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Soil carbon sequestration in urban afforestation sites in New York City

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ABSTRACT

There is great interest in the ability of afforestation programs to sequester carbon, improve soil health, and provide other ecological benefits to urban areas. However, the capacity of urban soils to support successful afforestation and sequester carbon is poorly understood. This study quantified soil carbon in a series of experimental restoration sites established between 2009 and 2011 as part of the MillionTreesNYC Afforestation Project in New York City. Soil cores (0–100 cm) were collected at 10 sites and analyzed for total carbon content. Data were analyzed with respect to depth (0–10, 10–30, 30–70, 70–90, 90–100 cm), high (six species) versus low (two species) diversity planting palettes, and afforestation success (high or low). Results were compared with data from regional reference forest, degraded urban sites in New York City, and disturbed and undisturbed sites in other cities. High success afforestation sites had significantly larger carbon pools than low success afforestation sites and degraded NYC sites. We suggest that these differences were created by interactions between initial site conditions that facilitated plant community establishment and growth, which in turn increased soil carbon accumulation. These initial site conditions include land use history that influences soil physical and chemical factors, as well as proximity to existing forest stands. Diversity treatments had no effect on soil carbon levels, but these may need a longer time period to emerge. These results suggest that afforestation may enhance the capacity of urban soils to store carbon compared to urban degraded soils, but that urban soil properties and site characteristics constrain this capacity.

1. Introduction

Maintenance of natural ecosystems and the services they provide is a great challenge in urban ecosystems (Keeler et al., 2019). While much attention has been focused on urban vegetation, particularly forests, there is recognition that soils have significant effects on ecosystem functions and services (Pouyat et al., 2010). Soil plays an essential role in the carbon cycle as a carbon sink, i.e., it has the capacity to store significant amounts of carbon in stable form (Lal, 2004). Organic carbon in turn influences soil biogeochemical properties and functions through its influence on nutrient cycling and water retention, which supports plant growth (Ontl and Schulte, 2012). However, widespread human activity has disrupted that sink and soil carbon has been lost around the world, particularly as a result of agriculture and other land use changes (Schlesinger and Bernhardt, 2013). There is growing interest in understanding carbon dynamics in urban soils in relation to carbon budgets, as well as the health and function of a wide range of urban ecosystems (Hutyra et al., 2014; Lorenz and Lal, 2015; Canedoli et al., 2020).

Urban forests offer a unique opportunity to store carbon in an urban setting and bolster local ecosystem services. Urban landscapes have been

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shown to contain biologically active areas with relatively intact and/or functional soils that have a high potential for carbon storage (Pouyat et al., 2010; Lorenz and Lal, 2015; Scharenbroch et al., 2018; Canedoli et al., 2020). Efforts to restore urban soil carbon stocks thus improve the overall ecological function of urban areas, enabling cities to make greater use of natural ecosystem services, such as the biodegradation of pollutants, reduction of runoff, and mitigation of effects of climate change, to improve the quality of life of city residents (Grossmann, 1993; Rey Benayas et al., 2009; Pickett et al., 2011).

Afforestation, the establishment of stands of trees in previously unforested areas, is an important component of climate change mitigation programs around the world (Doelman et al., 2020). There is interest in afforestation in cities, but there are concerns that urban soil and environmental conditions may limit the potential for afforestation success in these areas (Oldfield et al., 2013, 2014; Pierre et al., 2015; Ward et al., 2021). The MillionTreesNYC (MTNYC) Program, which has planted one million new trees throughout New York City, including in parks, right-of-way, and private properties, is a public-private program in partnership with NYC Department of Parks & Recreation and New York Restoration Project, designed to address urban resilience to climate change. In association with the MTNYC Program, a number of research teams established long-term experimental restoration sites (McPhearson et al., 2010; Oldfield et al., 2013; Pierre et al., 2015; Ward et al., 2021), with the goal of better understanding the physical, chemical, and biological responses of park ecosystems to forest restoration. In the plots established by McPhearson et al. (2010), known as the MillionTreesNYC Afforestation Project, high (six species) and low (two species) diversity restoration techniques were applied, including shrubs/ground cover in some cases. The success of these sites has varied significantly; while some sites have grown into impressive young forests, others have very little tree cover after 7–9 years of growth. We hypothesized that soil conditions played an integral role in this variation; however, little assessment had been done of the soils in these plots. The variation in success among sites thus created a “natural experiment” to test our hypothesis about the importance of soils in afforestation success and carbon sequestration capacity.

In the summer of 2018, we revisited the MTNYC Afforestation Project sites and took soil samples to evaluate soil carbon concentrations and pools and how these vary with soil profile depth (0–10, 10–30, 30–70, 70–90, 90–100 cm), high versus low diversity planting palette, and afforestation success (high or low). Results were compared with previously collected soil carbon data from degraded urban sites in the New York City metropolitan area and regional reference forests reported by Pouyat et al. (2002). We addressed the following questions:

1 Is soil carbon greater in successful afforestation sites than in unsuccessful sites?
2 Do different planted-tree diversity treatments have an influence on the amount of carbon found in urban soils?
3 How does soil carbon in afforestation sites compare to urban degraded sites and established forests?

