

# An Arboriculture Treatment of Biochar, Fertilization, and Tillage Improves Soil Organic Matter and Tree Growth in a Suburban Street Tree Landscape in Bolingbrook, Illinois, USA

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**Abstract.** Background: Urban tree growth may be reduced due to poor urban soil conditions. Soil management to alleviate poor urban soil conditions often includes organic amendments, fertilization, and/or tillage. A 3-year experiment was conducted in an urban landscape in Bolingbrook, Illinois, USA, to test whether an arboriculture treatment with biochar, fertilization, and tillage could improve soil quality and tree growth. Methods: The urban landscape included 75 street trees (*Gleditsia triacanthos*, *Ulmus parvifolia*, and *Acer rubrum*) growing in compacted, fine-textured soils. Results: The results of this experiment suggest that the arboricultural treatment of biochar, fertilization, and tillage (BFT) may improve soil quality and urban tree growth. Relative height growth was significantly greater ( $P \leq 0.05$ ) for *Acer rubrum* trees with BFT treatment (+ 28.9%) compared to tillage alone (+ 13.3%). Total soil organic matter (SOM), particulate soil organic matter (POM), and a soil quality index (SQI) were significantly ( $P \leq 0.05$ ) greater in the BFT treatment (total SOM = 6.00%, POM = 9.73%, and SQI = 70.2) compared to the tillage treatment (total SOM = 5.29%, POM = 7.23%, and SQI = 60.8). The SOM responses to the BFT treatment appear to be relatively short-lived but correlated with measures of tree growth. Conclusion: This arboricultural treatment of biochar, fertilization, and tillage has potential to be used to improve soil quality and promote growth for trees growing in compacted, fine-textured soils in suburban street tree landscapes.

**Keywords.** Soil Amendment; Soil Compaction; Soil Quality; Urban Soil.

## INTRODUCTION

Soil management is critical for urban tree care. It includes a wide variety of activities such as protection, assessment, and actions to maintain or improve soil quality for urban trees (Scharenbroch and Smiley 2021). Three common actions that arborists and urban foresters perform for soil improvement include tillage, fertilization, and amendment with organic materials. Practitioners performing these actions often utilize them in combination. For example, tillage and fertilization may be used to attempt to repair a compacted soil. Research conducted on these actions has mostly focused their isolated effects in artificial settings and rarely investigates their combined impacts as an arboricultural treatment in actual urban landscapes.

### Tillage

A variety of tillage approaches including surface tillage, subsoiling, pneumatic injection, vertical and radial

mulching, and air tillage have been developed for alleviating urban soil compaction. Mechanical tillage (e.g., moldboard plow or rototiller) may be effective at breaking up compacted surfaces but would likely cause significant root damage if performed in soils with existing urban trees. Subsoil tillage with organic amendment has been found to improve physical properties of compacted soils (Chen et al. 2014). However, subsoiling may also damage existing tree roots and may not be practical in certain urban landscapes such as street trees. Pneumatic injection devices have been developed to physically fracture compacted soils with high pressure or nitrogen. These injections have seldom improved soil physical properties, and the results have been highly dependent on location and soil type (Smiley et al. 1990). Vertical mulching involves drilling shallow holes in the root zone and filling the holes with amendments such as fertilizers and compost. Vertical mulching may be an appropriate

tillage treatment for trees growing in turfgrass, but so few studies have been conducted on this practice that the efficacy is unknown (Kalisz et al. 1994). Radial mulching is similar, but instead of shallow holes, trenches are dug and amended in a radial pattern from the trunk to the drip line. Radial mulching results in replacing larger soil volumes in radial trenches or pits compared to vertical mulching. Watson et al. (1996) found deeper and denser rooting in amended radial trenches and greater tree growth with this practice. Air tillage uses high-pressure air to disturb and mix the surface soil horizons. Air tillage will destroy a turfgrass cover so may be most appropriate for treating the mulched rooting zone of the trees. This method is thought to have a minimal impact on existing tree root systems. Air tillage when used in combination with fertilization and mulching has been found to reduce soil strength and increase soil organic matter levels, but results varied by location and soil type (Fite et al. 2011).

## Fertilization

Fertilization is a common practice for urban tree management. An extensive amount of research has been conducted on this topic extending back to the 1920s (e.g., Ferrini and Baietto 2006; Harris et al. 2008). A review of urban tree fertilization by Struve (2002) found that tree growth often increased in response to nitrogen (N) applications, especially when soil N levels were low. Current recommended fertilization rates for urban trees range from 1 to 3 kg N 100 m<sup>-2</sup> (1 to 4 lb N 1,000 ft<sup>-2</sup>) depending on the tree life stage and type of fertilizer (ANSI 2018). Slow- and quick-release fertilizers differ in the form of available nutrients for tree uptake and potential for these nutrients to be lost from the soil via leaching and volatilization.

## Biochar

Biochar is a stable, carbon-rich, charcoal-like soil amendment that is produced by thermal decomposition of organic material under limited supply of oxygen at relatively low temperatures (Lehmann and Joseph 2015). Biochar is being utilized for soil quality improvement around the world in mostly agricultural settings (e.g., Palansooriya et al. 2019; Yu et al. 2019). Some of the major benefits of biochar as a soil amendment are increased water-holding capacity (Basso et al. 2013), increased nutrient retention (Hagemann et al. 2017), and increased organic matter and biological condition (Mitchell et al. 2015; Dong et al. 2016).

Relatively few scientific studies of biochar in arboriculture and urban forestry exist. Most of these studies have been conducted in greenhouses with young trees. Ghosh et al. (2015) found biochar (and compost) to improve soil quality and the health of *Samanea saman* and *Suregada multiflora* seedlings. Biochar improved the quality of 3 soil types and growth of *Acer saccharum* and *Gleditsia triacanthos* seedlings (Scharenbroch et al. 2013). Zwart and Kim (2012) found biochar to increase resistance of *Quercus rubra* and *Acer rubrum* seedlings to *Phytophthora*. Studies have found biochar to be an acceptable horticultural substrate for growing trees (Sax and Scharenbroch 2017; Álvarez et al. 2018) and might help limit salt damage in nursery substrates (Di Lonardo et al. 2017). A field-based study with biochar and urban trees by Somerville et al. (2020) found biochar to improve available water in sandy soils and reduce drought-induced tree stress.

