractable N was reduced to NH_4^+ with persulfate and Devarda's alloy for NH_4^+ absorbance readings at 650 nm (Model ELx 800; Biotek Instruments Inc., Winooski, VT) (Sims et al., 1995). Microbial biomass N was the difference in N between the fumigated and unfumigated samples using an extraction efficiency factor of $_kEN = 0.54$ (Joergensen and Mueller, 1996). Potential N mineralization was measured as the net increase or decrease in available NH_4^+ and NO_3^- in aerobic 10-d incubation at 25 °C at 40% water-filled pore spaces. Nitrate in the 0.5 M K_2SO_4 extract was reduced to NH_4^+ using a Devarda's alloy and 0.1 M H_2SO_4 and then read colorimetrically, as described (Sims et al., 1995). Soil-available N was the sum of NH_4^+, NO_3^-, and dissolved organic N in unfumigated and unincubated soil subsamples (Sims et al., 1995). Microbial respiration was the CO_2 evolution measured in the 10-d incubations, sequestered in NaOH traps, and titrated to a phenophalthein end point with 0.25 N standardized HCl (Parkin et al., 1996).

Statistical analyses were conducted using SAS JMP 7.0 software (SAS Inc., Cary, NC). Data distributions were checked for normality using the Shapiro-Wilk W test. Transformations of non-normal data were performed with log10, natural log, square root, or exponential functions. The treatment and interaction effects were analyzed using analysis of variance. 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). Mean separations were carried out with Tukey-Kramer honestly significant difference tests. Simple and multiple regression analyses were used to model relationships between dependent and explanatory variables. Significant effects were identified as $P \leq 0.05$.

Results

Main treatments effects were not significant for most tree (Table 2) and soil properties (Table 3). No significant treatment differences were detected for total, shoot, and root biomass for trees growing in the loam or sandy soils (Fig. 1). However, total biomass, shoot biomass, root biomass, and the R/S ratio were significantly greater with the highest ACT application rate compared with the water control for *Quercus macrocarpa* growing in compact loam (Fig. 1). Similar trends were observed for *Acer saccharum* in compact loam, but these differences were not significant at $P \leq 0.05$.

Table 2. Tree properties from five aerated compost tea (ACT) treatments, two tree species (*Acer saccharum* and *Quercus macrocarpa*), and three soil types (sand, uncompacted loam, and compacted loam).

Tree response	0 kL ACT/ha	2 kL ACT/ha	4 kL ACT/ha	40 kL ACT/ha	400 kL ACT/ha	T	So	Sp	TxSo	TxSp	SoxSp	TxSoxSp
Root biomass (g)	4.27 (0.5)[z]	5.25 (0.5)	5.29 (0.5)	4.91 (0.5)	6.06 (0.5)	NS	***	NS	*	NS	**	NS
Shoot biomass (g)	3.77 (0.4)	3.64 (0.4)	3.84 (0.4)	4.43 (0.6)	3.91 (0.3)	NS	***	***	NS	NS	*	NS
Total biomass (g)	8.04 (1.0)	8.89 (0.8)	9.12 (0.8)	9.34 (1.1)	9.96 (0.7)	NS	***	***	NS	NS	*	NS
R/S ratio	1.53 (0.2)	1.98 (0.2)	1.65 (0.1)	1.53 (0.2)	2.15 (0.2)	NS	**	***	NS	NS	NS	NS
Leaf chlorophyll (SPAD)	24.5 (0.8)	23.6 (0.7)	22.3 (0.6)	21.8 (0.7)	23.4 (0.6)	NS	***	***	NS	NS	**	NS
Caliper growth (mm)	0.881 (0.2)	0.890 (0.2)	0.919 (0.2)	0.620 (0.2)	1.01 (0.2)	NS	***	***	NS	NS	*	NS

[z]SEM in parentheses with means from 36 replicate samples. Means are from both species, because interactions were not significant for treatment × species. Any two means within a row not followed by the same letter are significantly different at $P \leq 0.05$ using analysis of variance standard least squares and Tukey-Kramer's honest significant difference. Significance of main effects of treatment (T), soil (So), and species (Sp) and interaction effects are denoted as NS, *, **, *** for nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively, after a Bonferroni's correction for multiple testing.