2. Materials and methods

2.1. Study sites

Study sites were located in New York City (40.7128 ° N, 74.0060 ° W), NY, USA, a dense coastal urban center with a population of 8,537,673 residents (U.S. Census Bureau (USCB, 2016). NYC has a humid subtropical climate, with an annual average high temperature of 16.8 °C, an annual average low temperature of 8.9 °C, and average annual precipitation of 117.4 cm, occurring on an average of 121 days per year (U.S. Climate Data (USCD, 2017).

We sampled soils from 10 permanent MillionTreesNYC Afforestation Project research sites, established in 2009–2011 (Table 1, Fig. 1). The sites were established in collaboration with managers and staff ecologists from NYC Department of Parks & Recreation, as well as MTNYC Project staff, to minimize site variability, maximize management comparability across sites, and ensure site access. Sites were categorized by hydric (Pelham Bay, Conference House) or mesic soils (all other sites). Hydric sites received a slightly different tree-planting palette. Site preparation for afforestation included removing invasive vines and weeds, debris, structures, and other barriers to forest establishment. Then, 7.6 L (2 gallon) container trees (tree height 0.5–1.0 m) and 3.8 L (1 gallon) shrubs were planted in high and low diversity plots. Tree establishment was facilitated by management practices that included soil amendments, such as mulch, to newly planted trees, as well as watering the sites during the most susceptible periods of early tree establishment (McPhearson et al., 2010). Photos of high and low success sites can be found in supplementary material.

Each site includes four 15 × 15 m plots: two plots using a high diversity planting palette, and two plots using a low diversity planting

Table 1
MillionTreesNYC Afforestation Project sites sampled in this study.

Site	Borough	Year Est.	Plots	Lithology	Parent material
Pelham Bay Park	Bronx	2009	4	Black, organic-rich fine clay and silt	Coarse-silty glaciolacustrine deposits and/or eolian deposits over till
Fort Totten	Queens	2011	2	Grayish-black coarse sand	Loamy-skeletal human-transported material, over an intact or truncated glacial till soil derived from granitic material
Clearview Park	Queens	2011	4	Brown, with fine clay and coarse sand	Coarse-loamy over sandy lodgment till derived from gneiss, granite, and/or schist
Alley Pond	Queens	2009	4	Silty brown with white sand specks	Loamy human-transported material
Canarsie Park	Brooklyn	2009	4	Dark brown, fine silt	Sandy human-transported material
Marine Park 1	Brooklyn	2009	4	Dark bgrain + white sandy silt	Loamy human-transported material over sandy beach sand and/or outwash and/or dredge spoils
Marine Park 2	Brooklyn	2010	4	Bark on top, dark brown, black mixed white sand	Loamy human-transported material over sandy beach sand and/or outwash and/or dredge spoils
Marine Park 3	Brooklyn	2011	4	Black organic with mulch	Loamy human-transported material over sandy beach sand and/or outwash and/or dredge spoils
Clove Lakes	Staten Island	2009–10	4	Brown, fine, silt	Red coarse-loamy supraglacial till
Conference House	Staten Island	2010	2	Brown, white with small pebbles	Coarse-loamy outwash over gravelly outwash and/or sandy outwash

Fig. 1. MillionTreesNYC Afforestation Project sites in New York City. Map depicting the locations of afforestation sites sampled for this study.

palette (except for Conference House and Fort Totten sites, which have two plots each – one high and one low diversity). The high diversity plots feature six species (mesic sites: *Quercus rubra* L., *Nyssa sylvatica* Marshall, *Amelanchier canadensis* [L.] Medik., *Prunus serotina* Ehrh., *Quercus coccinea* Wangenh., *Celtis occidentalis* L.; hydric sites: *Quercus palustris* Du Roi, *Nyssa sylvatica* Marshall, *Quercus bicolor* Willd., *Liquidambar styraciflua* L., *Platanus occidentalis* L., *Diospyros virginiana* L.). The low diversity plots feature only two species (mesic sites: *Quercus rubra* L., *Nyssa sylvatica* Marshall; hydric sites: *Quercus palustris* Du Roi, *Nyssa sylvatica* Marshall). Both plot types were sampled for this study. Comparisons of individual sites were based on four (or two at Conference House and Fort Totten sites) replicate plots per site, with two samples collected per plot (n = 8, or 4 at Conference House and Fort Totten sites). Because diversity treatments were established at each site, comparisons between high and low diversity treatments were based on 10 replicate sites, with two (or one at Conference House and Fort Totten sites) replicate plots at each site, with two samples collected per plot (n = 36).