## Objectives

This study investigated the effects of an arboricultural treatment for existing street trees growing in a compacted soil. The arboriculture treatment included biochar, fertilization, and tillage (air tillage and vertical mulching). This treatment was examined for its effects on improving soil quality and urban tree growth and health in a suburban street tree landscape with compacted, fine-textured soils. The research tested the following hypotheses: (1) Tillage alone will not improve urban soil quality and tree health; (2) Tillage plus fertilizer and tillage plus biochar will marginally improve urban soil quality and tree health; (3) The greatest improvement in soil quality and tree health will occur with the tillage plus fertilization and biochar treatment.

## MATERIALS AND METHODS

### Study Site

This research was conducted with 75 street trees on N. Janes Avenue and Falconridge Way in Bolingbrook, IL, USA (41.7134994, -88.0396979). Bolingbrook is a southwest suburb of Chicago, IL, in Will and DuPage counties. The study plots were located on the east and west sides of N. Janes Avenue and north and south sides of Falconridge Way. All plots were located in the 3- to 4-m-wide space between the street and the sidewalk on these streets. Twenty-five trees for each of three species (*Gleditsia triacanthos*, *Ulmus parvifolia*, and *Acer rubrum*) were randomly selected for study trees. Tree ages were estimated to

be between 5 and 15 years old. The diameters at breast height at the beginning of the study ranged from 2.7 to 7.8 cm, and the tree heights ranged from 1.3 to 2.8 m.

The undisturbed soils in the vicinity of the study area included Varna silt loam, Markham silt loam, Graymont silt loam, and Elpaso silty clay loam (NRCS 1999). These soils are forming in loess overlying glacial till from the late Wisconsin age (ca. 15,000 BP). The slopes in the study area range from 0% to 4%. The soil moisture regime is udic, and the soil temperature regime is mesic. The soils are moderately well drained to poorly drained Mollisols (Typic Endoaquolls and Oxyaquic Argiudolls) and Alfisols (Mollic Oxyaquic Hapludalfs).

The soils in the study area have been altered due to human activities associated with construction of the roads. Road construction activities on the Bolingbrook Promenade were completed in 2007, approximately 5 years before this study. Compaction is the most significant alteration on these soils. Soil bulk densities of the surface horizons (0- to 15-cm depth) ranged from 1.6 to 1.8 g cm<sup>-3</sup>. Other evidence of soil compaction in the study area included platy and massive soil structure, surface crusting, and erosion. Massive soil structure and redoximorphic features in the subsurface soils (2- to 100-cm depth) suggest that they have also been compacted. The study trees and turfgrass appeared to be stressed from soil compaction. Signs of this stress included dieback, chlorosis, necrosis, reduced growth, and some secondary pests.

## Treatments

Treatments were applied to the 75 tree plots at the Bolingbrook site in May of 2012. The tree plots included a rooting zone of a 1-m-radius circle (approximately 3 m<sup>2</sup>) surrounding each tree with an existing wood chip mulch cover and a turfgrass area to the extent of the 9-m<sup>2</sup> plot. The 5 treatments were (1) null (N); (2) tillage (T); (3) fertilizer and tillage (FT); (4) biochar and tillage (BT); and (5) biochar, fertilizer, and tillage (BFT). The null treatment involved no tillage, no fertilizer, and no amendment. Each treatment was replicated 15 times (5 times for each species). The treatments were designed by an arborist to mimic practical and typical treatments for soil management on this site with these trees and site constraints.

Air tillage was performed using a high-pressure air excavation tool (AirSpade 2000, AirSpade Pneumatic Soil Excavation, Chicopee, MA, USA). Prior to this tillage, the existing wood chip mulch was raked back.

The soil was tilled with the AirSpade for 5 minutes. For plots receiving the biochar and/or fertilizer amendments, biochar and/or fertilizer was spread on the tilled soil. The amendments and soil were then tilled again for 5 minutes to homogenize the amended soil. The tillage-only treatment was applied as described but without the biochar and fertilizer amendments. The null (control) trees received no tillage nor amendment.

The fertilizer used in this study was a 30-0-12 that included 30% total N (15% water insoluble N), 12% soluble K<sub>2</sub>O, 0.05% Cu, 0.1% Fe, 0.05% Mn, and 0.05% Zn (Boost Granular NK, Bartlett Tree Expert Company, Stamford, CT, USA). This fertilizer was prescribed based on initial soil testing results from the site. The fertilizer was applied at a rate of 1 kg N 100 m<sup>-2</sup> following the ANSI standards (ANSI 2018). Each fertilization tree received a total of 0.3 kg of fertilizer.

The biochar used in this study was made from *Pinus* spp. feedstocks at pyrolysis temperatures of 500 to 600 °C (BioChar Solutions, Inc., Niwot, CO, USA). The dry mass macronutrient concentrations were 87.4% total C (86.5% organic and 0.09% inorganic C), 0.67% total N (3.0 and 21 mg kg<sup>-1</sup> NH<sub>4</sub><sup>+</sup> and NO<sub>3</sub><sup>-</sup>, respectively), 0.29% P (68 mg kg<sup>-1</sup> available P), and 0.35% K. The dry mass microelement concentrations (mg kg<sup>-1</sup>) of the biochar were 2.0 As, < 0.1 Cd, 22 Co, 14 Cu, 5.9 Pb, 0.86 Mo, < 0.1 Hg, 60 Ni, < 0.1 Se, 26 Zn, 27 Bo, 395 Cl, and 213 Na. The biochar contained 4.5% ash and 0.8% water. The electrical conductivity of the biochar was 33.2 dS m<sup>-1</sup>, and the pH was 8.17. Particle size distribution of the biochar was 10.8% in 9.5 to 16 mm, 25.6% in 6.3 to 9.5 mm, 56.3% in 2.0 to 6.3 mm, 6.9% in 0.85 to 2.0 mm, and 0.5% in 0.85 mm and smaller size class. The envelope density of the biochar was 0.3 g cm<sup>-3</sup> (0.3 kg L<sup>-1</sup>). Each biochar-treated tree received 0.0375 m<sup>3</sup> (37.5 L) of biochar.