Table 3. Soil properties from five aerated compost tea (ACT) treatments, two tree species (*Acer saccharum* and *Quercus macrocarpa*), and three soil types (sand, uncompacted loam, and compacted loam).

Soil response	0 kL ACT/ha	2 kL ACT/ha	4 kL ACT/ha	40 kL ACT/ha	400 kL ACT/ha	T	So	Sp	TxSo	TxSp	SoxSp	TxSoxSp
Penetration resistance (kg·cm^{-2})	1.52 (0.2)	1.73 (0.2)	1.33 (0.2)	1.77 (0.2)	1.89 (0.2)	NS	***	NS	NS	NS	**	NS
Ped size (mm)	32.7 (1.9)	30.2 (1.1)	29.1 (1.1)	30.1 (1.6)	32.1 (1.7)	NS	***	**	**	*	NS	NS
Soil moisture (%)	16.0 (1.6)	16.5 (1.7)	16.7 (1.7)	17.6 (1.7)	17.5 (1.7)	NS	***	**	**	NS	***	***
pH	7.69 (0.1)	7.81 (0.2)	7.88 (0.2)	7.90 (0.2)	7.90 (0.2)	NS	***	**	NS	NS	**	**
EC (dS·m^{-1})	39.3 (3.1)	37.3 (2.5)	36.6 (2.1)	39.8 (2.7)	37.8 (2.4)	NS	***	***	NS	NS	NS	NS
Ca (mg·kg^{-1})	727 (27.1)	774 (28.7)	768 (36.4)	776 (34.4)	789 (36.2)	NS	***	***	***	***	***	***
Mg (mg·kg^{-1})	365 (9.4)	404 (14.7)	401 (13.0)	410 (17.9)	405 (19.3)	NS	***	***	***	***	***	***
K (mg·kg^{-1})	69.9 (2.3) b	74.8 (2.8) b	77.4 (3.7) b	84.1 (3.8) ab	94.4 (3.8) a	*	**	***	*	*	*	*
Na (mg·kg^{-1})	26.5 (3.0)	27.3 (3.1)	24.8 (2.8)	28.1 (3.1)	28.1 (3.1)	NS	***	***	**	NS	***	**
P (mg·kg^{-1})	0.641 (0.1)	0.524 (0.1)	0.428 (0.0)	0.467 (0.1)	0.725 (0.8)	NS	***	NS	NS	NS	*	NS
NH_4^+ (mg·kg^{-1})	0.816 (0.2)	0.844 (0.2)	0.591 (0.1)	0.571 (0.1)	0.566 (0.1)	NS	***	***	*	NS	***	NS
NO_3^- (mg·kg^{-1})	7.39 (1.2)	6.01 (1.1)	4.60 (0.6)	7.11 (1.2)	4.03 (0.7)	NS	***	NS	**	NS	NS	NS
Dissolved organic N (mg·kg^{-1})	13.0 (1.4)	11.4 (1.3)	11.2 (1.3)	10.6 (1.1)	9.19 (1.0)	NS	***	**	NS	NS	NS	NS
Available N (mg NH_4^+ + NO_3^- + DON kg^{-1})	21.2 (2.1)	18.2 (2.1)	16.1 (1.7)	18.3 (1.8)	13.8 (1.4)	*	***	*	NS	NS	NS	NS
Particulate organic matter (%)	2.56 (0.2)	2.45 (0.2)	2.58 (0.2)	2.45 (0.2)	2.44 (0.2)	NS	***	**	**	***	***	***
Total organic matter (%)	4.29 (0.5)	4.24 (0.5)	4.31 (0.5)	4.29 (0.5)	4.39 (0.5)	NS	***	NS	NS	NS	***	***
Microbial biomass N (mg·kg^{-1})	9.34 (1.7)	10.6 (1.6)	11.2 (1.7)	11.2 (1.7)	15.3 (2.1)	*	***	***	**	**	*	NS
N min. (mg NH_4^+ + NO_3^- kg^{-1}·d^{-1})	1.43 (0.1)	0.313 (0.1)	0.253 (0.1)	0.294 (0.1)	0.359 (0.1)	NS	***	NS	*	*	NS	NS
Microbial respiration (mg CO_2 kg^{-1}·d^{-1})	26.4 (3.7)	39.1 (3.8)	30.8 (3.6)	30.3 (3.3)	44.9 (6.8)	NS	***	***	**	NS	NS	NS
Surface C efflux (μg CO_2 m^{-2}·d^{-1})	29.2 (1.1)	30.6 (1.0)	30.4 (1.1)	29.1 (0.9)	33.1 (1.0)	NS	***	*	NS	NS	**	NS
Leachate NO_3^- (mg·kg^{-1})	2.82 (0.4)	2.55 (0.3)	2.26 (0.3)	2.89 (0.3)	2.07 (0.3)	NS	***	NS	*	NS	**	NS