By 2018, there were obvious differences in afforestation success (i.e., the visible presence of a closed canopy of trees and of leaf litter accumulation) across the 10 sites. We, therefore, grouped the sites into qualitative categories of "high success" and "low success." To be considered "high success," a site must have a closed canopy composed of trees planted during afforestation establishment in 2009–2011, and the presence of a leaf litter layer derived from those trees. Any site that did not meet both criteria was determined to be "low success." There were seven high success sites and three low success sites; thus, comparisons between high and low success sites were based on seven versus three replicate sites, with four (or two at Conference House and Fort Totten sites) replicate plots at each site (n = 24 for low success and n = 48 for high success).

2.2. Sample collection

Soil sampling locations for this study were taken from the existing sampling method established in 2009–2011. Within each 15 × 15 m plot, samples were taken from within a central 10 × 10 m area. In 2009–2011, samples were collected from each plot along a diagonal transect; we resampled the third and fifth sampling points in each plot (Fig. 2) for our study. All samples were collected over a three-week period in late June–early July 2018. Soil samples were collected using a 3.3 cm diameter soil corer, to a 1 m depth, or to the greatest depth possible. The presence of construction debris, soil compaction, and other barriers prevented cores from reaching the full 0–100 cm depth at the Alley Pond (18.9 cm), Canarsie (30.2 cm), and Clearview (76 cm) sites. Each soil sample was collected into a plastic sleeve, secured with an end cap, placed in a cooler for transport to the lab, and stored at 4 °C until analysis.

In 2009–2011, soil samples were taken from seven sites, including two of the three low success sites and five of the seven high success sites. Samples were taken with a 5 cm diameter soil probe to a 10 cm depth, using two methods: (i) 10 undisturbed samples were collected from one randomly selected subplot within each plot per site for high resolution soil analysis; and (ii) a composite soil sample to a 10 cm depth was collected, composited from 5 locations within each subplot (Fig. 2) (McPhearson et al., 2010). This was not a comprehensive assessment of

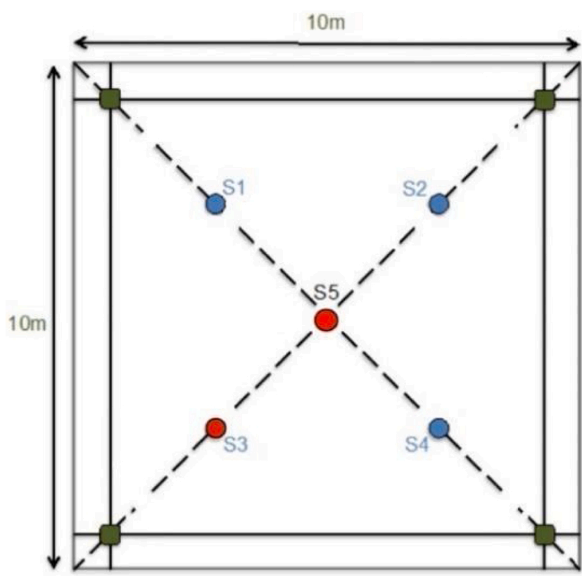

Fig. 2. Soil sampling method. Diagram of soil sampling methodology used by McPhearson et al. (2010), modified for the purposes of this study (shown in red). Two soil cores were collected from each plot at the third (S3) and fifth (S5) sampling points (for interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

pre-treatment soil conditions, but it does provide some indication of differences in site conditions as afforestation treatments were established.

2.3. Sample processing

Sample processing generally followed the methods used by Raciti et al. (2011). Each soil core was photographed using a digital camera, then inspected for: signs of disturbance, such as evidence of man-made materials or buried horizons; horizon depths; and Munsell color to classify samples according to hue (color), value (lightness and darkness), and chroma (color intensity). Following inspection, each core sample was divided into five subsamples representing different soil depth intervals (0–10, 10–30, 30–70, 70–90, and 90–100 cm). From these subsamples, all coarse roots and rocks (> 2 mm) were removed, dried at 105 °C, then weighed and set aside. Rock volume was determined by mass and an assumed density of 2.7 g/cm^3.

Each resulting homogenized subsample was oven-dried at 105 °C for 48 h and analyzed for soil dry weight as well as percentage moisture. Bulk density was calculated using the following formula: Bulk Density = (Total Dry Mass – Rock Mass)/(Total Volume – Rock Volume).

Total carbon content was quantified using a flash combustion/oxidation technique with an Elementar varioMax Cube elemental analyzer (detection limit 0.02–500 mg C, or 100 %). Carbon density (kg/m^2) to specific depths was calculated using bulk density values measured on each core depth segment. Carbonates were not removed from samples before analysis of total carbon because the pH of our soils was low enough that carbonates were likely not present in significant quantities (Mejía et al., 2021).

Soil samples collected in 2010 were divided into pre-planted, dry-sieved subsamples and analyzed using comparable loss on ignition and combustion techniques to determine total and organic carbon at Cornell University's Nutrient Analysis Laboratory (McPhearson et al., 2010).