## Tree Properties

Tree health was quantified with 4 attributes: relative diameter growth (RDG), relative height growth (RHG), twig growth (TG), and chlorophyll content (SPAD). Tree diameters and heights were measured just prior to treatments in May of 2012 and at the end of each growing season in October of each year (2012 to 2015). Tree diameters were measured at a marked spot 1.3 m from the base of the tree. Tree heights were measured with a height pole. Tree height was defined as the distance from the base of the stem to the height of the highest live foliage. Relative growth

(RDG and RHG) were computed with the following equation:

$$\text{RDG or RHG (\%)} = \left( \frac{\text{current tree diameter or height} - \text{initial tree diameter or height}}{\text{initial tree diameter or height}} \right) \times 100$$

Twig growth (TG) was measured on 5 twigs for each tree in the fall of each year (2012 to 2015). The most recent growth was measured on each twig from the current terminal bud to the terminal bud of the previous year. The twigs were randomly selected from all aspects of the tree crown. Leaf chlorophyll content (SPAD) was measured once in July of 2014. Ten leaves from each tree were randomly selected from all aspects for measurement of leaf chlorophyll using the SPAD meter (SPAD 502 Plus, Konica Minolta, Inc.). A mean TG and SPAD reading were calculated for each tree at each sampling time.

## Soil Properties

Soils were sampled in October for 3 consecutive years (2012 to 2014). On each plot, ten 2.5 cm wide  $\times$  15 cm deep soil cores were randomly collected throughout each sample plot. The cores were mixed in a bucket, and a subsample was collected in a labeled plastic bag. Samples were kept on ice in a cooler until transported to the laboratory where they were then stored at 5 °C until laboratory analyses were performed. In the laboratory, each soil sample was sieved through a 6-mm screen for homogenization and removal of coarse material (Parkin et al. 1996; Gregorich et al. 2006).

Gravimetric soil moisture (GSM) content was determined by mass lost after drying at 105 °C for 24 hours (Topp and Ferre 2002). Water aggregate stability (WAS) analyses were performed following methods of Nimmo and Perkins (2002). Soil pH and electrical conductivity (EC) were measured in 1:1 (soil:deionized) water pastes (Model Orion 5-Star, Thermo Fisher Scientific, Inc., Waltham, MA, USA) (Rhoades 1996; Thomas 1996). Soils were extracted with 1.0 M  $\text{NH}_4\text{OAc}$ , and the concentrations of calcium (Ca), magnesium (Mg), potassium (K), and sodium (Na) were determined by atomic adsorption spectroscopy (AAAnalyst 400, Perkin Elmer, Waltham, MA, USA) (Helmke and Sparks 1996). The sum of the extractable base cations was used to estimate cation exchange capacity (CEC) for these alkaline soils (Sumner and Miller 1996). Soil Ca, Mg, K, Na, and CEC were only measured for the 2012 sample date. The Olsen extraction was used to determine soil phosphorus (P) (Kuo 1996). Total soil carbon (C) and N concentrations and the C/N ratio

were determined using an automated dry combustion gas analyzer (Vario ELIII, elemental Analysensysteme, Hanau, Germany) (Bremner 1996; Nelson and Sommers 1996). Total organic matter was determined by loss-on-ignition at 360 °C for 6 hours (Nelson and Sommers 1996). Particulate organic matter (POM) was determined with particle size fractionation (Gregorich et al. 2006). Soil respiration (RES) was measured as the amount of  $\text{CO}_2$  in 0.25 M NaOH traps following a 7-day soil incubation, which was then titrated to a phenolphthalein endpoint using 0.25 N HCl (Parkin et al. 1996). Microbial biomass carbon (MBC) was determined using a chloroform fumigation and extraction with an efficiency factor of  $k_c = 0.45$  (Vance et al. 1987). After fumigation, samples were extracted using 0.5 M  $\text{K}_2\text{SO}_4$  and analyzed for microbial biomass carbon (1010 Total Organic Carbon Analyzer, OI Analytical, College Station, TX, USA). Nonfumigated subsamples were extracted and analyzed for dissolved organic carbon (DOC) following the same MBC methods. The metabolic quotient ( $\text{qCO}_2$ ) was computed with RES and MBC for each sample (Insam and Haselwandter 1989).

A soil quality index (SQI, 0 to 100) was computed by ranking the responses for each of the 18 soil properties on each of the 75 plots for the 3 sampling dates (225 total responses per soil property) (Doran and Parkin 1994). Ascending ranks were used for properties in which a “more is better” relationship was expected (GSM, WAS, EC, CEC, Ca, Mg, K, P, N, C, SOM, DOC, MBC, and RES). Descending ranks were used for properties in which a “less is better” relationship was expected (pH, Na, C/N, and  $\text{qCO}_2$ ). For example, the plot with the highest-measured SOM content received a 225 for SOM score and the plot with the lowest-measured soil pH received a 225 score for pH. The scores for each plot were summed. The sum of scores for each plot was then divided by the maximum score observed for any plot and multiplied by 100.

## Statistical Analysis

Analysis of variance (ANOVA) was used to determine if tree and soil properties were different among treatments. ANOVAs were conducted for each tree and soil property using treatment, species, and sample date as factors. Interaction terms between these factors were tested for significance. For each linear model, the residuals were plotted against the model



fitted values to check for homoscedasticity and a normal quantile-quantile plot was used to check for normality. To further investigate significant main effects from ANOVAs, Tukey's Honest Significant Difference (HSD) test was used for post hoc analysis. The presence and strength of linear relationships between tree and soil properties were tested using Pearson's correlations. The alpha level for all significance tests was 0.05. All statistical tests were conducted using SAS JMP 13.2.1 software (SAS Institute Inc., Cary, NC, USA).

