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Nitrogen cycling and urban afforestation success in New York City

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Abstract

Afforestation projects are a growing focus of urban restoration efforts to rehabilitate degraded landscapes and develop new forests. Urban forests provide myriad valuable ecosystem services essential for urban sustainability and resilience. These essential services are supported by natural soil microbial processes that transform organic matter to critical nutrients for plant community establishment and development. Nitrogen (N) is the most limiting nutrient in forest ecosystems, yet little information is known about N cycling in urban afforestation efforts. This study examined microbially mediated processes of carbon (C) and N cycling in 10 experimental afforested sites established across New York City parklands under the MillionTreesNYC initiative. Long-term research plots were established between 2009 and 2011 at each site with low and high diversity (two vs. six tree species) treatments. In 2018, 1-m soil cores were collected from plots at each site and analyzed for microbial biomass and respiration, potential net N mineralization, and nitrification, denitrification potential, soil inorganic N, and total soil N. Field observations revealed markedly different trajectories between sites that exhibited a closed canopy and leaf litter layer derived from trees that were planted and those that did not fit this description. These two metrics served to group sites into two categories (high vs. low) of afforestation success. We hypothesized that: (1) afforestation success would be correlated with rates of C and N cycling, (2) high diversity restoration techniques would affect these processes, and (3) inherent soil properties interact with plants and environmental conditions to affect the development of these processes over time. We found that high success sites had significantly higher rates of C and N cycling processes, but low and high diversity treatments showed no differences. Low success sites were more likely to have disturbed soil profiles with human-derived debris. Afforestation success appears to be driven by interactions between initial site conditions that facilitate plant community establishment and development that in turn enable N accumulation and cycling, creating positive feedbacks for success.

INTRODUCTION

Urban forests are significant features of the urban landscape that provide important ecosystem services, such as climate regulation (e.g., C sequestration) and cultural benefits (e.g., recreation) (Nowak & Dwyer, 2000). Yet, urban forests are exposed to altered environmental conditions (e.g., elevated temperatures, atmospheric pollution, non-native species invasion) that impact natural processes and patterns that support ecosystem functions (Carreiro & Tripler, 2005; Gregg et al., 2003). These anthropogenic disturbances can alter plant and microbial community development, affecting nutrient cycling processes integral to forest biophysical functions. C and N cycle processes critical to forest productivity have been extensively studied in rural landscapes but there have been relatively few studies of these processes in urban areas (Pouyat et al., 2007). Understanding the plant–soil feedbacks that govern nutrient dynamics is necessary to inform urban forest restoration strategies that enhance ecosystem services.

Urban afforestation—tree planting in previously treeless areas—has been an increasing focus of ecological restoration across cities, as growing urban expansion increases forest fragmentation and the need for ecosystem services. Many cities have launched large afforestation campaigns to expand the urban canopy, increase biodiversity, improve air and water quality, and enhance other key ecosystem services provided by urban forests (Forgione et al., 2016; McPhearson et al., 2011; Oldfield et al., 2013). These tree-planting projects have focused on tree establishment and species diversity by planting native species, which are expected to outcompete non-native or invasive species and promote natural regeneration similar to "natural" ecosystems, thereby improving soil health and ecosystem resilience (Oldfield et al., 2014; Pregitzer et al., 2016, 2019). However, one of the challenges of such initiatives is the lack of attention paid to the condition of urban soils, which are often altered by previous land-use histories and management regimes (De Kimpe & Morel, 2000; Morel et al., 2015; Pavao-Zuckerman, 2008; Pouyat et al., 2010; Pregitzer et al., 2016). These disturbance histories are spatially variable and it is not well understood how they affect microbially mediated plant–soil feedbacks (Ward et al., 2020). For example, is unclear how inherent soil parent material properties (e.g., texture, water holding capacity, nutrient

availability, pH) affect initial survival and establishment that enable trees to establish, grow and sequester N, creating positive feedbacks for further growth.

In 2007, the New York City Department of Parks and Recreation (NYCDPR) launched the MillionTreesNYC (MTNYC) initiative in partnership with the non-profit organization New York Restoration Project (NYRP). The goal of the MTNYC was to expand the urban canopy by more than 804 ha, to restore native vegetation, increase biodiversity, and provide key ecosystem services within the metropolitan area (Forgione et al., 2016; McPhearson et al., 2011). This project also provided the opportunity to study ecological restoration at the citywide scale (McPhearson et al., 2011). Studies based on MTNYC afforestation sites have examined vegetation establishment and survival, and natural regeneration (Doroski et al., 2018; Oldfield et al., 2013; Simmons et al., 2016), and others have investigated the role of soil amendments and soil composition on vegetation health and growth (Oldfield et al., 2014, 2016, Pregitzer et al., 2016). However, few studies have focused on soil patterns and processes that regulate nutrients integral to forest development, productivity, and health (Pierre et al., 2016). Such studies are critically needed as many of the MTNYC sites are located in areas with highly altered, anthropogenic soils and highly variable, often suboptimal properties (Huot et al., 2017). NYC Parks oversees more than 30,000 acres of parklands underlain with natural and human-made materials that create varied soil conditions; a critical challenge to initial establishment and survival of tree plantings in urban restoration efforts (Pregitzer et al., 2016).

