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# Feasibility of constructed soils for tree planting – A pilot study in New York City

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A R T I C L E I N F O

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A B S T R A C T

Constructed soils are soils that are created with a mixture of various materials. An innovative soil exchange program - the Clean Soil Bank (CSB) in New York City allows recycling of clean glacial outwash sediments excavated from depth at construction sites. One previous study showed that soils constructed from CSB sediment and compost can effectively support crop growth in community gardens, but no research has been conducted on its potential usage as a medium for tree growth. Moreover, biochar has been used to improve soil quality, but its efficacy for street trees incorporated into constructed soils has largely not been quantified in the field. The objective of this project was to evaluate the feasibility of using soils constructed from the CSB and compost for tree planting and to investigate the impact of biochar on tree performance. Thirty-six trees of two species (*Maackia amurensis* and *Zelkova serrata*) were planted in 2019, on the sidewalks of a residential-business neighborhood in Bronx, New York. Each tree pit contains one of three soil types: type A - existing and purchased topsoil mixed with 33% compost and biochar, type B - CSB sediment mixed with 33% compost, and type C - CSB sediment mixed with 33% compost and biochar. Soil samples were collected in 2019 (before planting) and in 2021. Tree health assessments were conducted in September 2020 and July 2021 using a protocol developed by the USDA Forest Service. Other tree health parameters collected include diameter at breast height (DBH), crown diameter, tree height, photosynthetic capacity, and foliar chemistry. Significant differences in bulk density, water holding capacity, and K, Fe, and Zn concentrations were found among the three soil types. However, comparison of tree performance and foliar chemistry showed no systematic differences among the three soil types. The results indicate that CSB sediment mixed with compost can be an effective replacement for purchased topsoil for tree growth. No evidence was found that biochar provides additional benefits to street tree performance. Considering the abundant availability of glacial outwash sediment at low cost to the city, as well as access to locally produced compost, constructed soils can be a reliable source of material for urban forestry programs.

## 1. Introduction

Globally, urban land cover is projected to increase by 1.2 million km$^2$ before 2030, nearly tripling the area circa 2000 (Seto et al., 2012). Because urban soils are often infertile, contaminated, and degraded, clean and arable soils are required to support planting, reclamation, and

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other earthwork in the city (Deeb et al., 2020; Pouyat et al., 2010, 2020). With increasing demand of green projects to mitigate impacts from climate change and population growth, many cities could experience increased demand for soil in coming decades (Walsh et al., 2019). Today, large quantities of topsoil are transported from agricultural and forest areas to cities, but soil transportation from nonurban areas is not sustainable since arable land is also rapidly decreasing. Soil is a limited resource as new soil formation takes hundreds to thousands of years (Deeb et al., 2020). In addition, transporting topsoil is expensive and contributes significantly to greenhouse gas emissions and air pollution. Alternatives to soil transportation are needed to meet the increasing demand of new urban soils.

Technosols are artificial soils that are created through mixtures of various materials (Deeb et al., 2020; Fabbri et al., 2021). The World Reference Base for Soil Resources defines technosols as soils which contain greater than 20% artificial materials by volume and are within the first 100 cm of the land surface (IUSS Working Group WRB (2015)). Technosols could be created intentionally or unintentionally, and intentionally created technosols are also referred to as constructed soils (Rodríguez-Espinosa et al., 2021). Soil construction was described by Séré et al. (2008) as a process "using wastes and industrial by-products which are formulated and stacked in layers to build a new soil profile over in situ degraded substrates." Deeb et al., (2020) defined constructed soil as "the result of the voluntary action of creating a soil using artefacts and intentionally shaping them to provide a suitable environment for vegetation growth." In this study, we will adopt the definition proposed by Deeb et al. (2020) because it includes one of the most important functions of soil – plant growth.

Recently, there has been increasing interest in developing constructed soils with recycled wastes and by-products as a way to meet the demands for urban soil (Fabbri et al., 2021; Rodríguez-Espinosa et al., 2021). The reuse of urban wastes that would otherwise be landfilled is consistent with sustainability and circular economy objectives. Wastes that have been used as a matrix for constructed soil include terrestrial or glacially deposited sediments, excavated subsoil, bricks, concrete, dredged sediment, compost, green wastes, and mining wastes (Darmody and Marlin, 2002; Egendorf et al., 2018; Fabbri et al., 2021; Rokia et al., 2014; Yilmaz et al., 2018).

Studies testing different urban waste mixtures have shown that soils constructed from wastes can effectively support plant growth (Barredo et al., 2020; Cannavo et al., 2018; Fourvel et al., 2019; Grard et al., 2018; Rokia et al., 2014; Séré et al., 2008, 2010; Yilmaz et al., 2018). Through monitoring soil quality and tree performance in constructed soils created from a mixture of excavated deep horizon soil, green waste compost, and crushed concrete, Pruvost et al. (2020) found that constructed soils are promising for planting trees and hosting soil biodiversity within cities. However, they also noticed varied rates of tree mortality among different tested species and different constructed soil mixtures. Many researchers believe that the choice of organic wastes for constructed soil is crucial for plant growth (Cannavo et al., 2018; Deeb, Grimaldi, Lerch, Pando, Podwojewski, et al., 2016; Yilmaz et al., 2018). For example, Deeb et al. (2016) found that while green waste compost can increase water holding capacity of constructed soils, a larger quantity (> 20%) of expensive green waste compost is unnecessary to achieve satisfactory plant performance. Impacts of organisms and plants should also be considered when designing constructed soils (Deeb, Grimaldi, Lerch, Pando, Gigon, et al., 2016; Dick et al., 2006; Jangorzo et al., 2015; Świątek et al., 2019). Further research is required to identify the most suitable constructed soil formulation for specific tree species in specific locations.