2.4. Statistical analysis

The Statistical Analysis System (SAS) version 9.4 was used for all analyses (SAS, 1988). One-way analysis of variance (ANOVA) was used, followed by a Duncan's multiple range test to determine specific differences where necessary. One-way ANOVA has high power, and can be run in both parametric and non-parametric modes (when data are not normally distributed). The Shapiro-Wilk test was used to determine if data were normally distributed and the NPAR1WAY non-parametric analysis of variance routine in SAS was used when data were non-normally distributed.

Comparisons of individual sites were based on four (or two at Conference House and Fort Totten sites) replicate plots per site, with two samples per plot (n = 8, or 4 at Conference House and Fort Totten sites). Because diversity treatments were established at each site, comparisons between high and low diversity treatments were based on 10 replicate sites, with two (or one at Conference House and Fort Totten sites) replicate plots at each site (n = 36). There were seven high success sites and three low success sites; thus, comparisons between high and low success sites were based on seven versus three replicate sites, with four (or two at Conference House and Fort Totten sites) replicate plots at each site with two samples per plot (n = 24 for low success and n = 48 for high success).

2.5. Comparisons with previously published values

We made comparisons between the data collected here with results from reference forest and urban sites in the NYC area compiled by Pouyat et al. (2002). Comparisons were also made with results from the literature.

3. Results

Total organic carbon pools (Table 2a, Fig. 3a) and concentrations (Table 2b, Fig. 3b) were greater in the surface/upper horizons (0–10 cm, 10–30 cm) than at deeper depths, with the exception of Canarsie, Conference House, and Marine Park 2, all of which had the greatest carbon pools at 30–70 cm. Because not all site samples had 100 cm of soil depth, comparisons of total soil profile C pools were made to both the depth of 0–30 cm and 0–100 cm. To 100 cm, Pelham Bay Park, Marine Park 1, 2, and 3, and Fort Totten Park had the greatest carbon pools and concentrations, while Clearview and Alley Pond had the least (specific significant differences indicated in Table 2). To 30 cm, Pelham Bay Park and Marine Park 3 had the largest carbon pools, while Canarsie and Clearview had the smallest. Differences between sites were most marked in the surface horizons (Fig. 3).

There were no statistically significant differences in carbon pools between high and low diversity treatments to a 0–30 cm or 0–100 cm depth in an analysis over all sites (n = 10 sites per treatment) (Table 3).

There were significant differences in carbon pools and concentrations between high and low success afforestation sites at 0–10 cm and 10–30 cm depth (Fig. 3), over 0–30 cm depth (Fig. 4), and over 0–100 cm depth (Table 2), with high success afforestation sites storing more carbon than low success sites. There were no significant differences with afforestation success below 30 cm (Fig. 3). High success afforestation sites had an overall mean carbon density of 6.30 (± 0.63) kg C/m^2 over 0–30 cm, and 8.29 (± 0.55) kg C/m^2 over 0–100 cm. Low success afforestation sites had an overall mean carbon density of 2.82 (± 0.32) kg C/m^2 over 0–30 cm, and 3.79 (± 0.38) over 0–100 cm.

Limited soil sampling in 2010 showed no significant difference in carbon concentrations over 0–10 cm between two low success sites (Alley Pond, Canarsie) and five high success sites (Clove Lakes, Conference House, Marine Park 1, Marine Park 2, Pelham Bay). Percent carbon was 5.0 (± 0.3) in the high success sites and 5.1 (± 0.7) in the low success sites.

Carbon pools in the afforestation plots fell within the range of urban soils reported by Pouyat et al. (2002). The carbon densities of high success urban afforestation sites to 0–100 cm (8.29 ± 0.55 kg/m^2) were similar to undisturbed and residential urban soils, less than regional forests, and greater than degraded ("other") urban soils to 0–100 cm reported by Pouyat et al. (Table 4). Low success afforestation sites (3.79

Table 2
Distribution of total C in afforestation sites. Total C pools (a) and concentrations (b) at five depths, over 0–30 cm, and over 0–100 cm in 10 urban afforestation sites in New York City. Values are means of two cores taken in each of two or four plots per site. Different lower−case superscripts within a row indicate statistically significant ($p < 0.05$) differences between sites in a one−way analysis of variance followed by a Duncan's multiple range test. Light orange research sites had low afforestation success, while light green research sites had high afforestation success. The presence of construction debris, soil compaction, and other barriers prevented cores from reaching full 0–100 cm depth at Alley Pond, Canarsie, and Clearview; "ND" indicates no data for a given depth. Core sums for each site calculated to 0–30 cm represent the most complete dataset for cross-site comparisons.