As part of the MTNYC program, research was developed to investigate the short- and long-term impacts of these afforestation efforts and provide baseline empirical information to inform parkland management. Experimental forest plots measuring 900 m^2 were established in 2009 at 10 different sites within NYC Parklands (McPhearson et al., 2011). Some of the afforestation plots were set up within NYC's 2497 ha of natural area forest containing relatively "natural" soils, while others were located on highly modified and disturbed soils in urban parks. Afforestation treatments focused on variation in tree species diversity (2 vs. 6 planted species) and the presence/absence of understory plantings. Over time, the success of the plantings—based on observed presence of a closed canopy and a leaf litter layer formed by trees that were planted—has varied significantly between sites. We

hypothesized that soil conditions, especially N cycling, have had a strong influence on this variation. We, therefore, sampled soils at these sites and measured a suite of microbial C and N cycle process variables to determine: (1) if afforestation success was associated with rates of C and N cycling, (2) if high diversity afforestation techniques affect these processes, and (3) how inherent soil properties interact with plants and environmental conditions to affect the development of these processes over time.

METHODS

Study area

Field sampling took place at 10 MTNYC experimental afforestation sites located within the 30,000 km^2 of parkland in the NYC metropolitan area (40.7128° N, 74.0060° W) (McPhearson et al., 2011; Figure 1a). The metropolitan area consists of five counties (boroughs): Bronx, New York (Manhattan), Kings (Brooklyn), Queens, and Richmond (Staten Island) and is populated by 8,537,673 residents (USCB, 2020). Manhattan and Staten Island are separated by the Hudson estuary, where fresh water from the Hudson River and saline water from the Atlantic Ocean meet. The mean annual temperature ranges from 8.9–16.8°C, and annual mean precipitation is 117.42 cm (NOAA, 2020).

The geology and soils of the geographic area were shaped by the retreating ice sheet from the last glaciation (18,000 years ago) that left behind valleys, moraines and glacial till (NYC Soil Survey Staff, 2005). Human development of the landscape has modified much of the native glacial till from which natural forest soils developed in the northeast USA (NYC Parks, 2014). Extensive modification has also resulted in new parent material associated with 19th and 20th century coal ash dumps, excavated material from construction projects, and other anthropogenic contributions (e.g., construction debris; Pregitzer et al., 2016). The sites selected for this study represent the heterogeneity of NYC Parklands, with parent materials including native glacial till, human-derived material, and a combination of both natural remnant and human-made materials.

The 10 study sites differed in soil composition, disturbance history and landscape context (Appendix S1: Figures S1–S10). Well drained loamy soils at Alley Pond and loamy sand soils at Canarsie were developed on human-transported material containing up to 75% coarse fragments (e.g., construction debris) larger than 2 mm diameter (NYC Soil Survey Staff, 2005). The coarse-loamy soils at Clearview, conversely, developed on a mixture of

till derived from gneiss, granite, and/or schist and natural soil materials used for roads (e.g., fill), with up to 35% coarse fragments in the surface layers and up to 50% in the subsurface (USDA; NYC Soil Survey Staff, 2005). These three sites had previously been used as dumps or landfills as recently as the 1970s (McPhearson et al., 2011), and were also located adjacent to highly developed areas and high-traffic roads. In addition, Alley Pond, Canarsie, Clearview struggled after the first year of planting. As a result, selective tree removal and replanting was conducted at two (Alley Pond and Canarsie) of three sites to promote afforestation establishment.

Clove Lakes, Conference House, Fort Totten, Marine Park sites 1, 2, and 3, and Pelham Bay were all located within parklands mostly surrounded by wooded areas. Loamy soils at Clove Lakes formed from red coarse-loamy supraglacial till (serpentine rocks), and Conference House developed on coarse-loamy and sandy glacial outwash (NYC Soil Survey Staff, 2005). In these two sites, major disturbance from park development ended in the 1930s (Falxa-Raymond et al., 2014). Soils at Fort Totten were derived from human-transported material and gneissic till, including anthropogenic soils and natural soil material used in residential areas (NYC Soil Survey Staff, 2005). The site at Fort Totten has been relatively intact since the construction of the fort along the East River in 1864 (NYC Parks, 2014). The loamy sand soils at all three Marine Park sites developed from sandy dredged materials from the surrounding coast, and contain concrete rubble deposited in the mid-20th century as the result of building construction in the area (Falxa-Raymond et al., 2014). Silt loam soils at Pelham Bay formed from glacial till derived from gneiss and schist, and have been relatively undisturbed since the late 1930s (Simmons et al., 2016).

A primary goal of urban forest restoration, including the MTNYC afforestation project, is to create a closed canopy of native trees to inhibit the growth of exotic and invasive vegetation (Forgione et al., 2016; McPearson et al., 2011; Oldfield et al., 2014; Simmons et al., 2016). Based on this overarching goal, the success of afforestation efforts depends on not only the establishment, but the growth and development of the trees planted.

