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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

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Abstract. Aerated compost tea (ACT) is gaining interest as a nutrient amendment for urban trees. This study examined the effects of ACT, synthetic fertilizer, and deionized water on 15 biochemical properties with two soil types. Significant effects for pH, Mg^{2+}, Na^+, C, N, and C/N ratio were not observed among treatments. No differences between dilute ACT (ACT_d) at 22.4 kL ha^{-1} and water were detected. Soil K^+ was greater with ACT concentrate (ACT_c) at 224 kL ha^{-1} compared to 30-10-7 fertilizer at 195 kg N ha^{-1} with A horizon soils. Soil K^+, NH_4^+, and microbial respiration were greater with ACT_c compared to water in A soils. Soil P (A soils only), NO_3^- (Bt soils only), dissolved organic N, microbial biomass N, and N mineralization were greater with fertilizer compared to ACT. Increases in denitrification were seen with ACT_c compared to fertilizer and water in the first 24 hours (+4 to +12 mg N_2O kg^{-1}), but greater increases were observed with fertilizer at hours 48 and 96 (+65 to +127 mg N_2O kg^{-1}). Greatest improvements in soil fertility were observed with fertilization. Minor improvements in soil fertility were observed with ACT_c, and denitrification losses were lower with ACT_c compared to the fertilizer.

Key Words. Compost Extract; Microbial Activity; Microbial Biomass; Nitrous Oxide; Nutrient Availability; Organic Fertilizer; Synthetic Fertilizer; Urban Trees.

Appropriate nutrient management of urban trees is important for tree and environmental health. Traditionally, supplemental nutrients to urban trees have been supplied primarily by inorganic fertilizers. When misapplied to urban landscapes, fertilizers represent threats to the environment. Phosphorus (P) in fertilizer applied to urban landscapes has been identified as a significant contributor to P loads to lakes, potentially leading to algae blooms, reduced oxygen, and fish kills (Corsi et al. 1997; Soldat and Petrovic 2008). Nitrogen (N) applied in excess of plant demands contributes to the acidification of surface waters, eutrophication of coastal water, and groundwater contamination (Vitousek et al. 1997; Mitsch et al. 2001; Driscoll et al. 2003).

Traditionally it has been thought that fertilizers increase primary productivity, and thus increase soil carbon (C) through greater plant residue returned to the soil (Halvorson et al. 1999). However, recent findings have shown long-term fertilization to decrease soil C storage via N stimulation of soil microbes and associated increase in CO_2 efflux (Khan et al. 2007; Mulvaney et al. 2009). Greenhouse gases are produced during fertilizer synthesis by burning fossil fuels (Jenssen and Kongshaug 2003) and following fertilizer applications (e.g., denitrification). Denitrification losses from the soil are important since soil N is lost and resulting NO and N_2O are gases contributing to the global climate change dilemma (Vitousek et al. 1997). In denitrification, bacteria use the N atom in NO_3^- as a terminal electron acceptor (in the absence of oxygen) in the process of carrying sugars through the respiration-glycolysis process in their cells. Under such conditions nitrate is converted to gaseous N (NO, N_2O, or N_2). Continual use of synthetic fertilizers may also reduce soil quality through salt accumulation (Follett et al. 1981; Finck 1982).

Organic fertilizers contain organic matter and include a diverse group of materials that are often classified as either organic farm manures (e.g., animal or green manure) or organic commercial fertilizers (e.g., peat, bone meal, biosolids, compost) (Finck 1982). The majority of the nutrients in organic fertilizers are 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 to synthetic fertilizers, they may be less likely to speed up CO_2 release from soil via 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).

Many studies demonstrate the positive impacts of mulch and compost on soil quality and urban tree health (see reviews by Chalker-Scott 2007; Scharenbroch 2009). However, clients and circumstances often dictate that turfgrass remain under urban trees in lieu of mulch. Furthermore, mulch rings rarely cover the full extent of the rooting area, which recently has been estimated to be 38 times the tree diameter (Day et al. 2010). Compost top-dressing applications on turfgrass show promise for improving soil quality and treating a greater extent of the rooting area (e.g., Watson 1988). However, liquid-based amendments are still a very popular nutrient delivery system for urban trees. Aerated compost teas (ACT) are one such liquid product that is rapidly gaining interest as an arboricultural amendment with the hopes of improving soil quality and managing tree nutrition. A relatively easy transition from synthetic fertilization to ACT may be feasible because much of the existing technology (e.g., spraying equipment) for applying fertilizers can be used to apply ACT to urban trees (pers. comm.: R. Bastian of Davey Tree Experts, and J. Lloyd of Rainbow Tree Care).

Aerated compost tea is made by mixing compost with aerated water (NOSB 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 10-50 parts water, constant aeration for 12–24 hours, and immediate application (NOSB 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 55°C for at least three days (NOSB 2002). ACT additives—such as molasses, yeast extract, and algal powders—are used to encourage growth of beneficial microbes, but they can also have nontarget negative effects by supporting the growth of bacterial human pathogens from undetectable levels in properly made compost to detectable levels in ACT. The NOSB (2004) specifies that ACT made with additives can be applied to ornamental plants not intended for human consumption, and it is exempt from EPA standards for bacterial indicators of fecal contamination. No standards exist for application rates of ACT in agriculture or horticulture. Current ACT application rates for horticultural and arboricultural plants range from 4 to 400 kL ACT ha^{-1} (pers. comm.: E. Ingham of Soil Foodweb, Inc., and R. Bastian of Davey Tree Experts), albeit these rates are not based on scientific evidence.