To promote recycling, soil exchange programs that transfer clean sediment directly from construction projects have been developed in many countries, but these programs are typically run at the national or provincial scale (Choi et al., 2017; Walsh et al., 2018). Established in 2013 by the New York City (NYC) Mayor's Office of Environmental Remediation, the Clean Soil Bank (CSB) is an innovative city scale soil exchange program that aims to beneficially reuse the clean glacial outwash sediment excavated from the city's construction sites. Benefits of recycling native sediment rather than disposing it outside of the city include reduced truck traffic, reduced transport distance and gasoline consumption, reduced air pollutant emissions, and availability of low-cost clean soil for construction projects in the city. Unlike natural soil materials used to construct soil (Pruvost et al., 2020 etc.), CSB sediment contains little clay and silt and therefore needs additional amendment to support plant growth. One study shows that CSB sediments mixed with 33%-50% compost by volume can provide comparable crop yields to purchased soils in community gardens while reducing exposure to lead (Pb) (Egendorf et al., 2018). However, no research has been conducted to investigate the potential of using CSB/compost mixtures as a medium for street tree growth. Furthermore, NYC uses biochar to improve soil quality and tree health, but the efficacy of this innovative material (a product that can also be derived from organic waste) needs further evaluation in this context.

This project aimed to study the feasibility of using constructed soil from the CSB for NYC's street tree planting program. Questions addressed in this project included: i) How does a CSB/compost mixture compare to purchased topsoil as a growing medium for street trees? ii) How does biochar affect street tree performance?

## 2. Methodology

Thirty-six trees of two species used in the NYC street tree planting program were studied in this project. Seventeen *Maackia amurensis* (Amur maackia) and nineteen *Zelkova serrata* (Japanese zelkova) were planted in total. Both species are common in NYC as street trees, and both are tolerant of conditions in the urban environment.

NYC is in USDA hardiness zone 7a/b and features a humid subtropical climate. Average annual temperature is 12 °C and average annual precipitation ranges from 109 to 127 cm. On December 20, 2019, the New York City Department of Parks & Recreation (NYC Parks) installed 36 street trees in the Soundview neighborhood of the Bronx, NYC, USA (Fig. 1) using street tree planting standard protocols (NYC Parks, 2016). All trees were classified under the same caliper size range of 6.35–7.63 cm (2.5–3 in) caliper at the time of planting. The trees were all dug at the same time, from the same nursery (Whitman Nurseries). Each tree pit contained 2.3 $m^3$ (3 $yd^3$) of soil, prepared in one of three different ways. Soil type A is existing and purchased topsoil mixed with 33% compost (in volume) and biochar. Soil type B is CSB mixed with 33% compost. Soil type C is CSB mixed with 33% compost and biochar. Compost was provided by the NYC Department of Sanitation and biochar was purchased by NYC Parks. For type A and type C, biochar was applied in the upper 0.15–0.2 m (6–8 in) of the tree pit at a rate of 0.003 $m^3$ (0.1 $ft^3$) per tree upon installation. There were six tree species × soil type combinations, each with five to seven replicates (Fig. 1). Hereafter, we will refer to soils as soil type A, B, and C, and trees installed in those soil types as group A, B, and C in this paper.

In 2019 and prior to mixing with compost, soil samples from three randomly selected tree pits and two CSB sediment batches were collected and sent to the Urban Soils Lab at Brooklyn College for analysis. Soil particle-size distribution was analyzed using the hydrometer method (Gee and Bauder, 1986). Soil pH was measured with a double junction pH meter with a 1:1 soil:water ratio, and salt content or electrical conductivity (EC) was measured with a conductivity probe with 1:2 soil:water ratio. The standard loss-on-ignition method was used to determine the organic content in soil. Total carbon (C), total nitrogen (N), and carbon-to-nitrogen ratio (C/N) were determined with a CHN analyzer.

In 2021, soil samples from each of 36 tree pits were collected: three duplicate cores were collected for bulk density measurements; a composite sample was collected to test for other soil properties. For composite sampling, soils up to 0.3 m (1 ft) depth were collected from a minimum of three spots in the tree pit with an auger and pooled