Field data collection campaigns from June–July 2018 provided evidence of distinct differences in site performance based on observed variation in canopy closure and leaf litter accumulation from planted species, which are a function of tree stand density and growth. Canopy closure and leaf litter layer were qualitatively assessed by visual inspection during soil data collection and verified with digital photographs taken in the field. Closed canopy was indicated by the presence of a developed tree canopy consisting of planted trees and low light
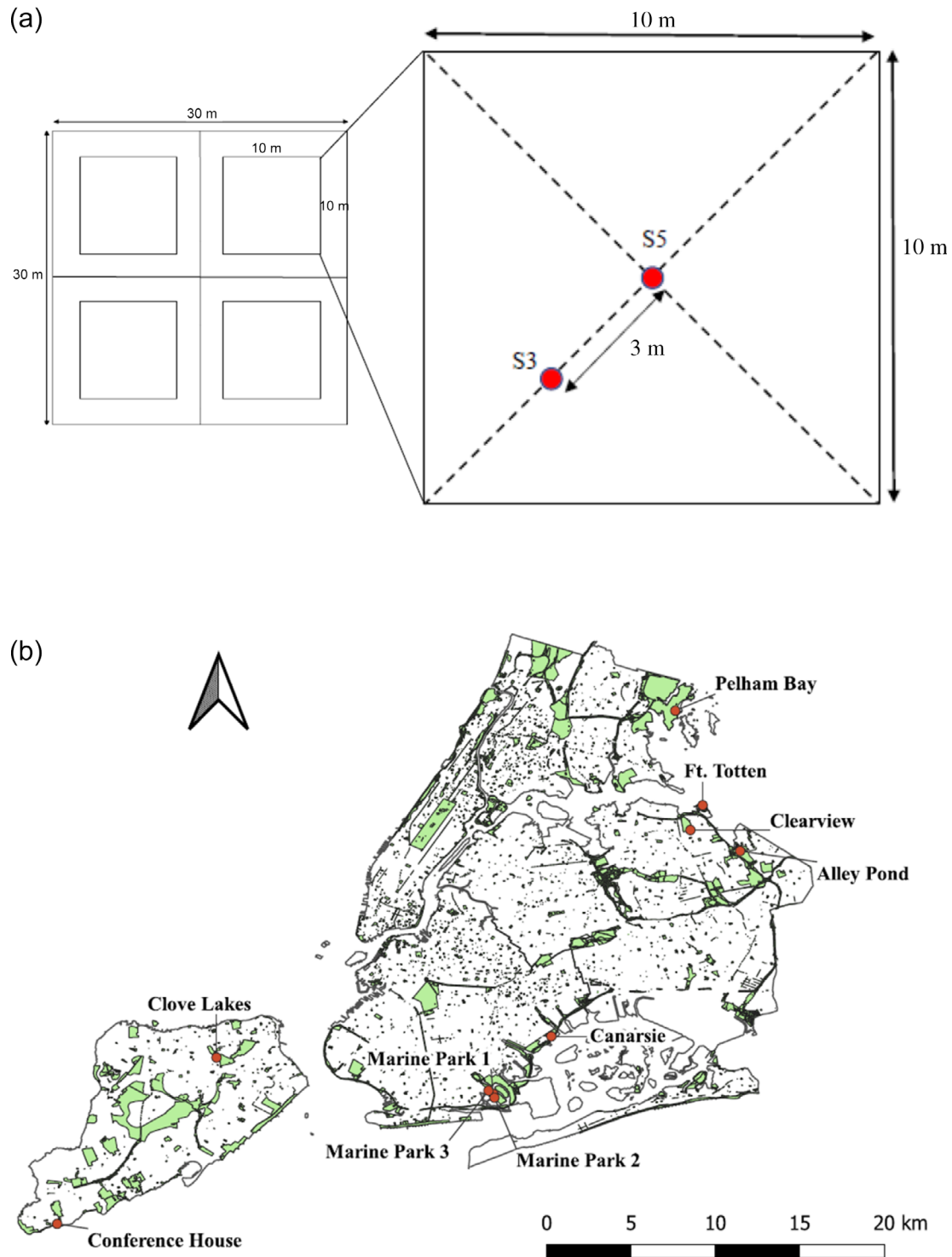
FIGURE 1 (a) Map of MillionTreesNYC Afforestation Project study sites across New York City, (b) diagram of soil sampling design developed by McPhearson et al. (2011) and modified for this study. Two soil cores were collected from each 10 m × 10 m subplot at randomly selected sampling points, the third (S3) and fifth (S5)

transparency, and the presence (>50%) or absence (<50%) of a leaf litter layer produced by those trees. At five high success sites, photographs taken vertically at four plot corners at 1.5 m height were visually assessed to identify the presence of a tree canopy formed by planted

trees, and the amount of light penetration in the frame of the photograph (Appendix S2: Figure S1). Vertical photographs were not taken at Pelham Bay and Fort Totten sites. Two photographs of the forest floor within the 10 m × 10 m sampling areas taken horizontally were

visually assessed to identify the presence/absence of tree leaf litter produced by the trees planted (Appendix S2: Figure S2). Photographs of leaf litter were not taken at Marine Park 3 site. At low success sites photographs were taken horizontally to capture absence of canopy and leaf little from planted trees (Appendix S2: Figure S3). A binary scale system was applied to each site where "1" represented the presence of a closed canopy and leaf litter from planted trees, and "0" if these two metrics were absent. This qualitative method has also been applied in other urban forest assessments in NYC to measure canopy closure (Forgione et al., 2016, Simmons & Auyeung, 2017).

Using this system, the Alley Pond, Canarsie, and Clearview sites were classified as "low success" and the Conference House, Clove Lakes, Fort Totten, Marine Park 1, 2 and 3, and Pelham Bay sites were classified as "high success" (Table 2). A more detailed, quantitative vegetation survey that included tree, shrub, and herbaceous species inventory and ground cover that was conducted in 2018 (Cook et al., in progress).