Proponents assert that ACT will transfer desirable microorganisms, fine particulate organic matter, and soluble nutrients to soil surfaces. Specifically, unsubstantiated claims are made that ACT will: 1) help retain nutrients via increased microbial immobilization, 2) increase microbial mineralization and make nutrients available at rates plants require them, 3) build soil structure and decrease the effects of compaction, 4) detoxify soil and water, and 5) suppress disease by inducing competition among disease (anaerobic) and beneficial (aerobic) organisms (e.g., Ingham 2003a; Ingham 2003b; Ingham 2004; Lowenfels and Lewis 2007). In comparison to the anecdotal experiences reported by ACT practitioners, relatively few peer-reviewed, controlled, replicated scientific studies have been performed on the impacts of ACT on plants, soil, and the environment (Duffy et al. 2004; Scheurell and Mahaffee 2004; Scheurell and Mahaffee 2006; Larkin 2008; Segarra et al. 2009). Furthermore, consistent findings among these studies have not been reported for the impacts of ACT on plants, soil, or the environment (see review by Scheurell and Mahaffee 2002). The objective of this research was to evaluate ACT, synthetic fertilization, and deionized water control treatments in conjunction with two soil types, for their effects on 15 soil biochemical properties, including denitrification.

MATERIALS AND METHODS

Making and Monitoring ACT

Aerated compost tea was made with a KIS compost tea brewer, 18.9 L (Keep It Simple, Inc., Redmond, Washington, U.S.). Deionized water (18.9 L) was combined with one commercially available package of compost (approximately 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., Redmond, Washington). The compost contained 11,648 μg bacteria g^{-1}, 3,547 μg fungi g^{-1} (mean hyphae diameter of 2.8 μm), 18,883 flagellates g^{-1}, 14,596 amoebae g^{-1}, 11,338 ciliates g^{-1}, and 1.2 nematodes g^{-1} (analyses performed by Soil Foodweb, Inc., Corvallis, Oregon, U.S.). 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. Humic acid (25 g) and soluble seaweed powder (25 g) were also added at the start of the brew. During the 24-hour brew cycle, dissolved oxygen, temperature, pH, and electrical conductivity were measured every hour. Dissolved oxygen remained above 6 mg kg^{-1}, with a mean value of 7.3 mg kg^{-1} throughout the brew cycle. Mean temperature, pH, and electrical conductivity were 21°C, 4.9, and 2,169 μS cm^{-1}, respectively. On average (12 brews over 2008 and 2010 under similar conditions described), the ACT contained only a fraction of what was in the compost itself: 1,972 μg bacteria g^{-1}, 4.9 μg fungi g^{-1} (mean hyphae diameter of 2.6 μm), 1,920 flagellates g^{-1}, 1,392 amoebae g^{-1}, 7.7 ciliates g^{-1}, and 0.1 nematodes g^{-1}. Six replicates of the ACT, fertilizer, water treatments, and baseline soils were analyzed for pH, Ca^{2+}, Mg^{2+}, K^+, Na^+, total C, N, NH_4^+, NO_3^-, dissolved organic N (DON), microbial biomass N (MBN), potential N mineralization (PMN), and microbial respiration (RES) (Table 1). The procedures used for these measurements are described below.

Laboratory Assay I

Laboratory assay I was a full-factorial experiment with two soil types, four treatments, and six replicates. The four treatments were: deionized water, NPK fertilizer at 195 kg N ha^{-1}, dilute ACT (ACT_d) at 22.4 kL ACT ha^{-1}, and concentrate ACT (ACT_c) at 224 kL ACT ha^{-1}. The fertilizer contained 30% elemental N (20% water insoluble synthesized N and 10% water-soluble synthesized N), 4.4% elemental P or 10% available phosphoric acid (P_2O_5), and 5.8% elemental K or 7% soluble potash (K_2O). The fertilizer N source is ureaformaldehyde, P source is monopotassium phosphate, and K source is monopotassium phosphate. Throughout this paper, the term “fertilizer” is used to represent the synthetic fertilizer, and “ACT” to represent compost tea.

The two soils tested were an A horizon silt loam (0 to 10 cm) and Bt horizon clay loam (10 to 25 cm)—both from a fine, illitic, mesic Oxyaquic Hapludalf, Ozaukee series soil profile (Kelsey 2000). The two soil types were collected from a two meter wide by three meter deep pit on the grounds of the Morton Arboretum (Lisle, Illinois). Soil was air-dried in the laboratory, passed through a two-millimeter sieve, and thoroughly homogenized. One hundred-gram soil samples were placed into 250 mL beakers, and liquid treatments were added to bring soils to 60% water-filled pore space. The treated soils were incubated in the dark at 25°C and sampled after 10 days.

After the incubation period, soil sub-samples were extracted with 1 M NH_4OAc (pH 7.0) and mg kg^{-1} of Ca^{2+}, Mg^{2+}, K^+, and Na^+ were determined with atomic adsorption spectroscopy (Model A5000, Perkin Elmer, Inc., Waltham, Massachusetts, U.S.) (Schollenberger and Simon 1945). Soil phosphorus was deter-

Table 1. Chemical and biological properties of A horizon silt loam, Bt horizon clay loam, deionized water control, dilute aerated compost tea (ACT_d), concentrated aerated compost tea (ACT_c), and 30-10-7 synthetic fertilizer treatment. Means with (SE) listed below are from three replicates.