## RESULTS AND DISCUSSION

### Tree Properties

Treatment effects were significant for RHG but not for RDG, TG, and SPAD (Table 1). A significant treatment by species interaction was detected for

RHG. Tukey's HSD post hoc test found that RHG was significantly greater for BFT treatment compared to the T treatment for *Acer* (Table 2). Significant differences were not observed for post hoc tests for RHG with other species.

Possible explanations for why only *Acer* RHG was impacted by these treatments are listed below. *Gleditsia* RHG may not have been impacted by treatments due to its decurrent growth form. *Gleditsia* RDG ( $P = 0.1772$ ) may have been more impacted by treatments compared to RHG ( $P = 0.2464$ ). Treatment effects for RHG for *Ulmus* were marginally significant ( $P = 0.0590$ ). *Ulmus* trees ( $9.0 \pm 1.3$  cm DBH and  $9.5 \pm 1.2$  m tall) were significantly ( $P < 0.0001$ ) larger than the *Acer* ( $6.3 \pm 1.1$  cm DBH and  $7.3 \pm 1.0$  m tall). Treatment effects for *Ulmus* may have been diluted by the larger tree size. Extreme variability in RDG of *Acer* trees in

**Table 1. Prob > F values for effect tests of ANOVA linear models on tree property responses. Abbreviations: relative diameter growth = RDG, relative height growth = RHG, twig growth = TG, chlorophyll content = SPAD, treatment = Tr, species = Sp, and date = D.**

Property	Tr	Sp	D	Tr × Sp	Tr × D	Sp × D	Tr × Sp × D
RDG	0.5510	0.3688	< 0.0001	0.0127	0.9997	0.0372	0.9995
RHG	0.0224	< 0.0001	< 0.0001	0.0022	0.9789	0.0015	0.9988
TG	0.8967	< 0.0001	< 0.0001	0.8072	0.7830	< 0.0001	0.9804
SPAD	0.9758	< 0.0001	n/a	0.7518	n/a	n/a	n/a

**Table 2. Mean, standard errors of the means, and Tukey's HSD post hoc tests for tree properties by genus and treatment. Abbreviations: relative diameter growth = RDG, relative height growth = RHG, twig growth = TG, chlorophyll content = SPAD, null = N, tillage = T, fertilization + tillage = FT, biochar + tillage = BT, and biochar + fertilization + tillage = BFT.**

Property	Genus	N		T		FT		BT		BFT	
		Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
RDG	<i>Acer</i>	27.7	4.3	32.9	6.0	32.9	5.4	29.4	4.8	34.0	5.2
	<i>Gleditsia</i>	30.0	4.5	25.0	4.2	32.2	4.9	30.4	4.8	34.4	4.7
	<i>Ulmus</i>	33.2	4.3	30.7	4.2	26.8	3.8	28.9	4.3	27.4	3.7
RHG	<i>Acer</i> *	18.2ab**	3.3	13.3b	2.8	21.0ab	3.7	19.2ab	3.4	28.9a	4.8
	<i>Gleditsia</i>	7.7	1.4	5.4	1.1	10.7	1.7	7.4	1.9	8.3	1.8
	<i>Ulmus</i>	16.1	2.4	19.8	2.2	20.3	2.6	25.0	2.9	15.9	2.0
TG	<i>Acer</i>	30.7	2.4	32.4	3.4	30.8	3.2	36.2	3.4	35.6	3.6
	<i>Gleditsia</i>	23.0	2.4	21.6	3.0	22.2	2.8	21.7	2.5	22.9	2.8
	<i>Ulmus</i>	32.2	3.1	31.2	2.5	32.4	3.1	32.2	3.7	29.9	2.6
SPAD	<i>Acer</i>	27.8	0.5	28.6	1.5	29.0	0.9	27.6	1.3	29.6	1.1
	<i>Gleditsia</i>	38.0	3.4	37.4	3.2	35.0	2.5	36.6	2.8	36.0	3.0
	<i>Ulmus</i>	41.2	3.3	40.2	3.7	44.6	1.8	45.2	0.4	44.2	1.2

\*Significant difference ( $P \leq 0.05$ ) with the post-hoc test.

\*\*Letters represent means separation by Tukey's Honest Significant Difference test.

the T treatment ( $33.9 \pm 26.7$  m) may have masked significant treatment effects. Relatively high variation in TG on individual trees may have masked treatment effects. Within 3 standard deviations, TG ranged from 6.1 to 29.3 cm. Leaf chlorophyll content (SPAD) was only measured once during the study, and this was 26 months after treatments were applied. Other results (see Soil Properties) suggest treatment effects diminished after 2 years.

## Soil Properties

Treatment effects were significant for N, C, C/N, POM, and SOM (Table 3). Treatment effects were not significant for the other soil properties. No significant treatment by species or treatment by date interactions were detected for N, C, C/N, POM, and SOM. Tukey's HSD post hoc tests found that SOM and POM were significantly greater for BFT compared to the T treatment (Table 4). Although date and treatment interactions were not significant for N, C, C/N, POM, and SOM with the ANOVAs, temporal differences were observed with Tukey's HSD post hoc tests. Significant treatment differences were found in the first and second

years but not the third year of the study. In years 1 and 2, SOM was significantly greater with BFT compared to the T treatment (Figure 1). Treatment effects for SOM in year 3 were not significant. Soil N was significantly ( $P = 0.0332$ ) greater in BFT compared to T in only year 1. Soil C was significantly ( $P = 0.0145$ ) greater with BT compared to T in only year 1. Soil C/N ratio was significantly greater with BT treatment compared to FT treatment in only years 1 ( $P = 0.0148$ ) and 2 ( $P = 0.0248$ ). Soil POM was significantly greater in BFT compared to T in years 1 ( $P = 0.0223$ ) and 2 ( $P = 0.0081$ ).