In 2009, a 30×30 m area at each site was cleared of weeds and invasive species and prepped for planting. Trees grown in 7.6 L containers ranging from 0.5–1.0 m in height were planted within four 10×10 m gridded sampling areas nested within four 15×15 m subplots within the 30×30 m total plot area per site. The 10×10 m sampling areas were established to allow for a buffered edge area between each 15×15 m subplot (Figure 1b). Understory shrub treatments included 36 species (from 3.8 L planters) per subplot. Each plot represented one of four planting pallets of native trees and shrubs: (1) two high diversity (with shrubs and herbs/without shrubs and herbs), and (2) two low diversity (with shrubs and herbs/without shrubs and herbs) at each site.

The Conference House and Pelham Bay sites were classified as hydric (saturated soils) by NYC Parks forest managers based on plant species indicators, while the rest were considered mesic (well drained soils). Two different tree species palettes were selected for planting according to this site type classification. High diversity plots at mesic sites were planted with *Quercus rubra*, *Nyssa sylvatica*, *Amelanchier canadensis*, *Prunus serotina*, *Quercus coccinea*, and *Celtis occidentalis*, while hydric sites contained *Quercus palustris*, *Nyssa sylvatica*, *Quercus bicolor*, *Liquidambar styraciflua*, *Platanus occidentalis*, and *Diospyros virginiana*. The low diversity plots at mesic sites were only planted with *Quercus rubra* and *Nyssa sylvatica*; hydric sites included *Quercus palustris* and *Nyssa sylvatica*. Due to space constraints, Conference House and Fort Totten sites contained two plots, instead of four, with one combination of high and low species diversity (Table 1). The four combinations of diversity composition were chosen to represent the range of species richness found in NYC woodlands (McPhearson et al., 2011).

Field sampling

Each 15 m $\times$ 15 m plot was divided into 25 sections (2×2 m), from which two sections were randomly selected for sampling, totaling eight sampling locations at eight sites (Table 1). These sampling locations represented a randomly selected subset of locations that were sampled in 2009. Fort Totten and Conference House sites only had two plots each, therefore, there were only a total of four sampling locations at these sites. To minimize the edge effect—high species richness along boundaries—sampling was done within a 10×10 m grid subplot. Sampling was conducted over a 1-month period in the summer of 2018 (mid-June to mid-July) using a standard 3.3 cm diameter soil corer to a depth of 1 m. High presence of construction debris (>2 mm) at Alley Pond and Canarsie sites restricted sampling to 30 cm depth and 70 cm depth, respectively. Sampling to 1 m also proved difficult due to compaction at Pelham Bay and Marine Park three sites, and only two of eight cores at each site were up to 1 m. Only one core was obtained for one of the plots at the Clearview site; a total of seven cores collected at this site. Each soil sample was enclosed in a plastic sleeve with secured end caps, then placed in a cooler for transport to the laboratory, where samples were stored in a refrigerator at 4°C until samples were processed. Sampling was repeated at all sites in fall of 2019 (September to October) to verify the soil data collected in 2018. Sampling took place in proximity to the sampling points from the previous year using a 3.81 cm diameter soil corer, to a depth of 30 cm.

Soil analysis, and KCl exchangeable NO_3^- and NH_4^+

Each soil core was first photographed, divided into different depths (0–10, 10–30, 30–70, and 70–100 cm), and inspected to identify horizons, Munsell color, signs of disturbance, and human artifacts smaller than the core diameter. Coarse debris (>2 mm) composed of rocks and roots were removed were dried at 105°C and weighed. Rock volume was estimated from mass and density was assumed at 2.7 h/cm³ (Hillel, 1998). Soil subsamples from each depth were homogenized by hand and analyzed for soil dry mass and percent moisture. Bulk density (BD) was calculated according to the following formula:

$$BD = (total\,dry\,mass - rock\,mass) \times /(total\,volume - rock\,volume)$$

TABLE 1 MTNYC Afforestation Project research site locations and descriptions

Site	Borough	Plots	Year planted	Site type[a]	Lithology[b]	Parent material[c]
Alley Pond Park	Queens	$n = 4$	2009	Mesic	Silty brown with white sand specks	Loamy human-transported material
Canarsie Park	Brooklyn	$n = 4$	2009	Mesic	Dark brown, fine silt	Sandy human-transported material
Clearview Park	Queens	$n = 4$	2011	Mesic	Brown, with fine clay and coarse sand	Coarse-loamy over sandy lodgment till derived from gneiss, granite, and/or schist
Clove Lakes Park	Staten Island	$n = 4$	2009–2010	Mesic	Brown, fine, silt	Red coarse-loamy supraglacial till
Conference House Park	Staten Island	$n = 2$	2010	Hydric	Brown, white sand with small pebbles	Coarse-loamy outwash over gravelly outwash and/or sandy outwash
Fort Totten Park	Queens	$n = 2$	2011	Mesic	Grayish-black coarse sand	Loamy-skeletal human-transported material, over an intact or truncated glacial till soil derived from granitic material
Marine Park 1	Brooklyn	$n = 4$	2009	Mesic	Dark grain and white sandy silt	Loamy human-transported material over sandy beach sand and/or outwash and/or dredge spoils
Marine Park 2	Brooklyn	$n = 4$	2010	Mesic	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	$n = 4$	2011	Mesic	Black organic with mulch	Loamy human-transported material over sandy beach sand and/or outwash and/or dredge spoils
Pelham Bay Park	Bronx	$n = 4$	2009	Hydric	Black, organic-rich fine clay and silt	Coarse-silty glaciolacustrine deposits and/or eolian deposits over till

[a]Planting palettes were specific to site type; species planted at mesic sites: *Quercus rubra*, *Nyssa sylvatica*, *Amelanchier Canadensis*, *Prunus serotina*, *Quercus coccinea*, *Celtis occidentalis*; species planted at hydric sites: *Quercus palustris*, *Nyssa sylvatica*, *Quercus bicolor*, *Liquidambar styraciflua*, *Platanus occidentalis*, *Diospyros virginiana*.