Parameter	pH (1:1)	Ca^{2+} (mg kg^{-1})	Mg^{2+} (mg kg^{-1})	K^+ (mg kg^{-1})	Na^+ (mg kg^{-1})	P (mg kg^{-1})	C (%)	N (%)	C/N (ratio)	NH_4^+ (mg kg^{-1})	NO_3^- (mg kg^{-1})	DON (mg kg^{-1})	MBN (mg kg^{-1})	RES (mg kg^{-1} d^{-1})	PMN (mg kg^{-1} d^{-1})
A horizon soil	6.20	1230	571	120	45.3	4.91	2.58	0.261	10.3	3.12	8.62	2.81	47.8	41.1	0.240
	(0.2)	(32)	(8)	(4)	(6)	(1.0)	(0.3)	(0.03)	(0)	(0.8)	(0.7)	(0.2)	(3)	(1)	(0.02)
Bt horizon soil	8.01	1922	319	200	48.8	1.62	1.87	0.073	26.8	0.502	0.803	1.22	20.7	10.5	0.042
	(0.3)	(18)	(5)	(1)	(2)	(1.1)	(0.1)	(0.01)	(1)	(0.61)	(0.41)	(0.4)	(5)	(2)	(0.08)
water treatment	7.52	1153	225	126	48.1	0.601	0.50	0.001	512	1.21	0.501	1.21	0.002	0.103	5.28
	(0.4)	(13)	(9)	(22)	(2)	(0.4)	(0.2)	(0.01)	(11)	(0.1)	(0.01)	(0.0)	(0.03)	(0.01)	(0.3)
ACT_d treatment	7.57	1886	509	154	48.8	2.21	5.14	0.903	5.91	5.32	0.911	1.62	13.2	0.101	15.2
	(0.1)	(38)	(9)	(9)	(3)	(2.1)	(0.7)	(0.20)	(0.6)	(0.1)	(0.31)	(0.7)	(1)	(0.04)	(6)
ACT_c treatment	4.88	1893	534	164	42.2	4.83	84.1	8.16	10.3	7.20	8.32	5.21	132	5.31	21.7
	(0.0)	(9)	(3)	(3)	(5)	(2.1)	(1)	(0.1)	(0)	(0.2)	(0.2)	(0.1)	(4)	(1.1)	(2)
fertilizer treatment	4.91	1401	528	117	42.2	4.82	36.4	29.7	1.22	4.91	4.10	4.53	148	9.52	11.2
	(0.1)	(276)	(10)	(6)	(10)	(2.2)	(1)	(1)	(0.1)	(1.1)	(0.2)	(0.9)	(45)	(4.2)	(6)

Abbreviations: aerated compost tea (ACT), calcium (Ca), magnesium (Mg), potassium (K), sodium (Na), Bray P1 phosphorus (P), organic carbon (C), total nitrogen (N), ammonium (NH_4^+), nitrate (NO_3^-), dissolved organic N (DON), microbial biomass N (MBN), Solvita test respiration (RES), and potential N mineralization (PMN).

mined with the Bray P-1 extraction and analyzed colorimetrically at 882 nm on a spectrophotometer (Model UV mini 1240, Shidmadzu, Inc., Kyoto, Japan) (Olsen and Sommers 1982). Soil pH and electrical conductivity in µs cm^{-1} were measured in 1:1 (soil:deionized) water pastes (Model Orion 5-Star, Thermo Fisher Scientific, Inc., Waltham, Massachusetts, U.S.). Total soil C and N were determined by automated dry combustion on a CN analyzer (Vario ELIII, Elementar Analysensysteme, Hanau, Germany) (Nelson and Sommers 1996). The soil fumigation-extraction method (Brookes et al. 1985) was used to determine microbial biomass N (MBN) in mg kg^{-1}. Soil sub-samples were fumigated with ethanol-free chloroform for five days, 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, Vermont, U.S.) (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^- over the 10 day incubation. 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). Carbon dioxide evolution was measured over a 24-hour period using Solvita CO_2 respiration paddles and a digital color reader (Haney et al. 2008).

Laboratory Assay II

The second laboratory assay was a full-factorial experiment with the same two soil types, three treatments, and six replicates. The three treatments were: water, NPK fertilizer (30:10:7) at 195 kg N ha^{-1} and ACT_c at 224 kL ACT ha^{-1}. Prior to adding the treatments the field-collected soils were dried and passed through a two-millimeter sieve. Sixty grams of each soil were weighed into 100 mL volumetric flasks. Liquid treatments (60 mL) were added to the soils bringing them to 100% water-filled pore space. The headspace of each volumetric flask was purged with helium and immediately capped with rubber septa to allow for gas headspace sampling. Sufficient acetylene was then added to bring the headspace to a 10/90 acetylene/helium mix. The soils were incubated in the dark at 25°C for a total of eight days.

Gas sampling for denitrification followed the acetylene inhibition method (Yoshinari and Knowles 1976; Drury et al. 2008). Gas samples were collected from each flask at 12, 24, 48, 96, and 192 hours. Prior to sample injection, 9 mL of 10% acetylene and 90% helium were added to10 mL vacuum vials. A 1000 µL sample was collected from the flask and added to the vacuum vial. A 1000 µL mixture of 10% acetylene and 90% helium was added to the flasks to replace the gas removed. A 500 µL subsample was extracted from the vacuum vials and concentrations of N_2O and CO_2 were determined using a thermal conductivity gas chromatograph (Hewlett Packard 5710A with Alltech Porapak Q 50/80 in series with Alltech Haysep Q 80/100 column, Agilent Technologies, Foster City, California, U.S.). The carrier gas used was helium, flow rate was 15 cm^3 min^{-1}, and detector temperature 100°C. Peak retention times for CO_2 and N_2O were 8 to 9 minutes and 11 to 12 minutes. Standards 3% CO_2 (Scotty II Analyzed Gas, CO_2, 3%, PN 24035, Plumsteadville, Pennsylvania, U.S.) and 100 mg N_2O kg^{-1} (Matheson Tri-Gas Analyzed Gas, Micro MAT10, 100 mg kg^{-1} N_20, Item # GMT10346TK, Oak Creek, Wisconsin, U.S.) were tested daily with samples.