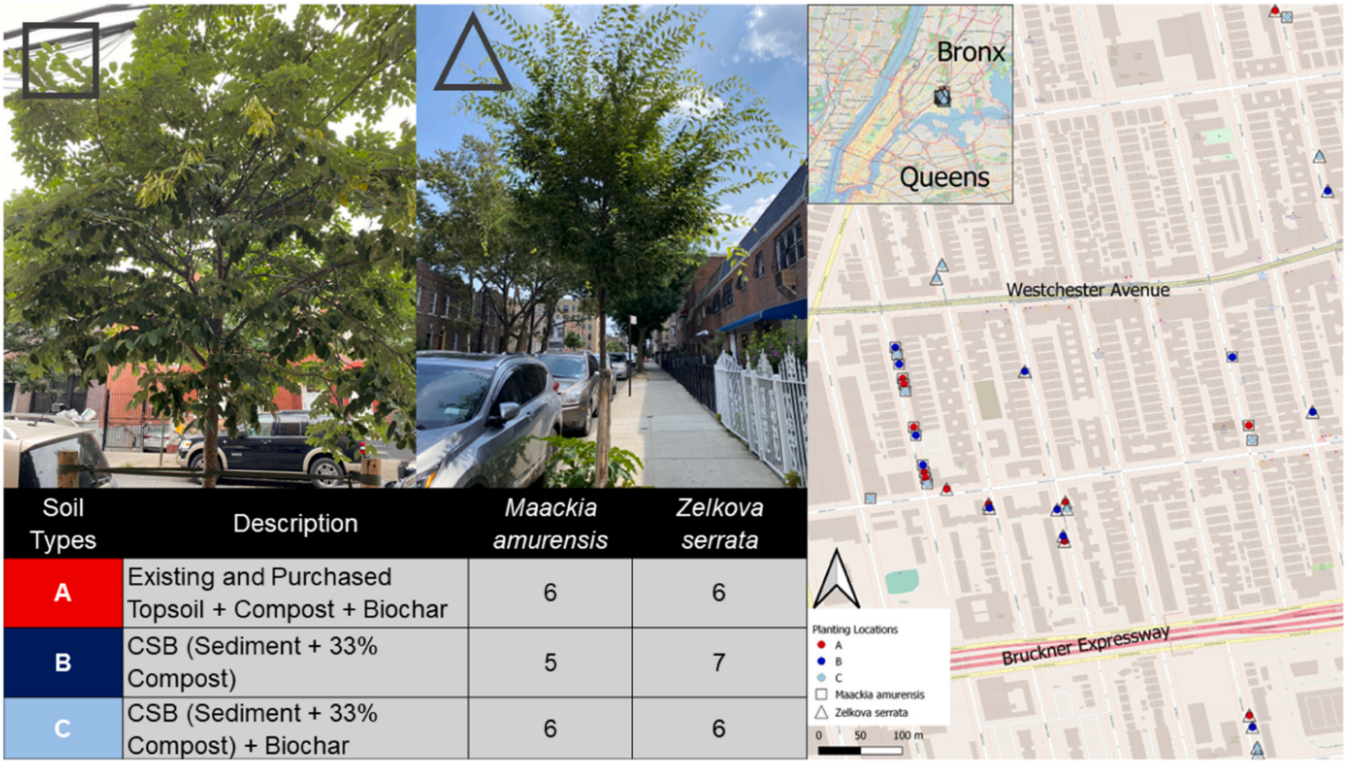


**Fig. 1.** 17 *Maackia amurensis* and 19 *Zelkova serrata* trees were installed in three soil types in Bronx, NYC. Soil type A is existing and purchased soil plus biochar and compost, type B is CSB/compost mixture, and type C is CSB/compost mixture plus biochar.

together. The sample was thoroughly mixed in clean plastic bucket on site, and then a sub-sample was put into a labeled plastic ziplock bag and shipped to the lab in a cooler with ice. Concentrations of C, N, phosphorus (P), potassium (K), sulphate ($SO_4$), calcium (Ca), magnesium (Mg), iron (Fe), zinc (Zn), boron (B), copper (Cu), and C/N were measured at the Soil, Water and Forage Analytical Laboratory (SWFAL) of Oklahoma State University. Bulk density, pH, EC, and water holding capacity were measured at Brooklyn College. Methods used to determine total C, total N, C/N, pH, EC, and water holding capacity were same as the ones applied in 2019. The protocols at the SWFAL lab can be found at https://extension.okstate.edu/fact-sheets/procedures-used-by-osu-soil-water-and-forage-analytical-laboratory.html#soil-fertility-tests. Microbial respiration, biomass C, and biomass N were analyzed at the Advanced Science Research Center of CUNY. Microbial biomass C and N content were measured using the chloroform fumigation-incubation method (Jenkinson and Powlson, 1976) as described by Bohlen et al. (2001). Microbial respiration was measured in ten-day laboratory incubations as described by Bohlen et al. (2001).

Tree health assessments were conducted in September 2020 and July 2021 using a protocol developed by the USDA Forest Service Northern Research Station (Pontius and Hallett, 2014). Five tree health variables (fine twig dieback, leaf discoloration, leaf defoliation, crown transparency, and crown vigor) were rated in the field visually and then standardized to the same scale as a z-score using the mean and standard deviation from USDA's tree database (https://www.conservationgateway.org/ConservationPractices/cities/hthc/Pages/default.aspx).
Because data for the crown transparency of *Maackia amurensis* is missing from USDA's database, the z-score for this variable was not calculated for this species. Finally, one overall z-score was calculated from those five variables (four for *Maackia amurensis*) for each tree. The overall z-score measures the tree stress compared to the average value of the USDA urban tree population for that species. A positive z-score indicates that the tree is more stressed than a regular urban tree, and the higher the z-score, the more stressed the tree is. This method has been adopted in previous studies of urban tree health (Hallett et al., 2018; Hallett and Hallett, 2018; Pregitzer et al., 2016).

Diameter at breast height for each tree was measured in both September 2020 and July 2021. In July 2021, crown diameter and tree height were also measured. In addition, tree leaves were collected in July 2021. A handy PEA chlorophyll fluorescence meter was used to measure metrics related to photosynthetic activity of five leaves from each tree after leaves were dark adapted for 30 min (Hansatech Instruments, 2006). Two indices were calculated by the handy PEA: Fv/Fm and PI. Fv/Fm is the ratio of variable fluorescence (Fv) divided by maximal fluorescence (Fm) and is a measure of the maximum quantum efficiency of photosystem II. The performance index (PI) reflects the overall photosynthetic performance and health of the leaf. Previous studies have shown that PI is more sensitive to water stress than Fv/Fm (Sepúlveda and M. Johnstone (2018); Živčák et al., 2008). Light exposure of all tree crowns was also assessed in the field.

Ten healthy leaves from each tree were oven-dried and digested using a microwave-assisted acid digestion procedure (USEPA Method 3052), and analyzed for P, K, sulfur (S), Ca, Mg, Fe, Zn, manganese (Mn), Cu, aluminum (Al), sodium (Na), cadmium (Cd), chromium (Cr), lead (Pb), and barium (Ba) by ICP spectroscopy (Agilent 740 ICPoes). Foliar C and N were determined through combustion with a PerkinElmer 2400 series II CHNS/O analyzer (PerkinElmer, Waltham, MA). All analyses were conducted at the Louis C. Wyman Forestry Sciences Laboratory, Durham, NH.

The software package R (version 4.0.2) was used for statistical analysis. Sample normality for all parameters was tested using the Shapiro–Wilk test. Outliers were detected with the 1.5*IRQ rule. After removing outliers, one-way analysis of variance (ANOVA) followed by Tukey's honestly significant difference (HSD) test was conducted to determine significant differences in tree performance or soil parameters among the three groups. Paired t-tests were used to compare the stress index (overall z-score) and DBH collected in 2021 and 2020. In all cases, differences were considered to be statistically significant at $p < 0.05$.

Nonparametric tests (Kruskal-Wallis rank sum test and paired sample Wilcoxon test) were used when the dataset did not fit the normal distribution or homogeneity of variances were not matched.

## 3. Results

### 3.1. Soil properties

Table 1 shows the properties of soil samples collected from existing tree pits (n = 3) and CSB sediment (n = 2) before mixing with compost in 2019. Compared to the existing soil, CSB sediment has a higher content of sand, and lower content of silt and clay. The average pH value of CSB sediment is 7.5, which is higher than the average pH value of 5.9 for the existing soil. The CSB sediment also has a lower organic content and higher C/N ratio than the existing soil.