[b]Site lithology based on 0–10 cm depth soil sampling conducted within first year (2009–2011) of planting at each site.

[c]Parent material based on USDA Web Soil Survey and NYC Soil Staff Survey.

Homogenized subsamples were used to determine KCl exchangeable NO_3^- and NH_4^+, potential N mineralization and nitrification, denitrification potential, basal respiration, microbial biomass C and N, and total soil C and N using methods described by Raciti et al. (2011a, 2011b). Exchangeable NO_3^- and NH_4^+ were extracted from the soil with 40 ml of 2 M potassium chloride (KCl). The liquid from each sample was extracted and filtered into scintillation vials. Samples were analyzed colorimetrically for NO_3^- and NH_4^+ concentrations using a SpectraMax® M Series Multi-Mode Microplate Reader (Doane & Horwath, 2003; Sims et al., 1995). Limited soil pH data collected postplanting in 2009, 2010 and 2011 (0–10 cm depth) only, were analyzed at the Cornell Nutrient Analysis Laboratory (Soil Report to NYC Parks 8-20-2014, S. Sritrairat, 2014, unpublished data).

Potential net N mineralization and net nitrification and microbial respiration

Rates of potential N mineralization, nitrification, and respiration were measured in a 10-day laboratory incubation of soils at constant room temperature following procedures described in Robertson et al. (1999). Soils were incubated in 985 ml Ball® glass jars fitted with rubber septa to allow for sampling of headspace gas. Following incubation, the headspace of the jars was sampled to analyze for CO_2 by thermal conductivity gas chromatography. Microbial respiration was calculated as the accumulation of CO_2 over the course of incubation. Following gas sampling, inorganic N (NH_4^+ and NO_3^-) were extracted from soil in the jars as described above. Potential net N mineralization was calculated as the

accumulation of inorganic N and potential net nitrification was calculated as the accumulation of NO_3^- over the 10-day incubation (Robertson et al., 1999).

Microbial biomass C and N

Microbial biomass C and N was measured using the chloroform ($CHCl_3$) fumigation-incubation method developed by Jenkinson and Powlson (1976). Soil samples were fumigated with chloroform for 16–24 h to lyse microbial cells, then reinoculated with 0.2 g of unfumigated fresh soil. Carbon dioxide and exchangeable inorganic N (NO_3^- and NH_4^+) released by the regrowth of microbial community during a 10-day incubation are assumed to be directly proportional to C and N content of the microbial biomass in the original sample. Microbial biomass C was calculated using a proportionality constant of 0.45. Microbial biomass N was calculated directly from the production of inorganic N during the incubation (Voroney & Paul, 1984).

Denitrification potential

Rates of potential denitrification were measured using the denitrification enzyme assay developed by Smith and Tiedje (1979) as described by Groffman et al. (1999). Each sample was placed in a 125-ml Erlenmeyer flask, and amended with growth media to stimulate the maximum potential activity of enzymes present in the sample. Flasks were capped with a rubber stopper, and the headspace was repeatedly evacuated and refilled with N_2 to create the anaerobic conditions that stimulate N-production by denitrifying bacteria. Each flask was injected with 5 ml of acetylene (C_2H_2) to prevent N_2O reduction to N_2 during the incubation. The samples were placed on a shaker table at 125 rpm for a 90-min incubation, and 8 ml of headspace gas was extracted at 30 min and 90 min. The gas samples were analyzed for N_2O by electron capture gas chromatography (Groffman et al., 1999).

Total soil N

Total N was measured by flash-combustion/oxidation using an Elementar varioMax Cube elemental analyzer (detection limit is 0.02–500 mg N, or 100%). For all data, the density of N in a unit area (1 m^2) was calculated as:

$$N = N_f B_D (1 - \partial_{2mm}) V$$

where N is N density, N_f is the fraction by mass of organic N, B_D is bulk density, ∂_{2mm} is the fraction of material larger than 2 mm in diameter, and V is the volume of the soil core (Sollins et al., 1999). Total soil N was not measured for samples collected in 2019.

Statistical analysis

Comparisons between sites, success categories, and diversity treatment were conducted for data aggregated to both the whole-core level (up to 1 m depth) and the surface level (0–30 cm depth). One-way analysis of variance (ANOVA) was applied to each individual response variable (exchangeable NO_3^- and NH_4^+, total inorganic N, potential net N mineralization and nitrification, microbial biomass C and N, basal respiration, denitrification potential, and total soil N) at the whole-core level (normalized by soil mass) with site, depth, diversity treatment, and afforestation success (high vs. low) as main factors. Duncan's new multiple range test (MRT) was conducted to identify significant differences within groups when appropriate. ANOVA and MRT were also applied to test differences between high and low afforestation success for soil controls (BD, moisture content, rocks, and pH), and root biomass. Pearson's correlation was conducted across sites and depths, to test for linear or curvilinear relationships between individual response variables. Interactions between sampling years (2018–2019) and afforestation success on microbial activity (exchangeable NO_3^- and NH_4^+, total inorganic N, potential net N mineralization and nitrification, denitrification potential), biomass (C and N), and respiration (up to 30 cm) were tested with a two-way ANOVA. All data were tested for normality using Shapiro–Wilk test ($\alpha = 0.05$). All statistical analyses were conducted using R (version 3.2.2; R Core Team, 2020) packages.