Statistical Analyses

Statistical analyses were conducted using SAS JMP 7.0 software (SAS, Inc., Cary, North Carolina, U.S.). 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 effects were analyzed using Analysis of Variance (ANOVA). 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 HSD tests.

RESULTS AND DISCUSSION

Soil Type Effects

Significant effects were detected for soil type on all soil properties (Table 2). The A horizon soils had lower pH, Ca^{2+}, K^+, and Na^+, and higher Mg^{2+}, P, total C, total N, NH_4^+, NO_3^-, DON, MBN, PMN, and RES compared to soils from the Bt horizon. Treatment by soil type interactions were detected for NH_4^+ (Table 2).

Soil pH, Ca, Mg, K, Na, and P

Soil pH was not significantly different in any treatments in either soil type (Table 2). Ammonium addition to soil results in acidification because two H^+ are generated with the oxidation of each NH_4^+ ion in the process of nitrification (Follet et al. 1981). Evolved CO_2 from microorganisms reacts with water to form bicarbonate, and in the process releases H^+ to solution, also acidifying soil. Relative to water, neither fertilization nor ACT appeared to acidify these soils to produce measureable changes in soil pH. Nonresponses in pH were likely due to high buffering capacities of these silt and clay loam soils (Kelsey 2000).

With the Bt horizon soils, Ca^{2+} was significantly greater with water and ACT_d treatment compared to the fertilizer treatment (Table 2). Soil Ca^{2+} did not differ among treatments for the A horizon soils. No differences were observed for soil Mg^{2+} among the treatments for either soil type. Researchers in this study surmise that the Ca^{2+} decrease with fertilizer and ACT_c is a result of microbial Ca^{2+} immobilization, since nitrifying bacteria are known to have a high requirement for calcium (Follet et al. 1981). Calcium is primarily applied to soils to change conditions related to its reaction, while Mg^{2+} is applied to correct a plant nutrient deficiency. Finck (1982) suggests urban soils are rarely deficient in either Ca^{2+} or Mg^{2+}. Deficiencies of Ca^{2+} and Mg^{2+} for crops are expected to occur at approximately 500 and 50 mg kg^{-1}, respectively, which were well below this study's measured values (Walsh and Beaton 1973). It is believed that these soils were not deficient in either of these nutrients. Similar to these results, Hargreaves et al. (2008) found no differences in soil Ca^{2+} and Mg^{2+} contents one and two-years after applying fertilizer and non-aerated compost teas made from municipal waste and ruminant compost.

In the A horizon soil, K^+ was greater with the ACT_c compared to other treatments (Table 2). Soil K^+ levels in the A horizon soils were greater with fertilizer compared to ACT_d and water (Table 2). No differences for K^+ were observed with the Bt horizon soils, which had significantly higher K^+ concentrations (197 to 205 mg kg^{-1}) as compared to the A horizon soils (118 to 134 mg kg^{-1}). Plants growing in soils with greater than 170 mg kg^{-1} K^+ have been found to be nonresponsive to K^+ fertilization (Walsh and Beaton 1973). Hargreaves et al. (2008) found soil K^+ levels to be lower with non-aerated compost teas as compared to inorganic fertilizer, but this was likely due to the compost teas being applied as foliar sprays and fertilization as a soil application. The amounts of K^+ in ACT_c (164 mg kg^{-1}) exceeded that in the 30-10-7 fertilizer (117 mg kg^{-1}) (Table 1). Several studies report increases in soil K^+ from compost (Giusquiani et al. 1988; Bar-Tal et al. 2004). This study's findings indicate that ACT_c may also be an effective method of increasing the soil available supply of K^+.

Sodium concentrations were not impacted by any of these treatments (Table 2). High Na^+ levels (exchangeable Na^+% > 10, which is Na^+ divided by the sum of other cations) are detrimental to soil tilth and plant growth (Marx et al. 1996). In this study, the exchangeable Na^+ % values were all <2%, and so the amendments added to these soils do not appear to present potential soil quality or tree health problems.

Soil P with the A horizon soil was greater with fertilization compared to other treatments (Table 2). No differences were observed among the treatments for soil P with the Bt horizon soils, possibly a result of Ca-P precipitation at these higher pH values (Essington 2003). Annual P use for five southwestern Wisconsin tree species of varying leaf longevities ranged from 6 to 13 kg P ha^{-1} (Son and Gower 1991). Values of less than 5 mg kg^{-1} for the Bray P test suggest very low corn yields in Minnesota (Rehm et al. 2006). Only the fertilizer treatment increased levels of soil P to the range of P usage reported by Son and Gower (1991) and above the >5 mg kg^{-1} P requirement for corn (6.1 mg kg^{-1} P equating to 15 kg P ha^{-1}, assuming 1.0 Mg m^{-3} and 0.25 m depth) (Table 2). Similar amounts of P were contained in the fertilizer and ACT_c treatment (Table 1). Researchers in this study suspect greater microbial P immobilization with ACT compared to fertilizer. Phosphorus immobilization is great with organic materials low in P content relative to energy sources (i.e., C contents) (Sauchelli 1965). The C/P ratio of the ACT_c was 18/1 compared to the 8/1 for the fertilizer treatment. Assuming soil pH is not limiting P availability, fertilization appears to be more effective than ACT at increasing P levels in A horizon soils.