Table 2 shows the average properties of soil samples collected from all 36 tree pits in 2021 grouped by soil types. Average pH value is 5.7 for soil type A and type B, and 6.3 for type C. No significant difference was detected for pH values over the three soil types. This was true for parameters including EC, N, P, $SO_4$, Ca, Mg, B, Cu, C/N, respiration, microbial biomass C, and microbial biomass N. Soil type B and C have a significantly higher bulk density than soil type A. Soil type A shows significantly higher levels of water holding capacity, K, Fe, and Zn than soil type C.

### 3.2. Tree performance indicators

#### 3.2.1. Overall z-scores

Fig. 2 shows the overall z-score for trees in 2020 and 2021, respectively. In 2020, the overall z-score ranged from −0.22–2.41 for *Maackia amurensis*, and −0.35–2.45 for *Zelkova serrata*. In 2021, the overall z-score ranged from −0.17–5.19 for *Maackia amurensis*, and 0.19–1.52 for *Zelkova serrata*. Comparison of overall z-scores showed no statistically significant difference among the three groups ($P > 0.05$). This was true for both species in 2020 and 2021. *Maackia amurensis* had a significantly higher overall z-score in 2021 than in 2020 ($P < 0.05$).

#### 3.2.2. Tree health variables

To better understand tree performance, tree health variables were also analyzed separately. Fig. 3 shows individual z-scores for the five tree health variables. For most trees, leaf discoloration was the main contributor to the overall z-score in 2020, whereas leaf defoliation was the main contributor in 2021. Crown vigor, which is impacted by leaf discoloration and leaf defoliation, also played an important role in both years.

Rating scores of the five tree health variables over the three soil types were compared separately. Significant differences over the three groups were only detected for leaf defoliation of *Zelkova serrata* during 2021 ($P < 0.01$). For *Maackia amurensis*, crown transparency was not included in overall z-score calculation due to lack of reference data. However, comparison of crown transparency rating scores showed no significant difference over the three groups.

#### 3.2.3. DBH and tree height

Fig. 4 shows the DBH for all 36 trees in 2020 and 2021. In 2020, the DBH ranged from 4.35 cm to 6.37 cm for *Maackia amurensis*, and from 4.95 cm to 6.52 cm for *Zelkova serrata*. In 2021, the DBH ranged from 4.71 cm to 7.38 cm for *Maackia amurensis*, and from 5.98 cm to 8.12 cm

**Table 2**
Mean ± SE, soil properties of type A (n = 12), B (n = 12), and C (n = 12) in 2021. The last column shows the comparison results of soil properties among the three types using one-way ANOVA or Kruskal-Wallis test after removing outliers (*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$). Soil type A is existing and purchased soil plus biochar and compost, type B is CSB/compost mixture, and type C is CSB/compost mixture plus biochar.

| | A | B | C | A vs B vs C (p-value) |
|---|---|---|---|---|
| pH | 5.7 ± 0.3 | 5.7 ± 0.3 | 6.3 ± 0.3 | 0.11 |
| Electrical conductivity (dS/m) | 0.1 ± 0.0 | 0.2 ± 0.1 | 0.2 ± 0.1 | 0.43 |
| Bulk Density (g/cm$^3$) | 0.8 ± 0.1 | 0.9 ± 0.1 | 0.9 ± 0.1 | **0.01*** |
| Water Holding Capacity (%) | 56.1 ± 5.3 | 47.5 ± 6.3 | 40.4 ± 3.8 | **0.01*** |
| N (mg kg$^{-1}$) | 105.5 ± 67.0 | 60.0 ±20.8 | 69.5 ± 30.1 | 0.36 |
| P (mg kg$^{-1}$) | 349.0 ± 53.4 | 269.0 ± 36.4 | 213.0 ± 36.0 | 0.09 |
| K (mg kg$^{-1}$) | 168.0 ± 50.1 | 97.5 ± 10.0 | 97.5 ± 17.5 | **0.02*** |
| $SO_4$ (mg kg$^{-1}$) | 18.0 ± 11.1 | 9.5 ± 2.3 | 11.5 ± 4.3 | 0.48 |
| Ca (mg kg$^{-1}$) | 1704.5 ± 194.6 | 1503.0 ± 124.2 | 1640.5 ± 65.3 | 0.38 |
| Mg (mg kg$^{-1}$) | 152.5 ± 9.6 | 159.5 ± 13.6 | 138.5 ± 11.9 | 0.14 |
| Fe (mg kg$^{-1}$) | 55.1 ± 5.7 | 45.2 ± 5.5 | 39.6 ± 7.3 | **4.79E-03*** ** |
| Zn (mg kg$^{-1}$) | 10.8 ± 1.2 | 8.2 ± 1.1 | 8.5 ± 1.6 | **0.01*** |
| B (mg kg$^{-1}$) | 0.4 ± 0.1 | 0.4 ± 0.0 | 0.5 ± 0.1 | 0.85 |
| Cu (mg kg$^{-1}$) | 7.8 ± 1.0 | 4.5 ± 0.5 | 5.7 ± 1.1 | 0.22 |
| C/N | 15.3 ± 0.7 | 15.8 ± 0.7 | 16.6 ± 0.7 | 0.29 |
| Respiration (ug C/g soil/day) | 9.9 ± 1.0 | 7.7 ± 1.1 | 8.0 ± 0.8 | 0.08 |
| Biomass C (ug C/g soil) | 641 ± 81.0 | 398 ± 60.6 | 433 ± 35.3 | 0.05 |
| Biomass N (ug N/g dry soil) | 88 ± 31.4 | 50 ± 8.6 | 46 ± 9.4 | 0.72 |

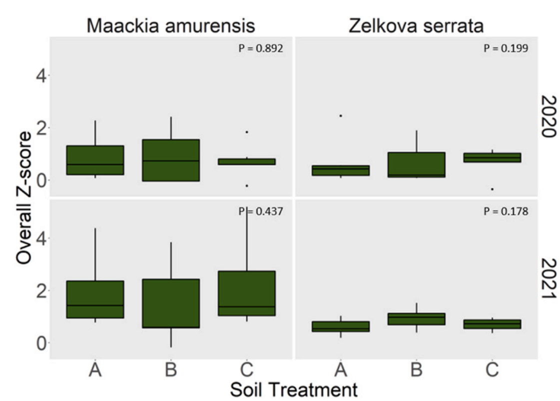


**Fig. 2.** Boxplot comparing overall z-score or stress for trees installed in three soil types measured in 2020 and 2021, the middle bar is the median, the box extends from 25% to 75% quartiles, and vertical lines extend to minimum and maximum values. Soil type A is existing and purchased soil plus biochar and compost, type B is CSB/compost mixture, and type C is CSB/compost mixture plus biochar. No statistically significant difference was detected among the three tree groups ($P > 0.05$).