RESULTS

Soil profile analysis

Surface depths (0–10 cm and 10–30 cm) contained the greatest amount of moisture, roots, rocks, and artifacts (Table 2). At the whole-core level, only soil moisture content and roots were significantly higher at sites with high afforestation success ($p < 0.001$ and $p < 0.01$, respectively; Figure 2). Alley Pond, Canarsie, and Clearview (low success) sites contained 30%, 15%, and 5% artifacts (>2 mm; respectively) in the form of construction debris (e.g., concrete or cement; Table 2). Bulk density increased

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T A B L E 2 Soil profile and characteristics across depth intervals (0–100 cm) at study sites

Site	Afforestation success	Depth (cm)	Munsell color	pH[a]	Root content (kg m²)	Rock content (kg m²)	Moisture content (%)	Artifact[b] (%)	Bulk density (g cm³)
Alley Pond Park	Low	0–10	Very dark grayish brown	7.22	0.20 ± 0.64	4.12 ± 0.64	10.18 ± 5.09	30	0.41 ± 0.02
		10–30	Grayish brown		0.02 ± 1.38	14.05 ± 1.38	4.84 ± 2.42		0.56 ± 0.01
Canarsie Park	Low	0–10	Dark gray/ dark grayish brown	7.68	0.05 ± 2.59	11.06 ± 2.59	5.50 ± 2.75	7.5	0.48 ± 0.01
		10–30	Dark brown/ dark yellowish brown		0.00 ± 0.00	14.89 ± 1.78	3.79 ± 1.89	15	0.64 ± 0.06
		30–70	Dark gray		0.00 ± 0.00	22.78 ± 2.57	7.68 ± 5.43	10	0.78 ± 0.08
Clearview Park	Low	0–10	Very dark gray	6.89	0.20 ± 0.96	5.27 ± 0.96	4.49 ± 2.25		0.50 ± 0.04
		10–30	Brown		0.00 ± 0.00	5.44 ± 0.83	6.14 ± 3.07	5	0.70 ± 0.01
		30–70	Brown/dark grayish brown		0.00 ± 0.00	8.47 ± 1.30	8.68 ± 4.34	10	0.74 ± 0.02
		70–90	Dark grayish brown		0.00 ± 0.00	4.30 ± 1.08	4.87 ± 2.43		0.81 ± 0.02
Clove Lakes Park	High	0–10	Dark reddish gray/ dusky red	6.26	0.26 ± 0.74	3.16 ± 0.74	6.55 ± 3.27		0.47 ± 0.03
		10–30	Dusky red		0.05 ± 2.27	6.54 ± 2.27	5.95 ± 2.97		0.62 ± 0.04
		30–70	Dark red		0.00 ± 1.16	6.57 ± 1.16	10.01 ± 5.01		0.71 ± 0.03
		70–90	Red		0.00 ± 0.99	7.65 ± 0.99	7.01 ± 3.50		0.76 ± 0.03
		90–100	Red		0 0.00 ± 0.00	9.46 ± 1.53	5.71 ± 2.85		0.85 ± 0.05
Conference House Park	High	0–10	Dark reddish brown	5.78	0.25 ± 2.54	3.89 ± 2.54	6.28 ± 4.44		0.45 ± 0.11
		10–30	Dark reddish brown		0.02 ± 1.92	4.93 ± 1.92	6.40 ± 4.53		0.64 ± 0.06
		30–70	Dark reddish brown		0.07 ± 0.69	2.19 ± 0.69	8.68 ± 6.13		0.75 ± 0.07
		70–90	Red		0.00 ± 0.00	4.57 ± 1.74	9.69 ± 6.85		0.75 ± 0.01
		90–100	Red		0.01 ± 1.45	5.71 ± 1.45	6.07 ± 4.29		0.73 ± 0.10
Fort Totten Park	High	0–10	Black	6.26	0.11 ± 0.19	1.04 ± 0.19	8.73 ± 6.17		0.36 ± 0.04
		10–30	Dark brown		0.17 ± 1.30	5.51 ± 1.30	9.84 ± 6.96		0.69 ± 0.00
		30–70	Brown		0.07 ± 0.05	2.62 ± 0.99	9.94 ± 7.03		0.75 ± 0.01
		70–90	Strong brown		0.00 ± 0.00	3.38	7.88 ± 5.57		0.74 ± 0.02
		90–100	Brown		0.00 ± 0.00	1.27	12.44		0.73
Marine Park 1	High	0–10	Black	5	0.21 ± 0.32	0.89 ± 0.32	25.94 ± 12.97		0.45 ± 0.01
		10–30	Black/dark reddish brown		0.05 ± 1.95	5 ± 1.95	25.27 ± 12.63		0.62 ± 0.02
		30–70	Reddish brown/ very dark gray		0.01 ± 0.80	5.44 ± 0.80	20.75 ± 10.37		0.75 ± 0.02
		70–90	Reddish gray		0.00 ± 0.00	1.64 ± 0.97	35.21 ± 17.61	20	0.75 ± 0.01
		90–100	Reddish brown		0.00 ± 0.00	0.02 ± 0.02	24.61 ± 12.30		0.76 ± 0.01
Marine Park 2	High	0–10	Black	5.68	0.31 ± 0.17	0.37 ± 0.17	12.56 ± 6.28		0.45 ± 0.01
		10–30	Dark reddish gray		0.10 ± 1.38	6.82 ± 1.38	10.53 ± 5.26		0.63 ± 0.03
		30–70	Reddish gray		0.01 ± 2.10	3.90 ± 1.89	9.15 ± 4.57		0.66 ± 0.02
		70–90	Pinkish gray		0.01 ± 0.53	1.92 ± 0.53	13.90 ± 6.95		0.77 ± 0.03
		90–100	Light gray		0.00 ± 0.00	0.01 ± 0.01	14.78 ± 8.53		0.73