Treatment ( $P = 0.0003$ ) and species ( $P < 0.0001$ ) effects were significant for the SQI. Treatment by species interaction effects were not significant ( $P = 0.1501$ ) for SQI (Table 3). According to Tukey's HSD post hoc test, SQI was significantly greater with the BFT compared to the T treatment (Table 4). The SQI included those organic matter properties (N, C, C/N, POM, and SOM) that did respond to the treatments and other soil properties that were not individually treatment responsive.

Soil properties that were not significantly impacted by treatments included pH, salts (Na and EC), nutrients (P, K, Ca, Mg, and CEC), biological properties (MBC,

**Table 3. Prob > F values for effect tests of ANOVA linear models on soil property responses. Abbreviations: gravimetric soil moisture = GSM, water aggregate stability = WAS, electrical conductivity = EC, cation exchange capacity = CEC, calcium = Ca, magnesium = Mg, sodium = Na, potassium = K, phosphorus = P, nitrogen = N, carbon = C, soil organic matter = SOM, dissolved organic carbon = DOC, particulate organic matter = POM, microbial biomass carbon = MBC, respiration = RES, metabolic quotient =  $qCO_2$ , soil quality index = SQI, treatment = Tr, species = Sp, and date = D.**

Property	Tr	Sp	D	Tr × Sp	Tr × D	Sp × D	Tr × Sp × D
GSM	0.5688	< 0.0001	< 0.0001	0.4914	0.9494	0.0002	0.9843
WAS	0.1137	< 0.0001	< 0.0001	0.8121	0.8953	0.0799	0.9426
pH	0.5710	< 0.0001	< 0.0001	0.6734	0.8105	0.0013	0.9701
EC	0.7761	0.5262	0.0007	0.8647	0.5515	0.0003	0.9239
CEC	0.5317	0.0106	n/a	0.0368	n/a	n/a	n/a
Ca	0.4565	< 0.0001	n/a	0.1880	n/a	n/a	n/a
Mg	0.6382	< 0.0001	n/a	0.2539	n/a	n/a	n/a
Na	0.8075	< 0.0001	n/a	0.9587	n/a	n/a	n/a
K	0.1489	0.2917	n/a	0.4995	n/a	n/a	n/a
P	0.5107	< 0.0001	0.0001	0.0768	0.9939	0.0323	0.8713
N	0.0012	< 0.0001	< 0.0001	0.5675	0.6375	0.0063	0.9207
C	0.0085	< 0.0001	0.9467	0.9417	0.4794	0.5807	0.9999
C/N	0.0039	0.1863	< 0.0001	0.3456	0.9815	0.0229	0.9995
SOM	0.0004	< 0.0001	< 0.0001	0.0843	0.6006	0.0443	0.6297
DOC	0.8036	< 0.0001	< 0.0001	0.4009	0.1641	< 0.0001	0.8683
POM	0.0403	< 0.0001	< 0.0001	0.4526	0.3597	0.5798	0.8762
MBC	0.1791	< 0.0001	< 0.0001	0.7571	0.5057	0.0229	0.6038
RES	0.4889	< 0.0001	< 0.0001	0.8118	0.5991	0.0006	0.4199
$qCO_2$	0.4746	0.6294	0.0259	0.4396	0.5563	0.1875	0.3377
SQI	0.0003	< 0.0001	< 0.0001	0.1501	0.9130	0.0669	0.6480

**Table 4.** Mean, standard errors of the means, and Tukey's HSD post hoc tests for soil properties by treatment. Abbreviations: gravimetric soil moisture = GSM, water aggregate stability = WAS, electrical conductivity = EC, cation exchange capacity = CEC, calcium = Ca, magnesium = Mg, sodium = Na, potassium = K, phosphorus = P, nitrogen = N, carbon = C, soil organic matter = SOM, dissolved organic carbon = DOC, particulate organic matter = POM, microbial biomass carbon = MBC, respiration = RES, metabolic quotient =  $qCO_2$ , soil quality index = SQI, null = N, tillage = T, fertilization + tillage = FT, biochar + tillage = BT, and biochar + fertilization + tillage = BFT.

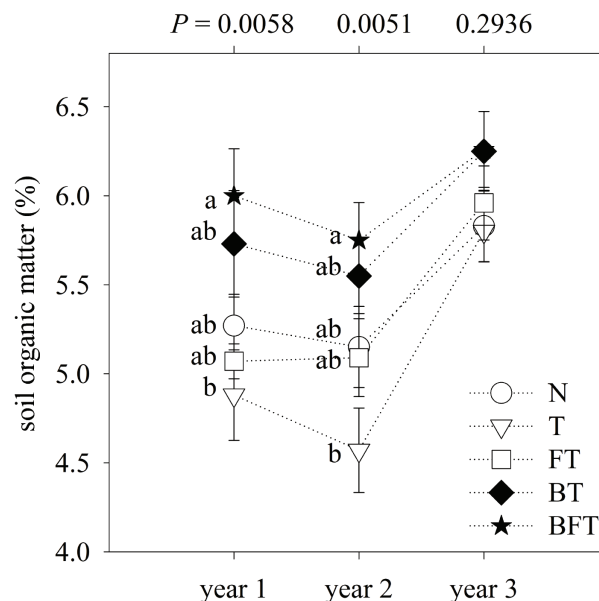
Property	N		T		FT		BT		BFT	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
GSM	17.2	0.9	16.2	0.8	16.3	0.5	17.3	0.7	16.5	0.5
WAS	59.6	2.4	60.0	1.8	61.7	2.1	55.5	2.2	61.5	2.2
pH	7.69	0.10	7.72	0.09	7.72	0.10	7.74	0.09	7.62	0.09
EC	201.7	22.8	200.9	26.7	200.9	13.2	241.4	41.4	223.2	30.4
CEC	24.8	1.1	24.4	0.8	24.9	1.4	23.7	0.6	23.1	0.3
Ca	3337	216	3286	147	3252	225	3160	135	3019	72
Mg	669	24	681	28	710	43	654	25	674	25
Na	499	93	436	74	534	80	478	75	464	77
K	179	4	166	4	172	3	167	5	178	6
P	13.0	0.9	13.0	1.1	15.4	2.1	14.8	1.7	13.6	0.9
N	0.168	0.009	0.157	0.007	0.173	0.009	0.161	0.009	0.181	0.009
C	3.49	0.18	3.42	0.14	3.43	0.16	3.74	0.15	3.88	0.19
C/N	22.2	0.9	23.1	1.0	21.2	0.9	24.8	0.9	23.0	1.2
SOM*	5.63ab**	0.16	5.29b	0.16	5.49ab	0.14	5.84ab	0.15	6.00a	0.13
DOC	52.7	1.6	54.2	1.6	54.0	1.8	52.7	1.2	53.8	1.7
POM*	7.53ab	0.90	7.23b	0.65	7.89ab	0.77	9.61ab	0.64	9.73a	0.72
MBC	219	14	204	11	196	12	188	11	216	13
RES	126	10	120	10	113	8	124	13	113	8
$qCO_2$	0.0261	0.0020	0.0249	0.0015	0.0369	0.0120	0.0284	0.0025	0.0236	0.0015
SQI*	64.9ab	2.2	60.8b	2.2	64.1ab	2.2	63.6ab	2.3	70.2a	2.3