a. Average Total C (kg C/m^2) by Depth

Depth (cm)	Alley Pond n=8	Canarsie n=8	Clear-view n=8	Clove Lakes n=8	Confer-ence House n=4	Fort Totten n=4	Marine Park 1 n=8	Marine Park 2 n=8	Marine Park 3 n=8	Pelham Bay Park n=8
0-10	1.91^{cd}	0.94^{de}	0.74^{e}	1.63^{cde}	1.16^{cde}	2.14^{c}	1.69^{cde}	1.62^{cde}	4.64^{a}	3.33^{b}
10-30	2.43^{cd}	1.65^{cd}	0.57^{d}	2.00^{cd}	1.82^{cd}	2.07^{cd}	2.77^{bcd}	3.14^{bc}	8.53^{a}	4.80^{b}
Sum to 30	4.35^{c}	2.59^{cd}	1.32^{d}	3.64^{cd}	2.99^{cd}	4.21^{c}	4.46^{c}	4.76^{c}	13.17^{a}	8.13^{b}
30-70	ND	4.22^{a}	1.00^{c}	1.42^{abc}	2.45^{abc}	1.29^{bc}	1.79^{abc}	4.05^{ab}	2.04^{abc}	0.84^{c}
70-90	ND	ND	0.61^{a}	0.32^{a}	0.82^{a}	0.43^{a}	0.72^{a}	0.17^{a}	0.10^{a}	0.37^{a}
90-100	ND	ND	ND	0.10^{a}	0.58^{a}	0.21^{a}	0.08^{a}	0.05^{a}	0.05^{a}	0.18^{a}
Sum	4.35^{de}	6.82^{de}	2.94^{e}	5.48^{cde}	6.84^{bcd}	6.15^{bcde}	7.07^{bcd}	9.05^{b}	15.39^{a}	9.54^{bc}

b. Average Total C (%) by Depth

Depth (cm)	Alley Pond	Canarsie	Clear-view	Clove Lakes	Confer-ence House	Fort Totten	Marine Park 1	Marine Park 2	Marine Park 3	Pelham Bay Park
0-10	4.8^{bc}	1.9^{c}	1.5^{c}	3.6^{bc}	3.3^{bc}	6.3^{b}	3.8^{bc}	3.6^{bc}	37.7^{a}	4.4^{bc}
10-30	2.2^{b}	1.2^{b}	0.4^{b}	1.6^{b}	1.5^{b}	1.6^{b}	2.2^{b}	2.5^{b}	10.0^{a}	2.4^{b}
30-70	ND	1.3^{ab}	0.3^{b}	0.5^{ab}	0.8^{ab}	0.4^{ab}	0.5^{ab}	1.6^{a}	0.9^{ab}	0.2^{b}
70-90	ND	ND	0.3^{a}	0.2^{a}	0.5^{a}	0.3^{a}	0.4^{a}	0.1^{a}	0.0^{a}	0.2^{a}
90-100	ND	ND	ND	0.1^{a}	1.0^{a}	0.2^{a}	0.1^{a}	0.0^{a}	0.1^{a}	0.2^{a}

± 0.38 kg/m^2) showed carbon densities similar to urban degraded sites. The results of this study were also comparable to results found in other urban soil studies in the literature (Table 5).

4. Discussion

There is great interest in, and uncertainty about, the ability of afforestation programs to sequester carbon, improve local soil health, and provide other ecological benefits in urban areas (Ward et al., 2021). While afforestation has been found to increase soil carbon in non-urban sites across the world (Jandl et al., 2007; Li et al., 2012; Nave et al., 2013), data from urban sites are rare. Our results suggest that, taking into account a number of constraining factors discussed below, afforestation practices may enhance the ability of urban soils to store carbon in New York City. Our clearest finding was that sites where afforestation was more successful stored significantly more carbon than sites where efforts to establish a forest community were less successful. There was no apparent difference in the performance of soil carbon storage in high diversity versus low diversity plots, and instead overall success appeared to be driven by inherent site characteristics.

While we did not have comprehensive sampling of initial levels of soil carbon in our sites, limited data on percent soil carbon in surface soils collected in 2010 at two of the three low success sites and at five of the seven high success sites suggest that there was not higher soil carbon in the high success sites when they were established. Also, the fact that the differences between high and low success sites were only significant in surface soils, and not at depth, suggests that the differences have developed over time in response to afforestation. If the differences between the high and low success sites were caused by a high carbon content of the soil parent materials at the site, this would be most obvious at the deeper depths, which are least affected by plant growth and surface organic matter dynamics. Rather, as discussed below, we suggest that at the high success sites, high plant production associated with afforestation success has led to increases in soil carbon storage.

Recent studies of urban soil organic carbon stocks elsewhere have shown similarly promising, though highly varied, results (Table 5). In the seven-county region surrounding Chicago, IL, Scharenbroch et al. (2017) sampled five land-use types including agriculture, commercial, industrial, transportation, utility and vacant, forested lands, park and other open lands, and residential, finding soil organic carbon densities ranged from 4.13 to 132 kg C/m^2 at 0–100 cm depth, with a mean of 34.2 kg C/m^2. In Milan, Italy, Canedoli et al. (2020) found that organic carbon stocks in urban park soils were comparable with those of nearby forest, pasture, and grassland in the region, averaging 6.9 kg C/m^2 at 0–40 cm depth. In Singapore, Ghosh et al. (2016) reported organic carbon stocks ranging 1.1–42.5 kg C/m^2 at 0–100 cm depth along urban roadsides. In Hamburg, Germany, Dorendorf et al. (2015) found average carbon stocks of 2.9 kg C/m^2 at 0–30 cm depth across a range of 10 urban habitat conditions (biotope types). Yan et al. (2015) reported an average 8.1 kg C/m^2 at 0–80 cm depth across pervious surface areas in Urumqi City, Xinjiang province, China, and Sarzhanov et al. (2017) found carbon stocks to ranging from 20 to 50 kg C/m^2 at 0–150 cm depth across a variety of industrial, residential, and recreational urban soils in Kursk, Russia.