(Continues)

TABLE 2 (Continued)

Site	Afforestation success	Depth (cm)	Munsell color	pH[a]	Root content (kg m²)	Rock content (kg m²)	Moisture content (%)	Artifact[b] (%)	Bulk density (g cm³)
Marine Park 3	High	0–10	Reddish black	6.29	2.17 ± 0.12	0.12 ± 0.12	10.83 ± 5.41		0.13 ± 0.02
		10–30	Reddish black		1.94 ± 3	6.07 ± 3	9.38 ± 4.69		0.56 ± 0.13
		30–70	Red		0.00	2.35	11.50		0.55
		70–90	Weak red		0.00	0.00 ± 0.00	8.08		0.56
		90–100	Weak red		0.00	0.00 ± 0.00	5.55		0.55
Pelham Bay Park	High	0–10	Reddish black	5.42	0.1 ± 2.67	3.76 ± 2.67	12.81 ± 6.41		0.74 ± 0.15
		10–30	Reddish black		0.18 ± 3.51	5.84 ± 3.51	13.78 ± 6.89		0.97 ± 0.14
		30–70	Weak red		0.00	5.22	11.29		0.74
		70–90	Dark reddish gray		0.00	13.32	17.94		0.8
		90–100	Dark reddish gray		0.00	8.8	11.58		0.9

Note: Means ± SE for one-time measurement of roots, rocks, soil moisture content (gravimetrically), and bulk density from 10 MTNYC research sites sampled in 2018.

[a]Soil pH based on 0–10 cm depth soil sampling conducted within first year (2009–2011) of planting at each site.

[b]Artifacts found at Alley Pond, Canarsie, and Clearview composed of construction material. Artifacts found at Marine Park 1 composed of charcoal.
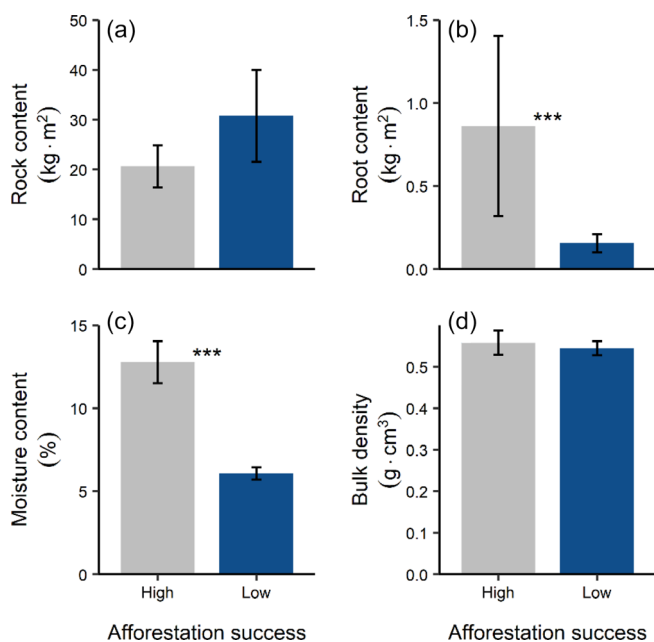

FIGURE 2 (a–d) Whole-core comparison of soil properties between high and low afforestation success (high success, $n = 7$; low success, $n = 3$). Error bars represent ± SE. Bars with asterisks are significantly different: *$p < 0.1$; **significant at $p < 0.05$; ***significant at $p < 0.01$; ****significant at $p < 0.001$

with soil depth at all sites (Figure 2), and was significantly higher at Marine Park 1 at the whole-core level ($p < 0.001$; Table 2). On average, soil color ranged from strong dark brown to black within surface depths (0–10, 10–30 cm), and grayish brown to reddish gray at deeper depths (30–70, 70–90, 90–100 cm) across sites (Table 2). Soils at the Clove Lakes and Conference House sites exhibited pronounced red hues at deeper depths (70–90 and 90–100 cm; Table 2).

Data previously collected at the time of planting at each site (2009–2011) showed that soil pH was significantly more alkaline in low success sites compared with high success sites ($p < 0.001$; Table 2).

N pools and processes

Whole-core (up to 1 m) total soil N was significantly higher at high success afforestation sites, with the differences most marked at the 10–30 cm depth ($p < 0.001$ and $p < 0.001$, respectively; Figure 3a). Exchangeable NO_3^- and total inorganic N at the whole-core level were also significantly higher at high success sites ($p < 0.001$ and $p < 0.01$, respectively; Figure 3c,d). These effects were most marked at the 10–30 cm depth ($p < 0.001$; Table 3). At the site level, Marine Park 3 had the highest N pools ($p < 0.001$; Table 3) over the whole sampling depth, with effects most marked at the surface (0–30 cm). There were no significant differences in N pools between high and low diversity treatments at the surface or whole-core level (Figure 4a–d).