\*Significant ( $P \leq 0.05$ ) difference with the post-hoc test.

\*\*Letters represent means separation by Tukey's Honest Significant Difference test.

RES, and  $qCO_2$ ), and aggregation (WAS). These soil properties did not respond to treatments for at least 3 possible reasons. First, treatments may not have had an impact on those specific soil properties. Second, the treatment effects may not have been significant due to masking effects from baseline levels or statistical variation. Thirdly, the amount of the treatment material may not have been sufficient to produce a significant effect for those soil properties.

It is difficult to discern which, or if any, of these explanations are correct, however, some speculation is provided below. The soils in this study were relatively alkaline and had high buffering capacities. Baseline soil sampling and characterization prior to treatments did not identify nutrient deficiencies, harmful levels of salts, low biological activity, nor low aggregate stability. Levels of N, P, K, Ca, Mg, and CEC were found to be in the medium to very high ranges for the purposes of maintaining urban tree health (Scharenbroch and Watson 2014).



**Figure 1.** Temporal responses of soil organic matter. Mean, standard errors of the means, and Tukey's HSD post hoc tests for soil organic matter. Abbreviations: null = N, tillage = T, fertilization + tillage = FT, biochar + tillage = BT, and biochar + fertilization + tillage = BFT.

Nutrient levels in the biochar are relatively low, and the N, K, and micronutrients in the fertilizer were a prescription fertilizer to meet the expected demand of the trees. Soil EC and Na were not high enough to be harmful for urban trees, and salt contents of the treatments were not excessive (Rhoades 1996). Baseline MBC and RES were not low compared to other urban soil studies (Scharenbroch et al. 2005). Even though the site has soil compaction problems, the stability of individual soil aggregates (WAS) was not low for these soils, likely due to the high clay, Ca, Mg, and organic matter levels.

### Relationships Among Tree and Soil Properties

Significant correlations were detected for soil and tree properties. Greater tree growth was correlated with lower soil pH, EC, Na,  $qCO_2$ , and higher C, C/N, MBC, and SQI (Table 5). A few other soil properties were correlated with tree properties, but these correlations were weaker and/or less consistently correlated across tree properties. Significant correlations suggest that soil properties are, at least in part, related to tree responses. These findings were expected and not particularly novel. However, these analyses distinguish some soil properties that were correlated with tree growth and may also be impacted by treatments in this study.

Measurements of organic matter (e.g., C, SOM, POM) were positively correlated with tree growth. Furthermore, significant increases in organic matter were observed with the BFT treatments. These findings suggest that improvements in soil organic matter can be attained with the BFT treatment, and this may lead to increases in tree growth. Soil organic matter is often considered the single most important soil quality parameter due to influence on most every other soil property such as nutrient mineralization and exchange, water retention, microbial activity, and habitat (Doran and Parkin 1994).

Some soil properties appeared to be important for tree growth but were not impacted by the treatments. For example, soil pH was not significantly impacted by treatments, but pH was correlated with tree properties. Tree growth tended to be negatively related to soil pH, which was reasonable and expected in these alkaline soils. Other soil properties that were correlated with tree attributes but were not impacted by treatments included salts (e.g., Na and EC) and biological

properties (MBC, RES, and  $qCO_2$ ). Tree growth was greater on sites with lower salts and higher biological activity, but these properties were not impacted by treatments. Soil nutrients (e.g., N, P, K, Ca, and Mg), moisture (GSM), and aggregation (WAS) did not appear to be important for tree growth and did not respond to treatments in this study.

### Soil Quality and Tree Growth with the Biochar, Fertilizer, and Tillage Treatment

Soil quality and tree growth were improved with the BFT treatment compared to the T alone treatment. This finding is supported by other studies showing these biochar and fertilization treatments to increase soil quality, organic matter, and plant growth (e.g., Ghosh

**Table 5. Pearson's correlation values and Prob > F values from linear fit models for soil and tree properties.**

**Abbreviations:** gravimetric soil moisture = GSM, water aggregate stability = WAS, electrical conductivity = EC, cation exchange capacity = CEC, calcium = Ca, magnesium = Mg, sodium = Na, potassium = K, phosphorus = P, nitrogen = N, carbon = C, loss on ignition = LOI, dissolved organic carbon = DOC, particulate organic matter = POM, microbial biomass carbon = MBC, respiration = RES, metabolic quotient =  $qCO_2$ , soil quality index = SQI, relative diameter growth = RDG, relative height growth = RHG, twig growth = TG, and chlorophyll content = SPAD.