These comparisons with other urban soil studies highlight that our estimates of carbon stocks are consistent with previous studies in the New York City region (Table 4), and low but within the range of comparative studies elsewhere (Table 5). Comparisons between studies are complicated by differences in methods of site selection, sampling depth, and analysis of carbon and bulk density. Bulk density values measured in this study were relatively low but not uncommon for mineral forest soils (mean 0.6 g/cm^3 bulk density across all sites) (Page-Dumroese et al., 1999), and carbon concentrations (mean 3.0 % C across all sites) were comparable to similar urban studies. In Baltimore, MD, Pouyat et al. (2002) reported a mean of 1.6 % C and 1.2 g/cm^3 bulk density across urban residential sites, and 3.1 % C and 1.1 g/cm^3 bulk

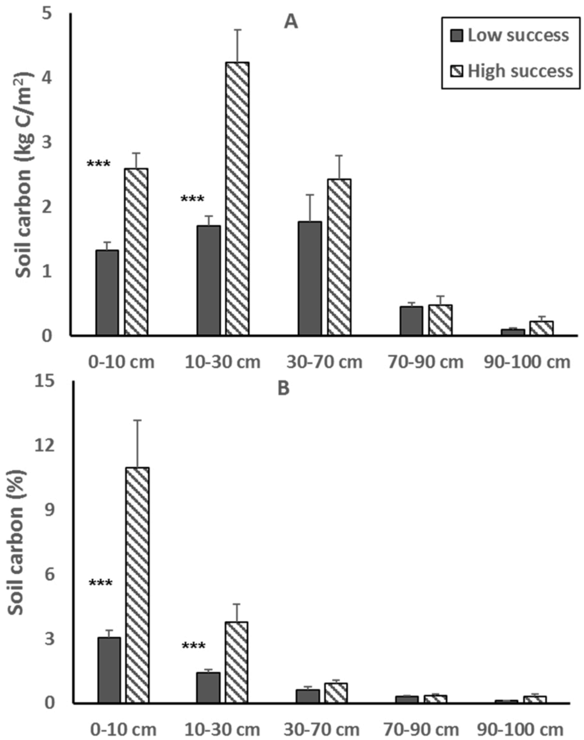

Fig. 3. Mean total carbon pools (A) (kg C/m^2) and percent carbon (B) at five sampling depths in 3 low success (n = 12) and 7 high success (n = 24) afforestation plots in New York City with four replicate plots per site, except for two of the high success sites that had only two replicate plots. Values are mean with standard error of from 27 – 71 samples depending on specific samples available from particular cores at particular depths. ***indicates statistically significant differences between high and low success sites at p < 0.001.

Table 3
Total carbon pools of high and low diversity plots. Total carbon pools (kg C/m^2) to 30 cm depth in high and low diversity plots, and overall means to 30 cm, for high and low diversity plots in 10 afforestation sites in New York City. Values are means (with standard error) of two cores taken in each of two (n = 4) or four (n = 8) plots per site. There was no significant difference between high and low diversity treatments in an analysis over all sites (n = 36).

Research Site	High Diversity (total C pool)	Low Diversity (total C pool)
Alley Pond	4.9 (± 0.4)	3.8 (± 0.8)
Canarsie	3.1 (± 0.1)	2.1 (± 0.3)
Clearview	1.4 (± 0.1)	1.2 (± 0.2)
Clove Lakes	3.6 (± 0.7)	3.7 (± 0.6)
Conference House	1.7 (± 1.3)	4.3 (± 0.1)
Fort Totten	3.5 (± 0.5)	4.9 (± 0.0)
Marine Park 1	5.3 (± 0.5)	3.7 (± 0.6)
Marine Park 2	5.0 (± 0.5)	4.5 (± 0.5)
Marine Park 3	11.3 (± 3.3)	15.1 (± 1.9)
Pelham Bay Park	9.7 (± 0.5)	6.6 (± 1.9)
Means over all sites	**5.2 (± 0.6)**	**5.1 (± 0.7)**

density in a subsequent study (Pouyat et al., 2007). Sarzhanov et al. (2017) reported 1.9 % C and 1.1 g/cm^3 bulk density in Kursk, Russia, and Ghosh et al. (2016) found 2.8 % C and 1.1 g/cm^3 bulk density across urban sites in Singapore.