Soil C and N

No differences were observed in total C or N in either soil type with these treatments (Table 2). Total C and N are relatively stable pools, so researchers in this study did not expect these one-time treatments to have significant effects after only 10 days. Soil C has been thought to increase with fertilization by increasing the input of plant residues. However, recent results from the Morrow Plots, the world's oldest experimental site under continuous corn (*Zea mays* L.), indicate that after 40 to 50 years of synthetic fertilization that exceeded grain N removal by 60% to 190%, a net decline occurred in soil C despite increasingly massive residue C incorporation (Khan et al. 2007; Mulvaney et al. 2009). The decline in soil C with long-term fertilization was attributed to the excess fertilizer N promoting the decomposition of residues and soil C. To date, no studies have investigated the long-term impacts on soil C and N storage of fertilization or ACT application to urban trees.

Soil NO_3^- (Bt horizon only) and DON were greater with the fertilizer compared to the ACT treatments and water controls

Table 2. Chemical and biological properties of an A horizon silt loam and Bt horizon clay loam after addition of deionized water control, dilute aerated compost tea (ACT_d), concentrated aerated compost tea (ACT_c), and 30-10-7 synthetic fertilizer treatments. Means with (SE) listed below are from six replicates. ANOVA *P*-values listed for treatments effects within each soil type, soil type effects, and soil by treatment interactions. Significant effects after Bonferroni correction is applied are indicated with an asterisk (*). Values with unique letters are different according to Tukey's HSD test.

Parameter	pH (1:1)	Ca^{2+} (mg kg^{-1})	Mg^{2+} (mg kg^{-1})	K^+ (mg kg^{-1})	Na^+ (mg kg^{-1})	P (mg kg^{-1})	C (%)	N (%)	C/N (ratio)	NH_4^+ (mg kg^{-1})	NO_3^- (mg kg^{-1})	DON (mg kg^{-1})	MBN (mg kg^{-1})	RES (mg kg^{-1} d^{-1})	PMN (mg kg^{-1} d^{-1})
A horizon soil															
water	6.27	1238	589	120c	33.7	3.20b	2.60	0.237	10.9	4.30b	5.61	3.22b	55.2b	39.9c	0.191b
	(0.1)	(17)	(9)	(2)	(1)	(1.1)	(0.2)	(0.01)	(0)	(1.0)	(0.2)	(0.2)	(5)	(1)	(0.04)
ACT_d	6.25	1233	594	118c	41.6	2.81b	2.57	0.243	10.6	6.81ab	5.91	3.71b	64.1b	41.1bc	0.360b
	(0.1)	(8)	(14)	(1)	(3)	(1.0)	(0.0)	(0.02)	(0)	(3.0)	(0.1)	(0.3)	(5)	(1)	(0.10)
ACT_c	6.13	1236	592	134a	43.9	2.82b	2.57	0.249	10.3	6.91a	6.21	3.83b	65.8b	44.9ab	0.481b
	(0.1)	(17)	(5)	(1)	(1)	(1.0)	(0.0)	(0.01)	(0)	(1.1)	(0.1)	(0.3)	(5)	(1)	(0.14)
fertilizer	6.02	1218	580	125b	36.7	6.10a	2.62	0.245	10.7	9.20a	8.22	5.20a	92.3a	46.9a	0.881a
	(0.1)	(6)	(8)	(1)	(1)	(1.0)	(0.4)	(0.02)	(0)	(1.0)	(0.1)	(0.3)	(5)	(1)	(0.12)
treatment (prob>F)	0.0346	0.6836	0.5776	<0.0001*	0.0038	<0.0001*	0.4882	0.0069	0.0432	0.0003*	0.0304	0.0002*	0.0002*	0.0006*	0.0010*
Bt horizon soil															
water	7.85	1952ab	330	200	47.6	1.30	1.85	0.068	27.2	0.501	0.610b	1.01b	16.7b	9.41	-0.101b
	(0.1)	(15)	(5)	(2)	(1)	(1.1)	(0.0)	(0.01)	(1)	(0.01)	(0.20)	(0.2)	(3)	(1.0)	(0.02)
ACT_d	7.68	1978a	332	197	48.8	1.61	1.83	0.067	27.1	0.512	1.20b	1.02b	16.7b	12.6	-0.022b
	(0.1)	(10)	(5)	(4)	(1)	(1.1)	(0.0)	(0.03)	(0)	(0.10)	(0.2)	(0.1)	(2)	(3)	(0.06)
ACT_c	7.62	1903bc	327	205	51.5	1.62	1.87	0.071	26.3	0.613	1.01b	1.04b	18.7b	14.7	-0.051b
	(0.1)	(10)	(7)	(1)	(1)	(1.0)	(0.0)	(0.01)	(0)	(0.21)	(0.2)	(0.1)	(3)	(2)	(0.06)
fertilizer	7.62	1883c	328	203	48.9	2.71	1.87	0.072	25.8	0.420	4.61a	2.90a	52.8a	14.7	0.330a
	(0.1)	(15)	(7)	(2)	(1)	(1.0)	(0.0)	(0.01)	(1)	(0.10)	(0.3)	(0.4)	(8)	(1)	(0.03)
treatment (prob>F)	0.1038	0.0001*	0.9356	0.2519	0.0444	0.4516	0.7457	0.1165	0.0171	0.6884	<0.0001*	<0.0001*	<0.0001*	0.1153	<0.0001*
soil (prob>F)	<0.0001*	<0.0001*	<0.0001*	<0.0001*	<0.0001*	<0.0001*	<0.0001*	<0.0001*	<0.0001*	<0.0001*	<0.0001*	<0.0001*	<0.0001*	<0.0001*	<0.0001*
*treatment*soil* (prob>F)	0.4618	0.0087	0.5392	0.1706	0.0217	0.8626	0.7778	0.0559	0.0465	0.0001*	0.0680	0.6295	0.6386	0.6187	0.2368

Abbreviations: aerated compost tea (ACT), calcium (Ca), magnesium (Mg), potassium (K), sodium (Na), Bray P1 phosphorus (P), organic carbon (C), total nitrogen (N), ammonium (NH_4^+), nitrate (NO_3^-), dissolved organic N (DON), microbial biomass N (MBN), Solvita test respiration (RES), and potential N mineralization (PMN).