**Table 1**
Average soil properties of existing soil (n = 3) and Clean Soil Bank sediment (n = 2) before mixing with compost in 2019. EC: electrical conductivity, OC: organic content, WHC: water holding capacity).

| | pH | EC (dS/m) | OC (%) | WHC (%) | Texture | Sand % | Silt % | Clay % | Total C (%) | Total N (%) | C/N |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Existing Soil | 5.9 | 0.2 | 9.0 | 41.1 | Loamy sand or sandy loam | 77.9 | 17.6 | 4.5 | 5.1 | 0.2 | 24.8 |
| CSB Sediment | 7.5 | 0.1 | 3.3 | 54.9 | Sand | 93.5 | 4.24 | 2.26 | 2.9 | <0.1 | 70.6 |

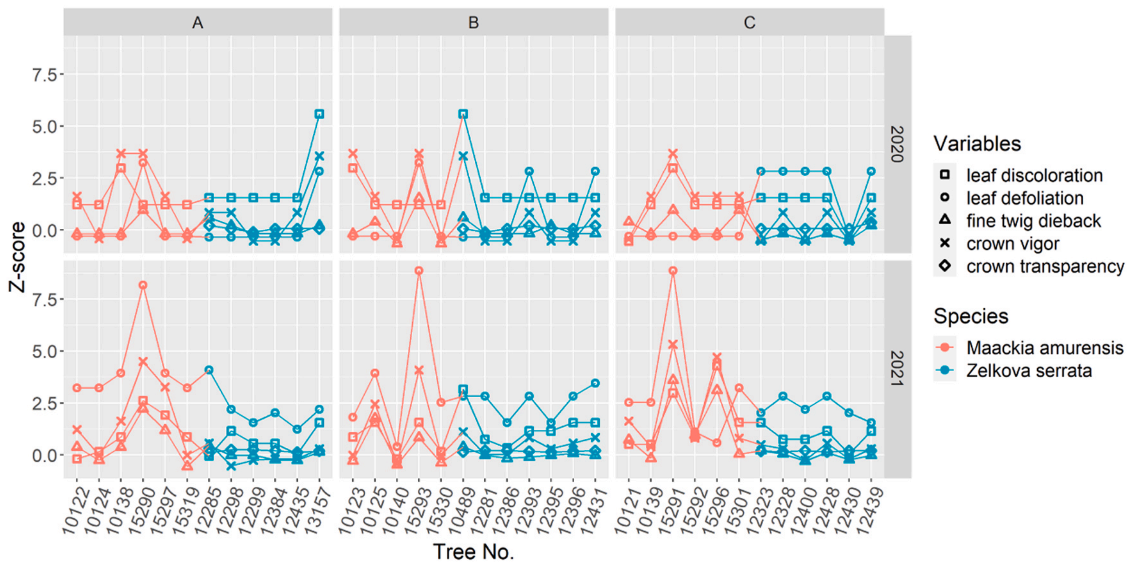


**Fig. 3.** Z-score of five tree health variables for tree groups planted in three soil types during 2020 and 2021. Soil type A is existing and purchased soil plus biochar and compost, type B is CSB/compost mixture, and type C is CSB/compost mixture plus biochar.

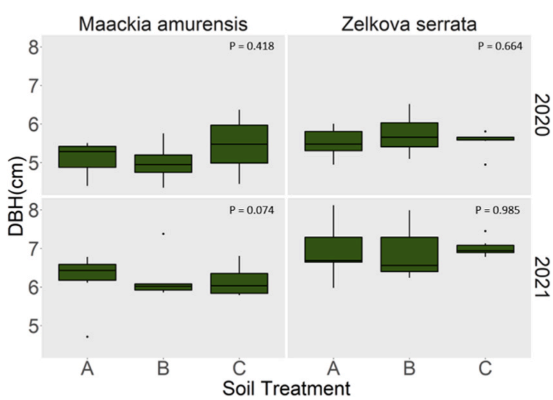


**Fig. 4.** Boxplot comparing diameter at breast height (DBH) for trees installed in three soil types measured in 2020 and 2021, the middle bar is the median, the box extends from 25% to 75% quartiles, and vertical lines extend to minimum and maximum values. Soil type A is existing and purchased soil plus biochar and compost, type B is CSB/compost mixture, and type C is CSB/compost mixture plus biochar. No statistically significant difference was detected among the three tree groups ($P > 0.05$).

for *Zelkova serrata*. DBH growth from 2020 to 2021 ranged from 0.31 cm to 1.62 cm or 6–34.7% for *Maackia amurensis*. DBH growth from 2020 to 2021 ranged from 0.79 cm to 2.46 cm or 13.5–43.5% for *Zelkova serrata*.

Comparison of DBH among the three groups showed no significant difference ($P > 0.05$), for either species in 2020 or 2021. Comparison of DBH growth from 2020 to 2021 among the three groups also showed no significant differences ($P > 0.05$).

In July 2021, the average height was 480 cm for *Maackia amurensis* trees and 582 cm for *Zelkova serrata* (Fig. 5). Average crown diameter was 224 cm for *Maackia amurensis* and 280 cm for *Zelkova serrata* (Fig. 5). Like DBH, no significant differences in crown diameter or height were observed among the three soil groups ($P > 0.05$) in either 2020 or 2021.