The most immediate driver of the differences between high and low success sites is that high plant production over the approximately 10 years since establishment at the high success sites drives increases in soil carbon. The differences in plant production are visually obvious at the sites (see photos in supplementary material) and there are well-established strong relationships between aboveground productivity and soil carbon levels (Frank et al., 2012). However, the factors

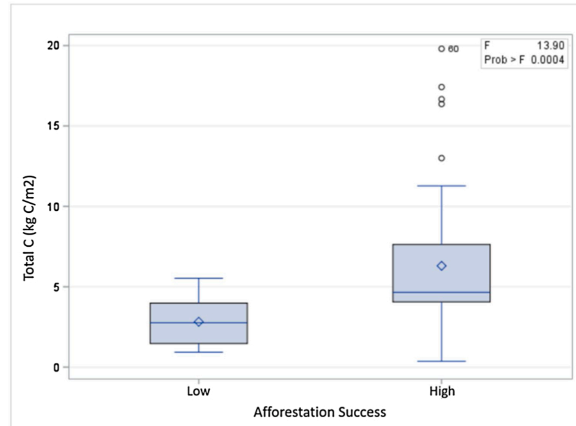

Fig. 4. Distribution of total carbon in afforestation sites. Mean total carbon pools (kg C/m^2) over 0–30 cm depth in 3 low success (n = 12) and 7 high success (n = 24) afforestation plots in New York City with four replicate plots per site, except for two of the high success sites that had only two replicate plots. The error bars show the maximum and minimum values, the boundaries of each box show the upper and lower quartile, and the diamond symbol shows the arithmetic mean.

Table 4
Comparison of regional and urban carbon densities. Carbon densities (kg/m^2) calculated to a 1 m depth for various disturbed and undisturbed urban soils in the New York City metropolitan area, regional forest soil and cropland soils, and afforestation site soils in New York City (this study). Original table is from Pouyat et al. (2002); afforestation data from this study added in bold.

Land-use/region	C density (kg/m^2)
Northeast forest	16.2
Northeast cropland	6
Mid-Atlantic forest	11.2
Mid-Atlantic cropland	4.2
Urban (residential)	15.5 (± 1.20)
Urban (undisturbed)	9.4 (± 1.40)
Urban (other)	5.14
Urban (other - old dredge)	3.8 (± 0.34)
Urban (other - refuse)	17.2 (± 3.34)
Urban (other - clean fill)	3.8 (± 0.99)
USA urban (total)	8.2
USA (total)	6.8
High success afforestation sites (this study)	8.3 (± 0.55)
Low success afforestation sites (this study)	3.8 (± 0.38)

Table 5
Comparison of mean urban soil carbon pools (kg C/m^2) in cities throughout the world.

Location	Depth (cm)	Total C (kg C/m^2)	Reference
New York City, NY (USA)	0–100	7.3	*this study*
Baltimore, MD and NYC, NY (USA)	0–100	8.2	Pouyat et al. (2002)
Chicago, IL (USA)	0–100	34.2	Scharenbroch et al. (2017)
Hamburg (Germany)	0–30	2.9	Dorendorf et al. (2015)
Kursk (Russia)	0–150	20–50	Sarzhanov et al. (2017)
Milan (Italy)	0–40	6.9	Canedoli et al. (2020)
Singapore	0–100	1.1–42.5	Ghosh et al. (2016)
Urumqi, Xinjiang (China)	0–80	8.1	Yan et al. (2015)

underlying afforestation success and high plant production at our sites are not clear. It is likely that site history plays a significant role in the success or failure of urban forest restoration (Morel et al., 2015). Other studies have found positive correlations between soil organic carbon storage and time since soil disturbance, suggesting that it is more likely to find greater carbon pools in older, less recently disturbed soils (Scharenbroch et al., 2005; Schmitt-Harsh et al., 2013; Huyler et al., 2014). Alley Pond, a site with very low afforestation success, was originally a tidal creek, before being converted to a landfill for use in the 1920s and 1960s, then covered over in the 1970s (Mike Feller, New York City Department Parks & Recreation, personal communication). Canarsie and Clearview, also sites with low afforestation success, were both previously construction-fill dumps and soils still contain much of that debris. On the other hand, Marine Park 1, a successful afforestation site, was filled with dredge material (primarily sand) taken from a coastal waterway in the 1940s and 1950s and appears to have developed an organic-rich surface horizon over the past 50 years. The high success Pelham Bay Park site was similarly filled with dredge material (sand), and in places original topsoil was removed and transported to other areas of the park. In both Marine Park 1 and Pelham Bay Park, major disturbances ceased at least 50 years ago, while Alley Pond, Canarsie, and Clearview have seen much more recent disturbances, in addition to different fills. Given these varied site histories, the starting points look very different from site to site, which has likely influenced each site's afforestation success. In general, we see higher carbon densities at the historically less disturbed sites. There are likely synergistic effects between initial site conditions and changes over time, such that sites with less disturbance and better soil physical and chemical conditions were better able to support plant growth and carbon sequestration.