(Table 2). Soil NH_4^+ was greater with ACT_c and fertilizer compared to water in the A horizon soil (Table 2). No differences were observed for these N pools between the ACT_d treatments and water, in either soil type. In a typical soil (1.0 Mg m^{-3} and top 25 cm), 50 mg kg^{-1} N would equate to 127 kg N ha^{-1}, and would fall within the current ANSI standard fertilization application rate of 98 to 195 kg N ha^{-1} (ANSI 2004). Combining the plant available N pools of NH_4^+, NO_3^-, DON, and MBN, the results of this study indicate that none of the A horizon soils would be deficient in N (68.3, 80.5, 82.7, and 114.9 mg kg^{-1} for water, ACT_d, ACT_c, and fertilizer, respectively). Nitrogen deficiencies may exist with the Bt soils for the water (18.4 mg kg^{-1}), ACT_d (19.4 mg kg^{-1}), and ACT_c (21.3 mg kg^{-1}), but not for the fertilizer treatment (60.7 mg kg^{-1}). The findings of this study demonstrate that fertilizer is best at increasing NO_3^- and DON levels in the soil, but ACT_c and fertilizer both increased soil NH_4^+ in A horizon soils.

Soil Microbial Biomass, Respiration, N Mineralization, and Denitrification

In the A horizon soils, MBN was 67, 44, and 39% greater with fertilizer compared to water, ACT_d, and ACT_c, respectively (Table 2). Microbial biomass N in the Bt horizon with fertilizer was 216%, 216%, and 182% greater compared to water, ACT_d, and ACT_c, respectively (Table 2). Microbial biomass N was not increased with either ACT treatment compared to water (Table 2). The researchers conclude that a one-time fertilizer application increased the existing soil microbial biomass N pool in excess of the microbial biomass N added in a one-time ACT treatment.

The Solvita test CO_2 respiration (RES) values for ACT_c and fertilizer were greater than water for the A horizon soils (Table 2). No differences were observed for RES among the treatments for the Bt horizon soils. Fertilizer CO_2 efflux exceeded water at all times and both soil types (sans hour 196 for the Bt horizon) (Figure 1). CO_2 efflux was greater with fertilizer compared to ACT_c at hours 12 and 196 for the A horizon soil, and at hours 12, 24, 48, and 96 for the Bt horizon soils (Figure 1). With the A horizon soils, CO_2 efflux with ACT_c was greater than water at hours 12 and 24 (Figure 1). At hours 12, 24, 48, and 96 ACT CO_2 efflux exceeded water for the Bt horizon soils (Figure 1). The data show that ACT_c, compared to water, temporarily increases microbial respiration. Larkin (2008) showed significantly greater microbial substrate utilization in Biolog plates with ACT compared to