Property	RDG	RHG	TG	SPAD
GSM	-0.166	-0.161	-0.174	-0.028
WAS	0.288	0.096	0.194	0.104
pH	-0.308**	-0.018	-0.355**	-0.273*
EC	-0.392**	-0.055	-0.420**	-0.251*
CEC	-0.150	0.092	0.039	0.379**
Ca	0.019	0.059	0.182	0.507***
Mg	-0.162	0.163	-0.002	0.431**
Na	-0.337**	0.007	-0.330**	-0.508***
K	-0.162	0.017	-0.128	0.034
P	-0.166	0.049	-0.172	-0.375**
N	0.206	-0.094	0.172	0.206
C	0.543***	0.029	0.503***	0.020
C/N	0.573***	0.153	0.561***	-0.051
LOI	0.076	-0.184	0.063	-0.030
DOC	-0.259	0.075	-0.337**	0.540***
POM	0.219	-0.077	0.114	-0.083
MBC	0.471***	0.118	0.499***	0.218
RES	0.118	0.001	0.034	0.071
$qCO_2$	-0.320*	-0.094	-0.366**	-0.266*
SQI	0.307**	0.044	0.333**	0.422**

\* $P \leq 0.05$

\*\* $P \leq 0.01$

\*\*\* $P < 0.0001$



et al. 2015; Plaza et al. 2016; Zhang et al. 2021). Organic matter levels increased with the BFT compared to the T treatment for 3 likely reasons.

First, it is likely that the direct addition of organic matter with the biochar increased the organic matter content in the soil. Biochar may directly increase organic matter levels in soil because it is recalcitrant and its decomposition is relatively slow (Lehmann and Joseph 2015). Biochar tree plots received  $1.075 \text{ kg organic C m}^{-2}$  ( $4.15 \text{ L m}^{-2} \times 0.3 \text{ kg L}^{-1} \times 0.865 \text{ kg organic C kg biochar}^{-1}$ ). Baseline soil organic carbon contents in these soils at the start of the experiment were approximately  $6.38 \text{ kg SOC m}^{-2}$  ( $1.7 \text{ g cm}^{-3} \times 15 \text{ cm depth} \times 0.025 \text{ g organic C g soil}^{-1} \times 1 \text{ kg 1,000 g}^{-1} \times 10,000 \text{ cm}^2 \text{ m}^{-2}$ ). Consequently, the biochar treatments were an addition of approximately 17% relative to the baseline SOC. The measured increase in SOC at year 3 with BFT treatments was on average  $2.65 \text{ kg SOC m}^{-2}$ . The biochar added in the BFT accounted for approximately 40% of this measured increase in organic C.

Secondly, the organic matter increase with the BFT treatment is likely from increased restitution of plant materials to the soil associated with increased root and shoot growth of the trees and possibly the turfgrass from the biochar and fertilization. The increased growth and restitution from the BFT treatment may be the unaccounted 19% increase in organic C contents from direct biochar addition. The current study did examine the effects of tillage alone and found no evidence of greater tree growth with tillage alone compared to the null treatment.

The greater organic matter contents in soils with the BFT relative to the T may also be a result of increased decomposition of organic matter in T treatment. Balesdent et al. (2000) reviewed the effects of tillage on organic matter levels and reported that tillage has the effect of destroying soil structure, which increases organic matter decomposition rates by exposing the organic matter that was physically protected in microaggregates. The increased decomposition and subsequent loss of organic matter associated with the T in the BFT is likely offset by increased organic matter from the fertilizer and biochar amendments. This study confirms findings of Fite et al. (2011) that tillage alone may lead to losses of organic matter.

This study did not attempt to isolate the effects of biochar and fertilization. Most research on biochar suggests that its efficacy is improved when it is charged

with a source of nutrients (e.g., Lehmann and Joseph 2015; Schmidt et al. 2017). Consequently, the arboriculture treatment that was tested in this research is based on the premise that biochar should be applied with a source of nutrients. Biochar by itself has a relatively low nutrient concentration; however, biochar has a relatively high nutrient-holding capacity (Wang et al. 2016). Consequently, an additional benefit of including biochar with a fertilizer is that it may work to limit nutrient loss that may occur with fast-release fertilizers (Widowati et al. 2011).

The effects of the BFT treatment on soil organic matter appear to be relatively short lived. No significant differences in soil properties were observed among the treatments in the third year. These results suggest that this arboricultural BFT treatment may need to be repeated for continued impact on soil properties in these types of urban landscapes.

## CONCLUSION

The results of this study suggest that the arboricultural treatment of biochar, fertilizer, and tillage may have potential for improving soils for urban trees. Soil organic matter (total and labile organic matter, total organic C, and total N) appears to be the most responsive soil attribute to this treatment, but the effects appear to be relatively short lived. The positive effects of this treatment do translate into minor short-term improvements in tree growth for at least some species. This research is important for urban tree care because it contributes field-based data on an arboricultural treatment with biochar, fertilization, and tillage with urban trees in an actual urban landscape. The vast majority of research on this topic to date has been conducted in greenhouse settings with young trees. Long-term, field-based experiments with established urban trees are needed to better understand the efficacy of arboricultural soil management of urban trees. Future research should focus on refining this arboricultural treatment. Specifically, research should be conducted on variable rates and types of biochars and fertilizers. Future research should also examine different tillage approaches. Lastly, these studies need to be conducted over longer durations on a wider range of urban trees, soils, and landscapes.

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### Conflicts of Interest:

The authors reported no conflicts of interest.