### 3.2.4. Photosynthetic capability

Fig. 6 shows the measurement ratio of maximum potential quantum efficiency of PSII (Fv/Fm) and performance index (PI) of healthy leaves, both of which measure photosynthetic capacity. The average Fv/Fm was 0.82 for both species. The average PI was 11.26 for *Maackia amurenis* and 8.48 for *Zelkova serrata*. Comparison of photosynthetic capacity indicators showed a significant difference in Fv/Fm for *Zelkova serrata* among the three tree groups ($P < 0.05$), but not for *Maackia amurensis* ($P > 0.05$). Using Turkey HSD test, we found that group B and C has significantly higher Fv/Fm than group A ($P < 0.05$). No significant difference in PI were detected over the three soil groups ($P > 0.05$). There were also no differences in light exposure of the tree crowns for either species in either year.

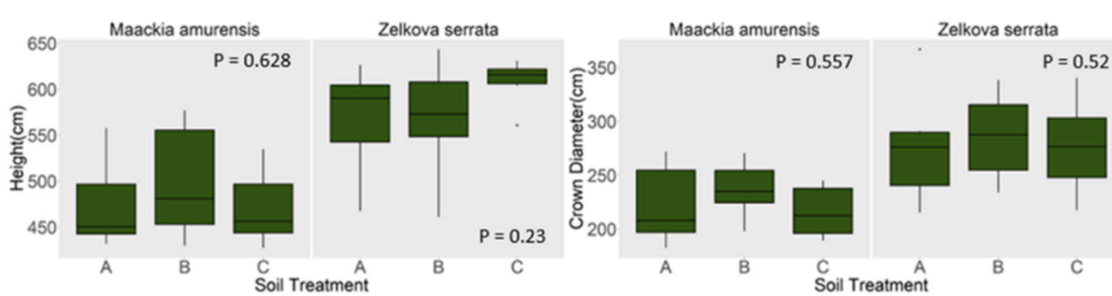


**Fig. 5.** Boxplot comparing growth indicators (crown size and height) for trees installed in three soil treatment types measured in 2021, the middle bar is the median, the box extends from 25% to 75% quartiles, and vertical lines extend to minimum and maximum values for three soil treatment types in 2021. Soil type A is existing and purchased soil plus biochar and compost, type B is CSB/compost mixture, and type C is CSB/compost mixture plus biochar. No statistically significant difference was detected among the three tree groups ($P > 0.05$).

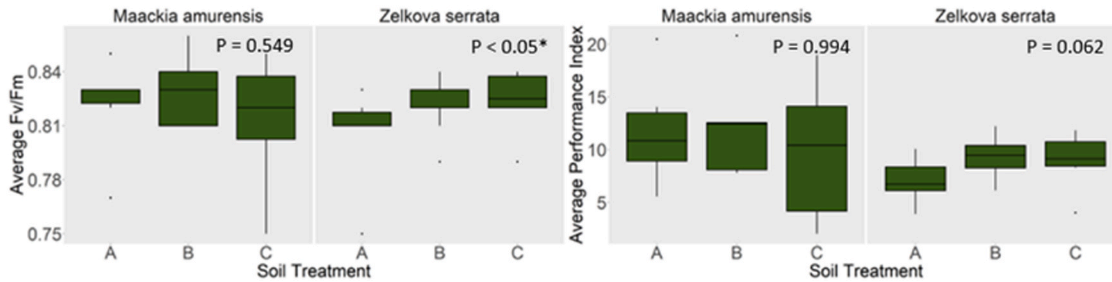


**Fig. 6.** Boxplot comparing photosynthetic capacity indicators (Fv/Fm and PI) for trees installed in three soil treatment types measured in 2021, the middle bar is the median, the box extends from 25% to 75% quartiles, and vertical lines extend to minimum and maximum values for three soil treatment types in 2021. Soil type A is existing and purchased soil plus biochar and compost, type B is CSB/compost mixture, and type C is CSB/compost mixture plus biochar. Except in Fv/Fm for *Zelkova serrata*, no statistically significant difference among the three tree groups (P < 0.05).

#### 3.2.5. Foliar chemical composition

Comparison of leaf chemistry among the three soil groups shows no significant difference for most elements (Table 3). For *Maackia amurensis*, significant differences were detected in P, Zn, and Na using ANOVA. Turkey's HSD test show that P content in group A was significantly higher than group B and C. Na content in group C was significantly higher than group A and B. However, Turkey's HSD test did not reveal any significant differences in Zn content among the three groups.

For *Zelkova serrata*, significant differences were detected in S, Na, and Pb by ANOVA. Turkey's HSD tests show that S content in group C was significantly higher than groups A and B, but no significant difference was detected for the other two elements.

## 4. Discussion

### 4.1. Experimental conditions

All three soil types were generally acidic two years after planting. This observation is consistent with findings from other studies conducted in NYC (e.g., Smith et al., 2021). It should be noted that the two species used in this study could adapt to a wide range of pH levels (Brady and Weil, 2008). Soil types B and C have slightly but significantly higher bulk densities than soil type A, but all soil types have bulk densities lower than the critical threshold of 1.4–1.6 g/cm$^3$, above which root growth will be severely impacted (Day et al., 2010; Day and Bassuk, 1994; Jim, 1993; Ley et al., 1995). Soil type A shows significantly higher levels of water holding capacity, K, Fe, and Zn than soil type C. However, we don't believe these differences are systematic since both soil type B and type C are constructed from the same glacial outwash sediment, and no significant differences were detected between type A and type B. Furthermore, the content of soil parameters generally falls into the ranges observed by other soil studies conducted in NYC (Deeb et al., 2018; Egendorf et al., 2018; Smith et al., 2021). No significant differences in tree performance indicators including overall z-score, DBH, height, crown diameter, and PI were detected among the three tree groups, indicating that the observed differences in soil parameters did not affect tree performance so far.

Based on the overall z-score, trees in all three soil types were slightly stressed compared to the average value of USDA's urban trees database (base population). One potential reason may be that our trees are all less than two years old and young trees may be less tolerant of urban conditions compared to mature trees. *Maackia amurensis* had a larger z-score variance than *Zelkova serrata*. Human activities may cause the large variation in z-score. For example, we observed that some tree pits had flowers installed by local residents, some had visible animal waste, and some still had Christmas lights on the stems and branches during our fieldwork. Moreover, we observed construction scaffolding around three *Maackia amurensis* and two *Zelkova serrata* trees.