[z]SEM in parentheses with means from 36 replicate samples. Any two means within a row not followed by the same letter are significantly different at $P \leq 0.05$ using analysis of variance standard least squares and Tukey-Kramer's honest significant difference. Significance of main effects of treatment (T), soil (So), and species (Sp) and interaction of these terms are denoted as NS, *, **, *** for nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively, after a Bonferroni's correction for multiple testing.

Ca = calcium; Mg = magnesiium; K = potassium; Na = sodium; P = phosphorus; DON = dissolved organic N; C = carbon; EC = electrical conductivity; N = nitrogen.

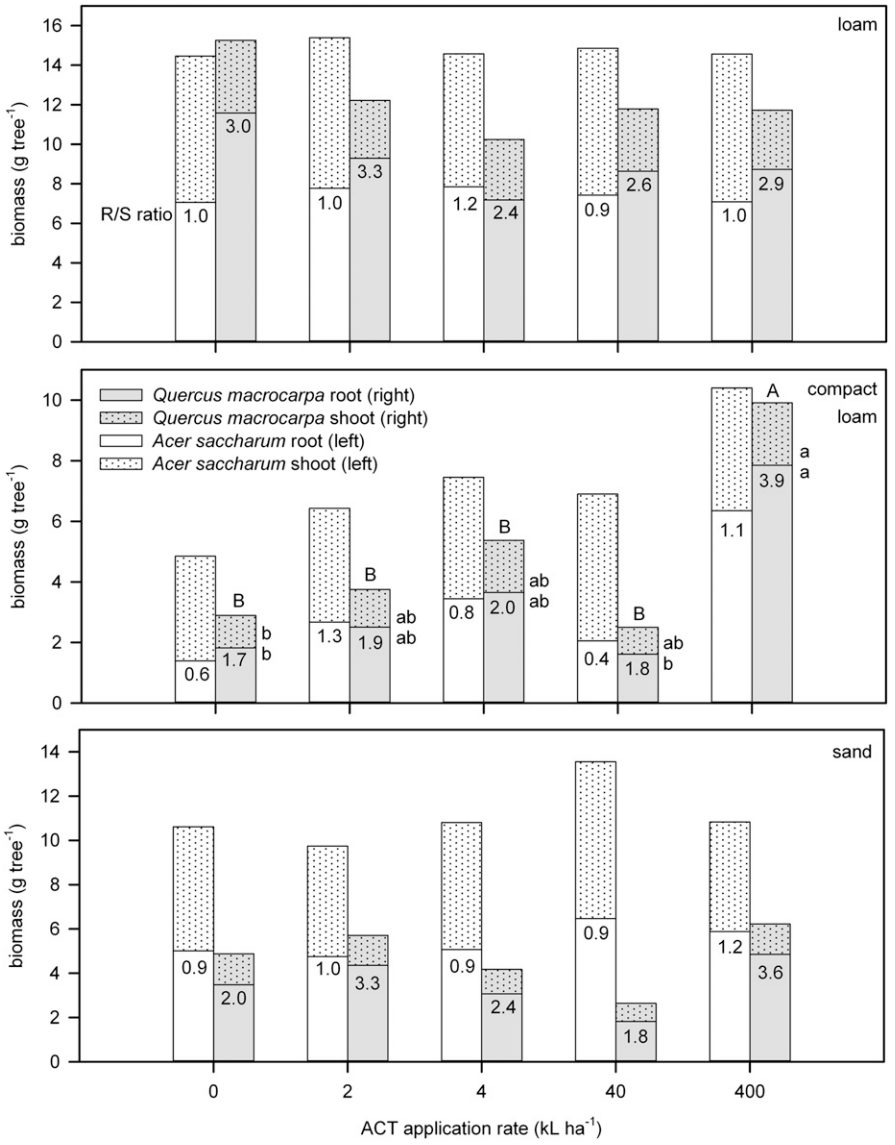

Fig. 1. Shoot (stipulated), root (open), total biomass (total bar), and the root/shoot ratio (R/S ratio; text) for *Acer saccharum* (left) and *Quercus macrocarpa* (right) from five aerated compost tea (ACT) treatments in three soil types (top is loam, middle is compact loam, and bottom is sand). Points on bars are means of six replicates. Significant differences were only observed for *Quercus macrocarpa* in compact loam soil for total ($P = 0.0004$), shoot ($P = 0.0106$), root ($P = 0.0003$), and the R/S ratio ($P = 0.0111$). Any two means within a biomass class, species, and soil type not followed by the same letter are significantly different at $P \leq 0.05$ using analysis of variance standard least squares and Tukey-Kramer's honest significant difference.

Of the soil properties measured, soil K, microbial biomass N, and total available N ($NH_4^+ + NO_3^- +$ dissolved organic N) were the most responsive to the ACT treatments (Table 1). Microbial biomass N and K tended to increase with increasing concentrations of ACT in all soil types and was significantly greater in the highest ACT rate compared with water control in all three soil types (Fig. 2). Available N was significantly greater in water compared with the highest ACT application rate in compact loam and loam soils, but differences were not detected in sand soils. Post hoc analyses were performed by pooling the intermediate ACT treatments (2, 4, and 40 kL ACT/ha) and comparing them against the water control and the 400 kL ACT/ha treatment (Fig. 2). Soil MBN, K, and available N were not significantly different in the 2 to 40 kL ACT/ha treatments compared with water controls. Soil MBN and K were significantly greater in the 400 kL ACT/ha rate compared with the other ACT treatments and water. An opposite trend was detected for total extractable N, showing significantly lower levels in the highest ACT compared with water and other ACT treatments. These findings were consistent across soil types (sans available N in sand) and species ($P >$ 0.05 for all interaction terms).