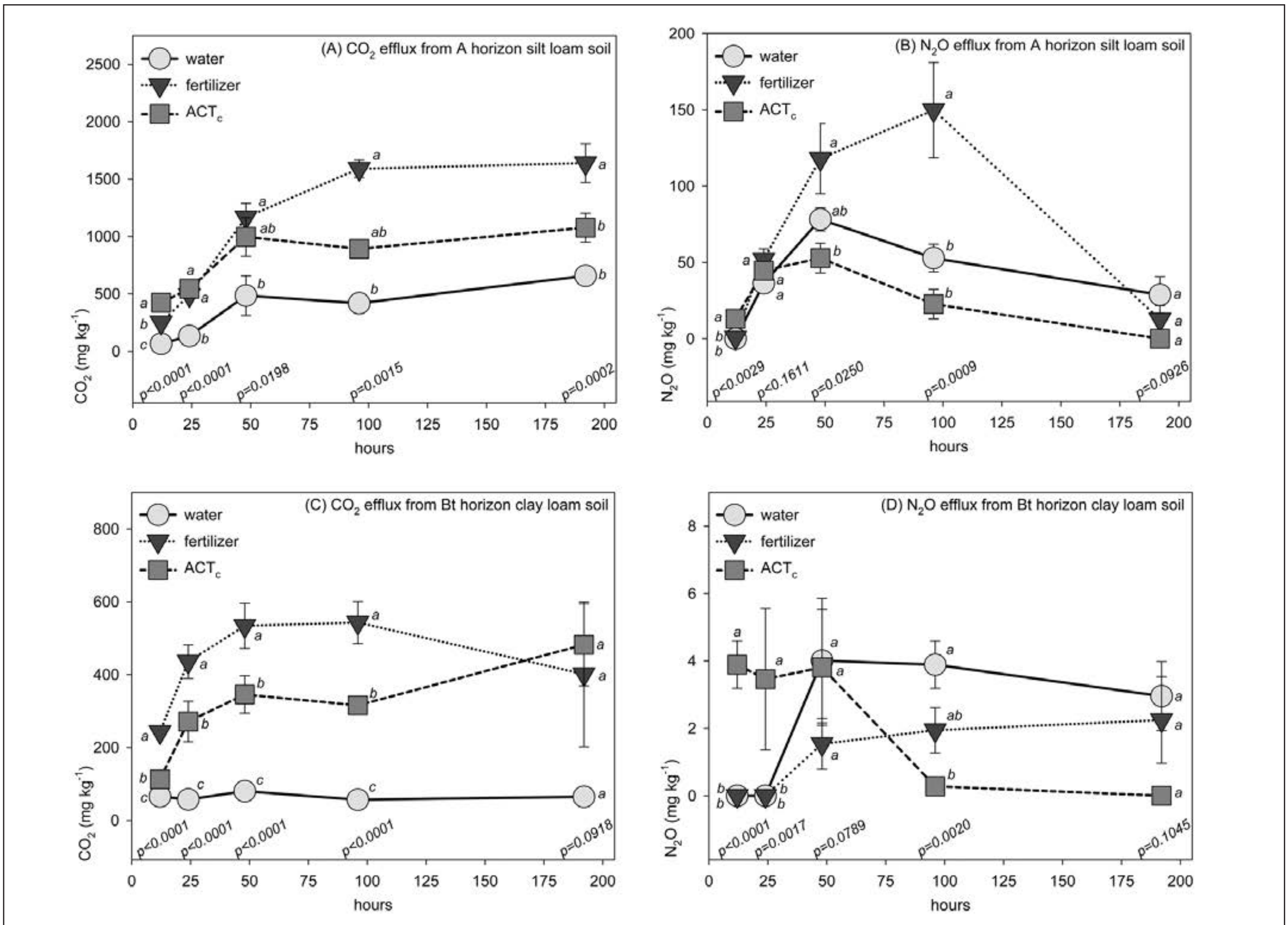

Figure 1. CO_2 and N_2O efflux from A and Bt horizon soils treated with concentrated aerobic compost tea (ACT_c), fertilizer, or deionized water under saturated conditions over a 192-hour laboratory assay. Each point is a mean of six replicates, with error bars showing standard error of the mean. *P*-values are given for each ANOVA at each collection time. Unique letters identify differences with Tukey's HSD test. Means, standard errors, and Tukey's HSD differences are also listed for samples averaged over the entire 192-hour assay.

control soils. However, the study authors conclude that microbial respiration is, for the most part, greatest with fertilizer.

Nitrogen mineralization was greater with fertilization compared to water and ACT treatments in both soil types (Table 2). Rates of N mineralization for the A horizon soils extended over a 180-day growing season would be: 86 (water), 162 (ACT_d), 216 (ACT_c), and 396 (fertilizer) kg N ha^{-1}. Annual N requirements for five tree species in southwestern Wisconsin were 38 for *Pinus resinosa* Ait., 80 for *Pinus strobus* L., 81 for *Picea abies* (L) Karst, 86 for *Larix decidua* Miller, and 126 kg N ha^{-1} for *Quercus rubra* L. (Son and Gower 1991). Soil N in the fertilization treatment exceeded these reported tree N requirements by as much as ten-fold. Soil N in the ACT treatments exceeded tree N requirements by up to five-fold. Soil N with the water treatment appeared to best match estimated tree N requirements. In the Bt horizon soils, only the fertilizer treatment increased N mineralization (149 kg N ha^{-1}) to a range close to meeting the tree N demands (Table 2). Nitrogen immobilization (i.e., negative potential N mineralization) was measured in the Bt horizon soils for the water and ACT treatments. Increased soil N mineralization is important for tree nutrition in urban soils, but N immobilization in the microbial biomass may also be important for nutrient retention in disturbed urban landscapes with a high propensity for nutrient losses to the hydrosphere or atmosphere.

In the A horizon soils, it was found that N_2O efflux increased with fertilizer compared to ACT_c at hours 48 (+65 mg kg^{-1}) and 96 (+127 mg kg^{-1}) of the 192-hour laboratory assay (Figure 1). At hour 12 in the A horizon soil, N_2O efflux was greater with ACT_c compared to fertilizer and water, but the +12 mg kg^{-1} increase was five to 11 times less than the fertilizer-associated N_2O increase at hours 48 and 96 (Figure 1). At hours 12 and 24 with the Bt horizon soils, N_2O efflux was approximately +4 mg kg^{-1} greater with ACT than water or fertilizer. No differences were observed at hours 24 and 196 for the A horizon and at hours 48 and 192 for the Bt horizon soils.

Environmental influences on denitrification include denitrifying organisms, pH, temperature, oxygen, moisture, oxidizable organic matter, and the amount of NO_3^- present (Follet et al. 1981). The researchers in this study suspect increases in readily available NO_3^- with the fertilizer treatment explain the larger increases in N_2O efflux with fertilization in the A-horizon soils at hours 24 and 48. The authors believe the initial denitrification increases with ACT_c were a consequence of increased available dissolved organic C in the ACT (Table 1). The researchers are aware of no other studies comparing denitrification responses of ACT and fertilization. Alluvione et al. (2010) found that compost application reduced the CO_2 equivalent of combined N_2O and CO_2 efflux by 49% compared to urea fertilization, and proposed that the availability of N to soil organisms was the likely driving factor in greater spring N_2O emissions following fertilization. Although the study authors observed increases in denitrification with ACT_c, (+4 to +12 mg N_2O kg^{-1}), the greatest absolute increases were observed with the fertilizer treatment in the A horizon soils (+65 to +127 mg N_2O kg^{-1}).

CONCLUSION

Over these short-term laboratory assays, ACT appears inferior compared to fertilizer in its ability to increase microbial biomass, microbial activity, DON, NO_3^-, and P in soil. These results show ACT_c to increase soil K^+, NH_4^+, and microbial respiration compared to water. In A horizon soils, NH_4^+ levels with ACT_c equaled fertilizer, and K^+ levels with ACT_c were greater when compared to fertilizer. In the A horizon soils, the greatest potential of surplus available N was observed with the fertilizer treatment. Only the fertilizer treatment appeared to deliver enough available N to potentially meet tree needs in the Bt horizon soils. Lower total N_2O efflux and greater microbial immobilization were observed with ACT compared to fertilizer showing greater potential nutrient retention with ACT compared to fertilizer. Urban soils are often infertile and highly disturbed, so nutrient limitations and potential losses are pertinent considerations for arborists and urban foresters. This research shows that fertilization is more effective at increasing short-term soil nutrient availability, but nutrient retention may be better preserved with ACT or water. The resource and application costs of water, ACT, and fertilizer must be weighed against the potential benefits these treatments may provide. The ACT contained only a fraction of the organisms found in the compost, and future research should examine compost and other organic fertilizer as soil amendments in comparison to ACT, synthetic fertilization, or water.