Based on the individual z-score, leaf discoloration and leaf defoliation were the main contributors to the overall z-score in 2020 and 2021 for most trees. Compared to the other three tree health variables (fine twig dieback, crown transparency, and crown vigor), leaf discoloration and leaf defoliation were more mild signs of stress, indicating that trees were still in the early stage of stress.

*Maackia amurensis* had a significantly higher overall z-score in 2021 than in 2020 (P < 0.05), which indicates higher stress in 2021.

**Table 3**
Mean ± SE, foliar chemistry of *Maackia amurensis* and *Zelkova serrata* installed in soil type A, B, and C measured in 2021. The last column shows the comparison results of foliar chemistry among the three types using One-way ANOVA or Kruskal–Wallis test after removing outliers (*p < 0.05, **p < 0.01, ***p < 0.001). Soil type A is existing soil plus biochar and compost, type B is CSB/compost mixture, and type C is CSB/compost mixture plus biochar.

| | Maackia amurensis | | | | Zelkova serrata | | | |
|---|---|---|---|---|---|---|---|---|
| | **A (n = 6)** | **B (n = 5)** | **C (n = 6)** | **A vs B vs C (p-value)** | **A (n = 6)** | **B (n = 7)** | **C (n = 6)** | **A vs B vs C (p-value)** |
| C% | 47.3 ± 0.3 | 47.1 ± 0.4 | 46.9 ± 0.2 | 0.370 | 45.1 ± 0.6 | 45.1 ± 0.2 | 45.5 ± 0.3 | 0.443 |
| N% | 3.8 ± 0.1 | 3.6 ± 0.1 | 3.1 ± 0.2 | 0.071 | 2.7 ± 0.1 | 2.7 ± 0.1 | 2.9 ± 0.1 | 0.070 |
| P (g kg$^{-1}$) | 2.2 ± 0.1 | 1.7 ± 0.2 | 2.4 ± 0.8 | **0.002**** | 1.6 ± 0.0 | 1.6 ± 0.1 | 1.9 ± 0.1 | 0.163 |
| K (g kg$^{-1}$) | 11.4 ± 1.3 | 10.2 ± 1.1 | 11.2 ± 1.5 | 0.992 | 11.2 ± 0.6 | 10.1 ± 0.9 | 12.9 ± 0.9 | 0.065 |
| S (g kg$^{-1}$) | 2.0 ± 0.1 | 1.8 ± 0.0 | 1.7 ± 0.1 | 0.083 | 1.4 ± 0.0 | 1.4 ± 0.0 | 1.5 ± 0.0 | **0.002**** |
| Ca (g kg$^{-1}$) | 15.3 ± 0.9 | 15.2 ± 0.9 | 16.1 ± 1.1 | 0.718 | 12.4 ± 1.7 | 13.7 ± 0.7 | 9.4 ± 1.2 | 0.067 |
| Mg (g kg$^{-1}$) | 2.5 ± 0.2 | 3.1 ± 0.1 | 3.0 ± 0.3 | 0.115 | 1.8 ± 0.2 | 2.0 ± 0.1 | 1.7 ± 0.1 | 0.248 |
| Fe (mg kg$^{-1}$) | 148.2 ± 12.4 | 136.6 ± 13.2 | 135.5 ± 22.5 | 0.840 | 92.0 ± 10.5 | 92.8 ± 7.2 | 89.7 ± 6.7 | 0.962 |
| Zn (mg kg$^{-1}$) | 23.5 ± 1.8 | 21.1 ± 2.8 | 24.4 ± 2.3 | **0.032*** | 23.7 ± 6.1 | 16.2 ± 1.8 | 18.6 ± 2.1 | 0.685 |
| Mn (mg kg$^{-1}$) | 87.4 ± 39.6 | 56.4 ± 7.0 | 68.7 ± 14.9 | 0.711 | 29.5 ± 5.4 | 67.8 ± 24.3 | 51.2 ± 20.8 | 0.079 |
| Cu (mg kg$^{-1}$) | 7.8 ± 0.5 | 8.3 ± 1.3 | 12.5 ± 2.7 | 0.301 | 7.4 ± 2.4 | 5.8 ± 0.6 | 5.9 ± 0.7 | 0.953 |
| Al (mg kg$^{-1}$) | 50.6 ± 10.3 | 40.9 ± 4.0 | 47.1 ± 9.3 | 0.994 | 25.6 ± 4.8 | 28.2 ± 3.6 | 22.7 ± 1.7 | 0.628 |
| Na (mg kg$^{-1}$) | 39.6 ± 7.3 | 27.2 ± 1.8 | 47.1 ± 3.8 | **0.001**** | 26.2 ± 6.2 | 29.6 ± 3.7 | 19.7 ± 1.8 | **0.040*** |
| Cd (mg kg$^{-1}$) | < 0.1 | < 0.1 | < 0.1 | 0.933 | < 0.1 | < 0.1 | < 0.1 | 0.783 |
| Cr (mg kg$^{-1}$) | 0.2 ± 0.1 | 0.3 ± 0.0 | 0.3 ± 0.1 | 0.719 | 0.1 ± 0.0 | 0.1 ± 0.0 | 0.1 ± 0.0 | 0.354 |
| Pb (mg kg$^{-1}$) | 1.8 ± 0.2 | 1.6 ± 0.2 | 1.9 ± 0.2 | 0.511 | 1.5 ± 0.1 | 2.0 ± 0.2 | 1.4 ± 0.2 | **0.026*** |
| Ba (mg kg$^{-1}$) | 13.6 ± 2.4 | 13.9 ± 3.0 | 12.9 ± 1.4 | 0.911 | 19.7 ± 5.3 | 19.8 ± 3.3 | 10.3 ± 1.8 | 0.077 |

Differences in sampling time may underlie this difference. In 2020, the tree health assessment was conducted at the beginning of fall (September), whereas in 2021 it was conducted in the middle of summer (July). July of 2021 was the third rainiest July in NYC on record. The unusual rainy weather and flash floodings in the city might have increased stress in *Maackia amurensis*. *Zelkova serrata* may have a higher flooding tolerance than *Maackia amurensis*, and therefore doesn't show any change in stress.