All soil and tree responses varied significantly by soil type and most varied by species (data not shown). Caliper growth, total tree biomass, shoot biomass, and root biomass were greater in loam soils compared with sand and compact loam soils. Leachate NO_3^- was greater in compact loam and sand soils compared with loam soils. Surface CO_2 efflux, microbial respiration, sodium, and NH_4^+ was greatest in loam, followed by compact loam, and then sand soils. Soil EC, POM, calcium (Ca), magnesium (Mg), and NO_3^- were greatest in compact loam, followed by loam, and then sand. Leaf chlorophyll, MBN, N mineralization, dissolved organic N (DON), total OM, and soil moisture were greater in compact loam and loam compared with sand. Penetration resistance was greater in sand, followed by compact loam, and loam soils. Caliper growth, leaf chlorophyll, R/S ratio, microbial respiration, MBN, soil Ca, Mg, K, and NH_4^+ were greater in *Quercus macrocarpa* compared with *Acer saccharum*. Shoot biomass, total tree biomass, and DON were greater in *Acer saccharum* compared with *Quercus macrocarpa*. Soil by treatment, species by treatment, and soil by species by treatment interactions were significant for root biomass, soil moisture, pH, Ca, Mg, K, Na, NO_3^-, NH_4^+, POM, total soil organic matter (SOM), MBN, microbial respiration, N mineralization, and NO_3^- in leachates.

Of the tree parameters, root biomass appeared most responsive to these treatments (Table 2). Modeling was performed to investigate correlations between individual soil parameters and root biomass. The best single regression model for root biomass was created using surface CO_2 efflux ($R^2 = 0.42$) (Fig. 3). This positive linear relationship was relatively strong with both species and three soil types but weakened with *Acer saccharum* in compact loam. Root biomass was negatively correlated with the concentration of NO_3^- in leachates ($R^2 = 0.26$) (Fig. 3). Correlations between root biomass and leachate NO_3^- were weaker and not significant for *Acer saccharum* in compact loam and sand and *Quercus macrocarpa* in compact loam. The best multiple regression model for root biomass included MBN, NH_4^+, NO_3^-, and P ($R^2 = 0.48$) (Fig. 3). This positive linear model was not significant for either species growing in sand but was significant for both species and the other two soil types.