**Résumé.** Contexte: La croissance des arbres urbains peut être restreinte en raison des mauvaises conditions du sol. La gestion du sol, afin d'atténuer les conditions déficientes des sols urbains, comprend souvent des amendements organiques, la fertilisation et/ou le travail du sol. Durant trois années, une expérience fut menée sur un aménagement urbain à Bolingbrook, Illinois, États-Unis, afin de tester si un traitement arboricole avec du biocharbon, de la fertilisation et le travail du sol pouvait améliorer la qualité du sol et la croissance des arbres. Méthodes: L'aménagement urbain comprenait 75 arbres en bordure de rues (*Gleditsia triacanthos*, *Ulmus parvifolia* et *Acer rubrum*) croissant dans des sols compactés à texture fine. Résultats: Les résultats de cette expérience suggèrent que le traitement arboricole de biocharbon, de fertilisation et de travail du sol (BFT) peut améliorer la qualité du sol et la croissance des arbres urbains. La croissance relative en hauteur était significativement plus importante ( $P \leq 0,05$ ) pour les *Acer rubrum* avec le traitement BFT (+ 28,9 %) par rapport au seul travail du sol (+ 13,3 %). La matière organique totale (MOS), la matière organique particulaire (MOP) et un indice de qualité (IQS) du sol étaient significativement ( $P \leq 0,05$ ) plus élevés dans le traitement BFT (MOS totale = 6,00 %, MOP = 9,73 % et IQS = 70,2) par rapport au seul travail du sol (MOS totale = 5,29 %, MOP = 7,23 % et IQS = 60,8). Les réactions de la MOS au traitement BFT semblent être relativement de courte durée mais corrélées aux mesures de la croissance des arbres. Conclusions: Ce traitement arboricole de biocharbon, de fertilisation et de travail du sol a le potentiel d'être utilisé afin d'améliorer la qualité du sol et de promouvoir la croissance des arbres qui poussent dans des sols compactés à texture fine dans les aménagements d'arbres de rue en banlieue.

**Zusammenfassung.** Hintergrund: Das Wachstum von Bäumen in Städten kann durch schlechte Bodenverhältnisse beeinträchtigt werden. Die Bodenbewirtschaftung zur Behebung schlechter städtischer Bodenverhältnisse umfasst häufig organische Ergänzungen, Düngung und/oder Bodenbearbeitung. In einer städtischen Landschaft in Bolingbrook (Illinois, USA) wurde ein dreijähriges Experiment durchgeführt, um zu prüfen, ob eine baumpflegerische Behandlung mit Biokohle, Düngung

und Bodenbearbeitung die Bodenqualität und das Baumwachstum verbessern kann. Methoden: Die städtische Landschaft umfasste 75 Straßenbäume die in verdichteten, feinkörnigen Böden wuchsen (*Gleditsia triacanthos*, *Ulmus parvifolia* und *Acer rubrum*). Ergebnisse: Die Ergebnisse dieses Experiments deuten darauf hin, dass die baumpflegerische Behandlung mit Biokohle, Düngung und Bodenbearbeitung (BFT) die Bodenqualität und das Wachstum der Stadtbäume verbessern kann. Das relative Höhenwachstum war bei *Acer rubrum* mit BFT-Behandlung (+ 28,9 %) signifikant größer ( $P \leq 0,05$ ) als bei alleiniger Bodenbearbeitung (+ 13,3 %). Die gesamte organische Bodensubstanz (SOM), die partikuläre organische Bodensubstanz (POM) und der Bodenqualitätsindex (SQI) waren bei der BFT-Behandlung signifikant ( $P \leq 0,05$ ) höher (gesamte SOM = 6,00 %, POM = 9,73 % und SQI = 70,2) als bei der Bodenbearbeitung (gesamte SOM = 5,29 %, POM = 7,23 % und SQI = 60,8). Die SOM-Reaktionen auf die BFT-Behandlung scheinen relativ kurzlebig zu sein, aber sie korrelieren mit Messungen des Baumwachstums. Schlussfolgerungen: Diese baumpflegerische Behandlung aus Biokohle, Düngung und Bodenbearbeitung hat das Potenzial, die Bodenqualität zu verbessern und das Wachstum von Bäumen zu fördern, die in verdichteten, fein strukturierten Böden in vorstädtischen Straßenbaumlandschaften wachsen.

**Resumen.** Antecedentes: El crecimiento de los árboles urbanos puede reducirse debido a las malas condiciones del suelo urbano. El manejo del suelo para aliviar las malas condiciones del suelo urbano a menudo incluye enmiendas orgánicas, fertilización y/o labranza. Se realizó un experimento de 3 años en un paisaje urbano en Bolingbrook, Illinois, EE. UU. para probar si un tratamiento de arboricultura con biocarbón, fertilización y labranza podría mejorar la calidad del suelo y el crecimiento de los árboles. Métodos: El paisaje urbano incluyó 75 árboles urbanos (*Gleditsia triacanthos*, *Ulmus parvifolia* y *Acer rubrum*) que crecen en suelos compactados y de textura fina. Resultados: Los resultados de este experimento sugieren que el tratamiento arboricultural del biochar, la fertilización y la labranza (BFT) puede mejorar la calidad del suelo y el crecimiento de los árboles urbanos. El crecimiento relativo de la altura fue significativamente mayor ( $P \leq 0,05$ ) para los árboles de *Acer rubrum* con tratamiento BFT (+ 28,9%) en comparación con la labranza sola (+ 13,3%). La materia orgánica total del suelo (SOM), la materia orgánica del suelo particulada (POM) y un índice de calidad del suelo (SQI) fueron significativamente ( $P \leq 0,05$ ) mayores en el tratamiento BFT (SOM total = 6,00%, POM = 9,73% y SQI = 70,2) en comparación con el tratamiento de labranza (SOM total = 5,29%, POM = 7,23% y SQI = 60,8). Las respuestas SOM al tratamiento BFT parecen ser relativamente de corta duración, pero se correlacionan con las medidas de crecimiento de los árboles. Conclusiones: Este tratamiento arboricultural del biocarbón, la fertilización y la labranza tiene potencial de ser utilizado para mejorar la calidad del suelo y promover el crecimiento de árboles que crecen en suelos compactados y de textura fina en paisajes arbóreos suburbanos.