*Zelkova serrata* in group B and C had significantly higher Fv/Fm than group A ($P < 0.05$), suggesting that trees planted in constructed soil may have higher photosynthetic capacity than trees planted in purchased topsoil. However, Fv/Fm values of all three groups of trees still fall into the ideal range of non-stressed plants (0.78–0.85) (Björkman and Demmig, 1987; Johnson et al., 1993; Maxwell and Johnson, 2000; Sepúlveda and M. Johnstone (2018)).

For foliar chemistry, the two tree species show significant differences in different elements, but no systemic differences were detected. No difference was detected in foliar contents of common urban soil contaminants (Cd, Cr, Pb, Ba) over the three groups, which indicates that the constructed soil has similar levels of contaminants to purchased and existing topsoil.

### 4.2. Constructed soil

Our results suggest that soil constructed from CSB sediment and compost can support street trees as well as conventionally used soils. Trees planted in constructed soil had similar performance to trees planted in existing and purchased topsoil. Except the Fv/Fm for *Zelkova serrata*, no significant difference was detected in tree health indicators among trees planted in the three soil types. The results were consistent with results reported by Egendorf et al. (2018) that show that topsoil manufactured from CSB sediment and 33%-50% compost can provide comparable crop yields to purchased topsoil in community gardens.

We also demonstrate that it is possible to grow trees in soils constructed from urban construction waste, which is consistent with the conclusion of Pruvost et al. (2020), who found that five out of six tested tree species including *Acer campestre, Prunus avium, Acer platanoides, Acer pseudoplatanus,* and *Tilia cordata* grew well in constructed soil. This study adds *Maackia amurensis* and *Zelkova serrata* to the list of trees that can grow well in constructed soils. It is important to note however, that CSB construction waste comes from deep excavation of construction sites and is therefore unaffected by exposure to contaminants. Other construction waste may not be as "clean."

Addition of organic waste is crucial to construct soils that can support plant growth (Cannavo et al., 2018; Deeb, Grimaldi, Lerch, Pando, Podwojewski, et al., 2016; Yilmaz et al., 2018). Assessing soil properties of the three soil types shows that soil constructed from CSB sediment and 33% compost have similar functional qualities to existing and purchased topsoil (Table 1). Although CSB sediments have less clay and silt than regular soil, organics used in this study were sufficient to improve water holding capacity and CEC. However, fast organic decomposition may require more frequent compost addition to the CSB-based constructed soils in the future. Further monitoring of tree performance and soil properties is needed to understand the stability and long-term performance of soils constructed from CSB sediment and compost. Other sources of compost should also be tested for their feasibility to support urban street tree growth.

### 4.3. Biochar

We found no evidence that biochar provides benefits to street tree performance. The results here are different from the findings of a previous study, which reported that biochar amendment not only increased P, K, and water availability in the soil, but also increased total tree biomass during the establishment phase of *Tilia* × *europaea* L. (Lo Piccolo et al., 2022). However, the biochar concentration applied in that study (1.5%) was much higher than the one used in this study (~0.37%). Biochar properties vary widely based on their biomass feedstocks and methods of pyrolysis. Other sources of biochar, as well as longer-term studies with higher doses of biochar may be warranted to fully understand the effects of biochar on street tree performance.

### 4.4. Reusing waste material

Using CSB sediment and locally produced compost for street tree planting allows recycling of waste materials that might otherwise end up in landfills. The recycling reduces truck traffic required for disposal of sediment outside of the city and transferring purchased topsoil to the city. The reduced traffic reduces gasoline consumption and greenhouse gas emissions. These environmental benefits align directly with NYC's sustainability goals, which call for reduction of solid waste disposal and greenhouse gas emissions (The City of New York, 2017).

Constructing soils from CSB sediment and locally produced compost also has economic benefits. NYC and other northern cities have high availability of glacial outwash sediments that make an effective growing medium (with compost addition) and that are deeply buried and contain minor amounts of contaminants (Egendorf et al., 2018). In seven years, the Mayor's Office of Environmental Remediation delivered over 420, 000 tons of native sediment to public and private soil development projects (Walsh et al., 2018). Moreover, composting initiatives in cities including NYC are expanding. For example, the NYC Department of Sanitation collected 48,000 tons of organics in 2019, but the collection volume is still low compared to its overall waste collection system (New York City Independent Budget Office, 2021). After a 3-year pause due to COVID-19, the city now plans to expand the curbside composting to the whole city by 2024. Using these inexpensive native sediments and compost for urban tree planting has the potential to reduce the cost of many urban greening projects.

## 5. Conclusions

The three soil types had similar properties, except for bulk density, water holding capacity, and K, Fe, and Zn. No significant difference in tree performance indicators, including overall z-score, DBH, height, crown diameter, and PI, were observed among the three groups, indicating that the differences in soil parameters did not significantly impact tree performance.

No systemic significant differences were detected in tree health indicators and foliar chemistry among trees planted in the three soil types. The results indicate that CSB sediment mixed with compost can be a replacement for purchased topsoil as a medium for tree growth. Considering the availability of abundant glacial outwash sediment at a low cost, as well as access to locally produced compost, the CSB program can be a reliable source of soil for urban forestry programs.

No evidence was found from this project that biochar provides additional benefits to street tree performance. However, since the study period was relatively short, and the biochar level used was low, longer-term studies with higher doses or other forms of biochar may be warranted to understand the effects of biochar on street tree performance.

## Author agreement statement

We the undersigned declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We understand that the Corresponding Author is the sole contact for the Editorial process.

He/she is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs

## CRediT authorship contribution statement

**Andrew Reinmann:** Writing – review & editing. **Peter Groffman:** Writing – review & editing. **Richard Hallett:** Data curation, Formal analysis, Methodology, Writing – review & editing. **Saidan Qi:** Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation. **Zhongqi Cheng:** Writing – review & editing, Supervision, Methodology, Formal analysis, Data curation, Conceptualization.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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