Discussion

No tree or soil parameters were significantly different with ACT treatment rates at 2, 4, or 40 kL·ha^{-1} compared with water. Furthermore, the majority of the tree and soil parameters did not differ significantly at any of the ACT concentrations, including water. Some significant effects were observed for soil properties when comparing the highest ACT rate (400 kL·ha^{-1}) with the control, specifically, soil K and microbial biomass N increased with the highest ACT rate compared with water. Total available N decreased with the highest ACT rate compared with water. Differences in tree properties were minimal. Shoot, root, total biomass, and the R/S ratio increased with highest ACT concentration for *Quercus macrocarpa* in the compact loam soil.

Microbial biomass N increased 94% with a rate of 400 kL ACT/ha compared with

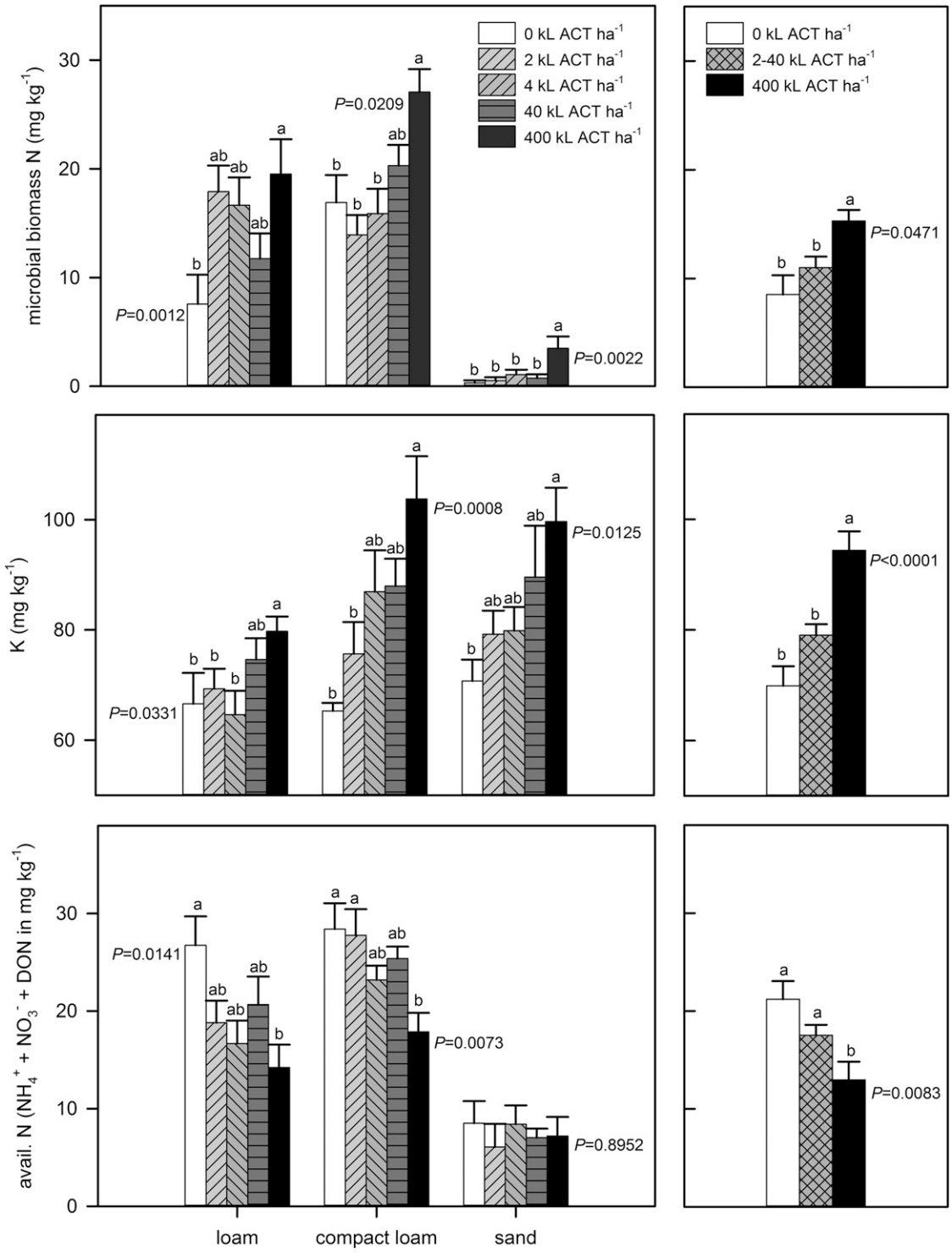

Fig. 2. Soil microbial biomass nitrogen (N), potassium (K), and available N ($NH_4^+ + NO_3^- +$ dissolved organic N) in loam, compact loam, and sand soils from five rates of aerated compost tea (ACT) treatments (figures on left) and also comparing three ACT treatment rates (figures on right). Bars are means of 12 replicates from species *Acer saccharum* (left) and *Quercus macrocarpa*. Any two within a soil type not followed by the same letter are significantly different at $P \leq 0.05$ using analysis of variance standard least squares and Tukey-Kramer's honest significant difference.

water across these soil types and tree species. In a laboratory incubation study, Scharenbroch et al. (2011) found soil microbial activity to increase with a similar ACT application rate compared with water-treated soils; however, greater increases were observed for soils treated with inorganic N–P–K fertilizer. Pant et al. (2011) also found soil microbial activity to increase 50% with applications of vermicompost tea.

It is thought that ACT is a direct source of soluble nutrients (e.g., Ingham, 2003; Lowenfels and Lewis 2007). Nutrient concentrations (Ca, Mg, K, P, and available N) in the ACT were elevated compared with those in the water treatment. However, only soil K increased with ACT compared with water. Background soil levels, nutrient fixation, tree uptake, volatilization, and leaching losses may be responsible for the non-responses observed for other nutrients. These findings suggest that ACT may increase soil K; however, K is rarely a limiting factor for plant growth. Hargreaves et al. (2008) found soil K levels to be lower