In addition to the influence of site histories on the success of our afforestation sites, current local land use and site conditions have likely played a role. The Alley Pond, Canarsie, and Clearview sites are all located in close proximity to open fields, paved surfaces, and other heavily trafficked land uses, and all three sites struggled to establish young forests. In contrast, Conference House, Fort Totten, Marine Parks 1, 2, and 3, and Pelham Bay Park are all located either directly adjacent to or very nearby wooded areas where tree canopies had already been established prior to afforestation planting. All these sites were determined to be high success afforestation sites in this study. It is not clear, however, if the presence of nearby existing tree canopies at the time of afforestation site establishment had a positive influence on long-term site success or if the more anthropogenic land uses had negative effects at the low success sites. Urban management teams should carefully consider the current conditions, as well as the land use history, of a location before committing the time and resources needed to establish an afforestation site at that location.

Our results indicate that the different diversity treatments, i.e., planting six or two species of trees, did not influence soil carbon densities after approximately 10 years on our plots. It is possible that 10 years is not long enough for diversity effects to become obvious, but our results do not suggest that different diversity plantings affect soil carbon storage. Additionally, the strong influence of preexisting soil conditions on our sites may overwhelm any potential diversity effects. There is a clear need for continued monitoring of these sites to determine if diversity effects emerge over time and in response to disturbance (Tilman et al., 2006; Lange et al., 2015; Chen et al., 2018, 2019; Vogel et al., 2019).

Other external factors may have influenced the carbon pools of our sites. When the MTNYC Afforestation sites were established, management practices included mulching of newly planted trees and watering during more susceptible periods of early tree establishment (McPhearson et al., 2010). Certain sites that struggled to establish after the first year (Alley Pond, Canarsie, Clearview) were subsequently replanted, which would have disturbed the soils at those sites and further delayed soil organic carbon accumulation. During our fieldwork in 2018, there was evidence of mowing, removal of planted trees, and planting of new trees outside the designated range of planting palette species at the Alley Pond, Canarsie, and Clearview sites. These activities likely contributed to continued site disturbances.

5. Limitations

A major limitation of our study is that we did not have comprehensive sampling of initial levels of soil carbon in our sites. Limited data on percent soil carbon in surface soils collected in 2010 at two of the three low success sites and at five of the seven high success sites suggest that there was not higher soil carbon in the high success sites when they were established. These data support the idea that higher soil carbon in the high success sites was associated with afforestation, but it is not conclusive proof of this idea.

A second limitation is that, while we suggest that the prime driver of the differences between high and low success sites is high plant production at the high success sites, the factors underlying this high productivity are unclear. The presence of anthropogenic parent materials (e.g., construction debris) and frequent site disturbance play a role, but our experimental design did not control for these numerous and diverse potential confounding factors.

An additional confounding factor in our analysis is variation in current local land use and site conditions amongst our sites. While it appears that high success sites were more likely to be located directly adjacent to or very nearby wooded areas, and low success sites were more likely to be located in close proximity to open fields, paved surfaces, and other heavily trafficked land uses, this was not a controlled comparison.

While our data suggest that successful afforestation can lead to increases in soil carbon storage in urban areas, our results are not conclusive and raise numerous mechanistic questions that should be explored in future research.

6. Conclusions

The findings of this study suggest that deliberate afforestation techniques, combined with careful consideration of site history and inherent characteristics, can enhance the ability of urban soils to store carbon at the local scale, which is vital to supporting and improving urban ecosystem functions. Sites with visibly successful establishment of young forests – here, the presence of a closed canopy and a developing leaf litter layer – had greater carbon pools than degraded urban sites and sites where afforestation was less successful.

The success of afforestation efforts to sequester carbon depends largely on inherent site conditions. This appears to be a synergistic effect, such that sites with better physical and chemical soil conditions were better able to support the establishment and growth of trees, which in turn produces biomass that contributes carbon to soil pools.

There is a clear need for long-term monitoring of soil carbon pools and processes in these afforestation sites. Our study raises important questions about the effect of diversity planting palettes and changes over time, which can only be resolved with careful, controlled measurements on these sites moving forward.

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CRediT authorship contribution statement

A. E. Downey: Conceptualization, Investigation, Data Curation, Writing – Original Draft, Visualization. **P. M. Groffman**: Conceptualization, Formal Analysis, Resources, Writing – Review & Editing, Supervision. **G. A. Mejía**: Data Curation, Investigation, Writing – Review & Editing. **E. M. Cook**: Investigation, Writing – Review & Editing, Project Management. **S. Sritrairat**: Research Design, Data Collection. **R. Karty**:

Research Design, Data Collection. **M. I. Palmer**: Research Design, Conceptualization, Data Collection, Writing - Review and Editing. **T. McPhearson**: Research Design, Conceptualization, Data Collection, Writing - Review and Editing.

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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Appendix A. Supplementary data

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