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Résumé. Le thé de compost gagne en intérêt comme amendement nutritif pour les arbres urbains. Cette étude examine les effets du thé de compost, des engrais synthétiques et de l'eau dé-ionisée en regard de 15 propriétés biochimiques de deux types de sols différents. Aucun effet significatif en regard du pH, des quantités en Mg^{2+}, en Na^{2+}, en C et en N, ainsi que du ratio C/N n'a été observé entre les divers traitements. Aucune différence entre le compost de thé dilué à 22,4 kL/ha et l'eau n'a été détecté. Le taux en K^+ du sol était plus grand avec le thé de compost concentré à 224 kL/ha comparativement à un engrais 30-10-7 à un taux de 195 kg en azote à l'hectare. Les quantités en K^+, et NH_4^+, ainsi que la respiration microbienne du sol, étaient plus élevées avec le thé de compost concentré comparativement à l'eau dans les sols A. Dans le sol P (sol A uniquement), les quantités en NO_3- (sols Bt uniquement), en N organique dissout, en biomasse microbienne en N et en N minéralisé étaient plus grandes avec les engrais comparativement au thé de compost. Une dénitrification accrue était observée avec le thé de compost concentré comparativement à l'engrais et à l'eau dans les premiers 24 heures (+4 à +12 mg en N_2O)/kg), mais un accroissement plus grand était observé avec l'engrais à 48 et 96 heures après (+65 à +127 mg en N_2O)/kg). Les meilleures améliorations dans la fertilité du sol ont été observées avec l'engrais. Des améliorations mineures dans la fertilité du sol ont été observées avec le thé de compost concentré et les perte en dénitrification ont été plus faibles avec le thé de compost concentré comparativement à l'engrais.

Zusammenfassung. Belüfteter Komposttee (ACT) als Nährstoflieferant wird für Straßenbäume zunehmend interessant. Diese Studie untersucht die Effekte von ACT, synthetischem Dünger und deionisiertem Wasser auf 15 biochemischen Standorten mit zwei verschiedenen Bodentypen. Während der Behandlung wurden keine signifikanten Auswirkungen auf pH, Mg^{2+}, Na^+, C, N, und C/N-Verhältnis beobachtet. Zwischen verdünntem ACT(ACT_d) bei 22.4 $kLha^{-1}$ and Wasser wurde kein Unterschied entdeckt. Der Bodengehalt an K^+ war größer mit ACT Konzentrat (ACT_c) bei 224 kL ha^{-1} verglichen mit 30-10-7 Dünger bei 195 kg N ha^{-1} mit A Horizont-Böden.

Der Bodengehalt an K^+, NH4+, und die mikrobielle Atmung war größer mit ACT_c verglichen mit Wasser in A Böden. Der Bodengehalt an P (nur bei A Böden) rep.NO_3- (nur Bt Böden),

gelöster organischer Stickstoff, mikrobielle Biomasse und Stickstoffmineralisation war bei gedüngten Böden besser als bei ACT. Zunahmen bei der Denitrifikation wurden bei ACT in Vergleich mit Dünger und Wasser innerhalb der ersten 24 h beobachtet, aber stärkere Zunahmen wurden beim Dünger bei 48 und 96 h (+65 to +127 mg N_2O kg^{-1}) gemessen. Die größten Verbesserungen in der Bodenfruchtbarkeit wurden bei der Düngung beobachtet. Kleinere Verbesserungen der Bodenfruchtbarkeit wurden bei ACT beobachtet und die Denitrifikationsverluste waren mit ACT geringer im Vergleich zu Dünger.

Resumen. El compost de té ACT (por sus siglas en inglés) está ganando interés como un nutriente mejorador para árboles urbanos. Este estudio examinó los efectos de ACT, fertilizante sintético y agua de-ionizada sobre 15 propiedades bioquímicas con dos tipos de suelos. No fueron observados efectos significantes entre los tratamientos para pH, Mg^{2+}, Na^+, C, N, y relación C/N. No se detectaron diferencias entre dilutos ACT (ACT_d) a 22.4 kL ha^{-1} y agua. K+ del suelo fue mayor con ACT concentrado (ACT_c) a 224 kL ha^{-1} comparado a fertilizante 30-10-7 a 195 kg N ha^{-1} con el horizonte A del suelo. El K^+, NH_4^+ en el suelo y la respiración microbial fueron mayores con ACT comparado con agua en suelos A. El P del suelo (suelos A solamente), NO_3- (Bt suelos solamente), N orgánico disuelto, biomasa de N microbial y mineralización de N fueron mayores con fertilizante comparado con ACT. Los incrementos en denitrificación fueron vistos con ACT, comparados a fertilizante y agua en las primeras 24 horas (+4 a +12 mg N_2O kg^{-1}), pero mayores incrementos fueron observados con fertilizante a 48 y 96 horas (+65 a +127 mg N_2O kg^{-1}). Los mayores mejoramientos en fertilidad del suelo fueron observados con fertilización. Los menores mejoramientos en fertilidad del suelo fueron observados con ACT y las pérdidas de denitrificación fueron más bajas con ACT comparado con el fertilizante.