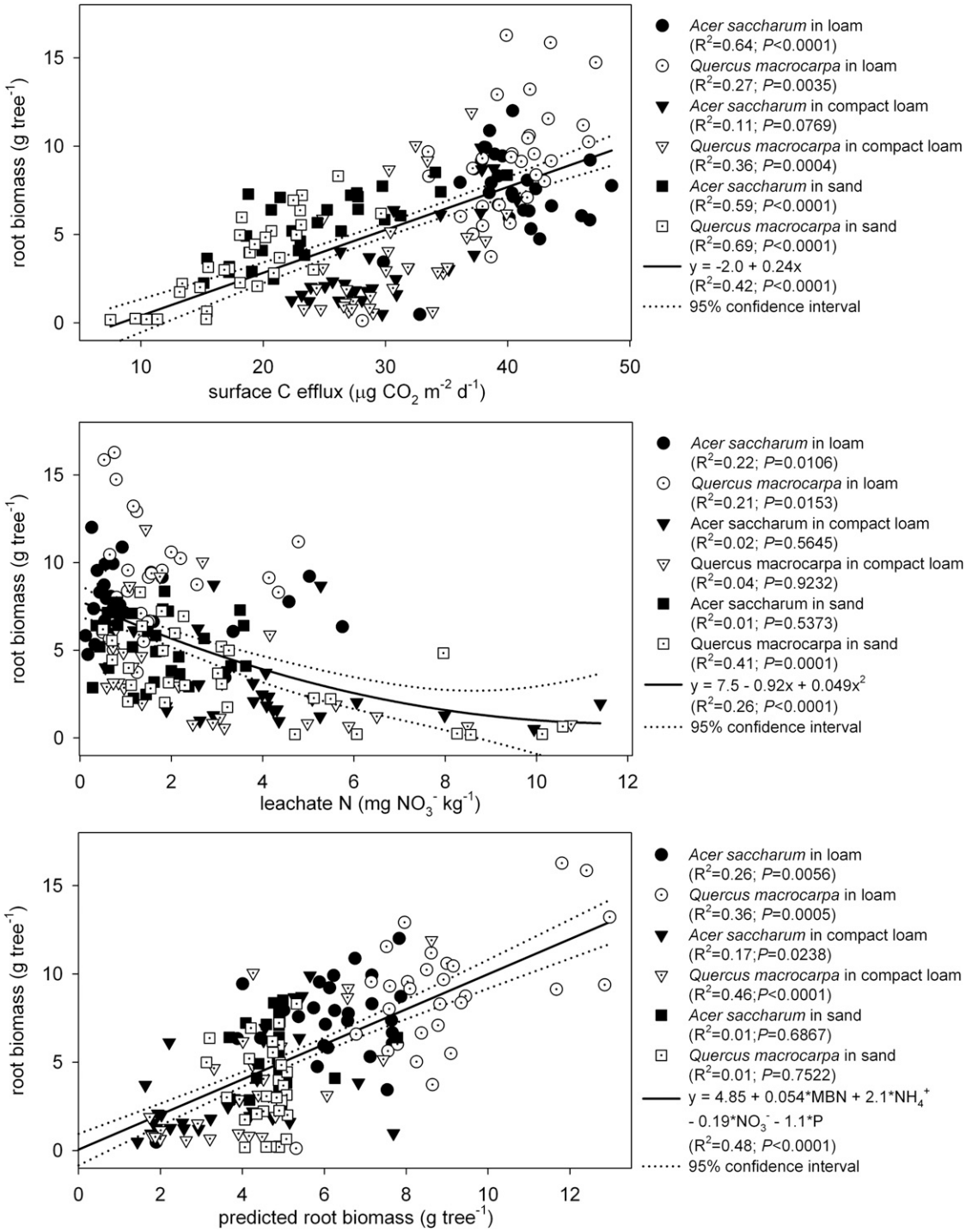

Fig. 3. Single and multiple regression models for root biomass and soil properties (surface C efflux on top, leachate nitrate in middle, and multiple parameter model on bottom) from five aerated compost tea treatments, two tree species (*Quercus macrocarpa* and *Acer saccharum*), and three soil types (sand, uncompacted loam, and compacted loam). R^2 and *P* values are given for each model with 95% confidence intervals denoted. Each point is a mean of six replicates.

with non-aerated compost teas as compared with inorganic fertilizer, but this was likely the result of the compost teas being applied as foliar sprays and fertilization as a soil application. Conversely, Scharenbroch et al. (2011) found soil K to significantly increase with ACT. The amount of K in ACT was quite high (164 mg·kg^{-1}) and exceeded K applied in a typical N–P–K fertilizer application for trees (Scharenbroch et al., 2011). Compost is known to be high in K, and several studies report increases in soil K from compost (Bar-Tal et al., 2004; Giusquiani et al., 1988).

Proponents assert that ACT will increase nutrient availability through increases in nutrient mineralization (e.g., Ingham, 2003; Lowenfels and Lewis, 2007). This study provides no direct evidence to support claims of increased N mineralization with ACT compared with water. Other studies on the impacts of compost teas on N mineralization are scarce. Hargreaves et al. (2009b) found N mineralization to be significantly greater in soils treated with municipal solid waste compared with soils treated with teas from municipal solid waste; however, they observed no differences in N mineralization in soils treated with ruminant compost and ruminant compost tea. Scharenbroch et al. (2011) found N mineralization to be greater in soils treated

with inorganic N–P–K fertilizer compared with soils treated with water and ACT with no differences between water and ACT-treated soils.

Significant decreases in available N were found with increasing ACT application rates. The decreases in available N with highest ACT application rate may be a result of decreased N mineralization, increased N leaching, increased N volatilization, increased plant N uptake, and/or increased microbial N immobilization. Significant differences in leachate NO_3^- and N mineralization were not observed. Scharenbroch et al. (2011) found denitrification to occur in soils treated with ACT, but the denitrification rates were quite low and significantly lower compared with soils treated with inorganic fertilizers. Microbial biomass N and tree biomass (*Quercus macrocarpa* in compact loam only) did increase with the highest ACT application rate. Furthermore, root biomass was significantly correlated to soil MBN, NH_4^+, and NO_3^-, and NO_3^- in leachates. It may be that the decrease in available N with the highest ACT application rate is from increased microbial N immobilization. The decrease in available N may be from increased tree N uptake; however, without data on plant N uptake, this is only speculation.

Observed significant responses in soil microbial biomass N, available N, and K do not appear to lead to increases in tree biomass for both species (*Quercus macrocarpa* and *Acer saccharum*) and in all three soil types (sand, loam, and compact loam). Increases in tree biomass were only observed for *Quercus macrocarpa* in compact loam. Speculation on why these differences were not observed with sand and loam soils is given. The fertility in the sandy soils may have been too low to be improved with these ACT applications. Soil quality in the loam soils may have been inherently high and masked any potential improvements that may have occurred with ACT. The compact loam soil was to mimic compaction found in typical urban landscapes. The ACT did not improve any of the physical soil properties measured (penetration resistance, ped size, and soil moisture), so it is unlikely the ACT improved aggregation or physical condition of these compacted soils. During leaching analyses, substantially greater times to leach microcosms were observed with compacted loam compared with uncompacted loam and sand soil types. It is speculated that compaction may have had a positive impact of reducing the infiltration rate and drainage from these microcosms, thus possibly increasing residence times of microbes and dissolved nutrients applied with ACT.

The lack of a growth response for *Acer saccharum* in this study is generally consistent with this species' negligible responses as saplings to increases in fertility, specifically soil-available N (Canham et al., 1996). Furthermore, Kobe (2006) found that radial growth of *Quercus rubra* was more sensitive to soil fertility compared with *Acer saccharum*. Species differences in growth responses to soil resources could also arise from differences in root morphological traits. The maples had greater biomass, but substantial differences through visual observations were not detected, and neither species appeared "pot-bound" at the conclusion of the experiment. Increased contact between roots and soil could convey greater access to soil nutrients. Comas et al. (2002) found higher specific root length (cm root g/root) for oaks compared with maples. Differences in mycorrhizal symbionts could also impact access to nutrients but were not assessed here.

No significant differences were detected for any soil and tree properties when comparing treatments of 2, 4, and 40 kL ACT/ha with water controls. Significant changes in soil microbial biomass N, K, and available N were observed comparing water with the highest ACT application rate (400 $kL \cdot ha^{-1}$). At this application rate, tree growth was only increased in *Quercus macrocarpa* in compact loam soils. The 400 $kL \cdot ha^{-1}$ ACT application rate may be appropriate for small trees in containers. Each tree in this experiment at this rate received 700 mL of concentrated ACT over the course of the experiment. The application of these results should be limited to young trees in containerized settings with relatively small soil volumes. Scaling these results to the landscape level may be problematic and is not advised. A rate of 400 kL ACT/ha would likely not be practical for landscape applications, because ≈1000 L of ACT would be required to treat the critical rooting zone of an urban tree in a relatively small growing space of 5 × 5 m (25 m^2).

It is important to consider the economics of a compost tea program. The total cost of the 10 ACT applications in this research was $482 [brewer ($140), compost and microbial food ($85), humic acids and soluble seaweed ($50), electricity to brew ACT ($3.82 = 0.1061 kW * 24 h * 10 brews * 0.15 $/kWh) and labor to brew and monitor ACT ($150 = 1 h * 10 brews * $15/h)]. The costs of water and labor to apply ACT are not included in this estimate, because these are relatively minimal and are not unique to a compost tea program. These 10 brews, at the highest ACT application rate (400 kL ACT/ha), would treat 270 saplings (10 brews * 18.9 L/brew/700 mL per tree), which is $1.78/tree. No significant growth responses were observed with *Acer saccharum* or *Quercus macrocarpa* in loam or sand or *Acer sacchaurum* in compact loam. It is difficult to discern if the increased growth observed for *Quercus macrocarpa* in compact loam with ACT is worth the additional cost of $1.78/tree, or ≈$0.25/g tree biomass gained for this species and soil type.

The use of ACT in arboriculture has in part grown as a result of the perceived decreased environmental threat with ACT compared with inorganic fertilization. The effectiveness of compost as an organic mulch, slow-release nutrient source, and soil conditioner for preserving and improving soil quality is well supported in scientific study [see reviews by Chalker-Scott (2007) and Scharenbroch (2009)]. In this research, the cost of brewing and applying ACT was 5.7 times greater than the cost of applying the compost as a top-dressing. Furthermore, the compost contained much greater numbers of organisms compared with ACT (six times more bacteria, 724 times more fungi, 10 times more flagellates, 11 times more amoebae, 1473 times more ciliates, and 12 more nematodes in compost compared with ACT). If the goal is to improve and manage soil microbial populations, direct application of compost to the soil should be considered. Future research is needed comparing ACT with compost and other soil fertility amendments with additional tree species in landscape and containerized settings.

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