There were no significant differences in potential net N mineralization and nitrification, and denitrification potential between high and low success sites. Microbial biomass N to either 30 cm or at the whole-core level was significantly higher in high than in low success sites ($p < 0.05$; Figure 3e–h). While most variables were concentrated at the surface (0–30 cm), pools of microbial biomass N were largest at the 10–30 cm depth ($p < 0.01$; Table 4). At the site level, microbial biomass N to either 30 cm or at the whole-core level was significantly higher at Marine Park 3 ($p < 0.001$; Table 4). Similar to N pools,
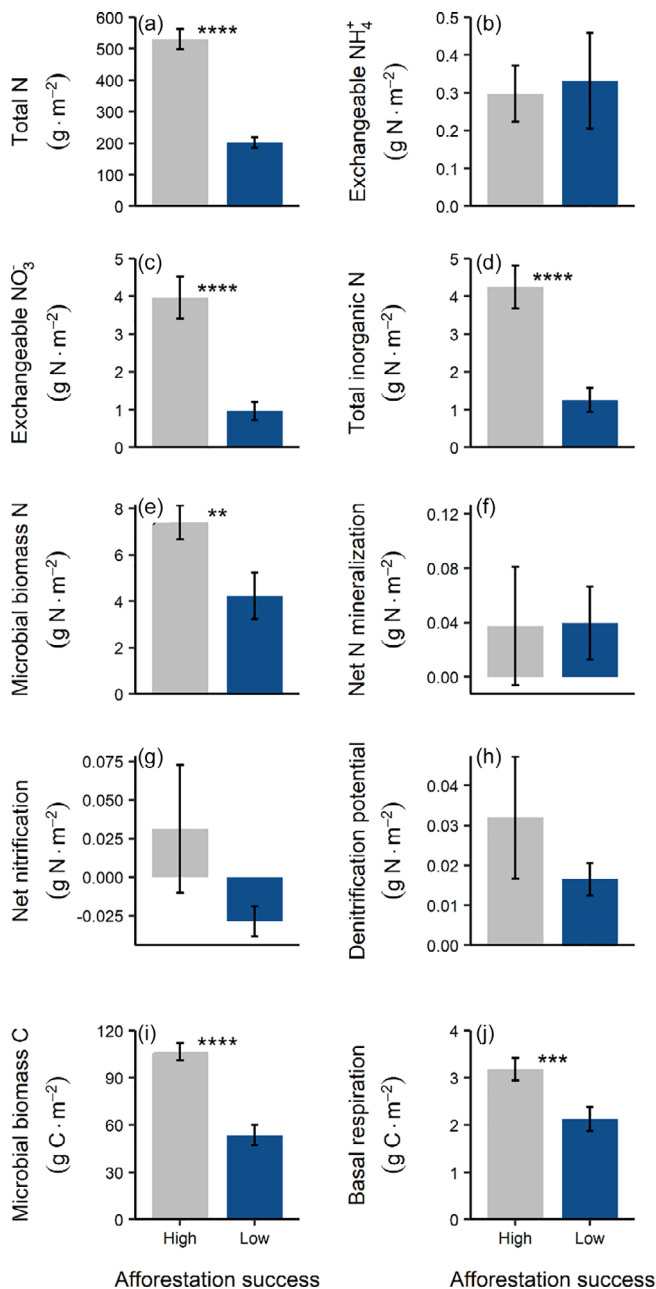
FIGURE 3 (a–j) Whole-core comparison of soil parameters between high and low afforestation success (high success, $n = 7$; low success, $n = 3$). Error bars represent $\pm$ SE. Bars with asterisks are significantly different: *$p < 0.1$; **significant at $p < 0.05$; ***significant at $p < 0.01$; ****significant at $p < 0.001$

there were no significant differences in microbial variables between high and low diversity treatments at the whole-core or 0–30 cm depths (Figure 4e–h).

C cycling

Microbial biomass C was significantly higher at high success afforestation sites at the whole-core ($p < 0.01$;

Figure 3i) and 0–30 cm level, and this difference was most marked at the 10–30 cm depth. At the site level, Marine Park 3 had significantly more microbial biomass C than all other sites ($p < 0.001$; Table 5). Whole-core and surface (0–30 cm) comparisons of respiration rates were also higher at high success sites ($p < 0.01$ and $p < 0.1$, respectively; Figure 3j). Across sites, respiration rates were significantly more pronounced at the 30–70 cm depth ($p < 0.001$; Table 5). Between sites, Fort Totten had significantly higher respiration rates than other sites at the whole-core level, but Marine Park 3 showed significantly higher respiration up to 30 cm ($p < 0.001$; Table 5). There were no significant differences in microbial biomass C and respiration between high and low diversity treatments at the whole-core or 0–30 cm level (Figure 4).

Relationships between variables

Total N was highly correlated with several indices of N richness and cycling, including exchangeable NO_3^-, total inorganic N, and microbial biomass N ($p < 0.001$; Table 6). There were also significant correlations between C and N cycling variables; microbial biomass C was significantly correlated with total N, exchangeable NO_3^-, total inorganic N, and microbial biomass N ($p < 0.001$; Table 6). In contrast, C and N cycle process rates (microbial respiration, potential net N mineralization and nitrification, denitrification potential) showed few correlations (Table 6).

Comparisons between 2018 and 2019 sampling years

Soil sampling conducted in 2019 showed similar patterns to samples collected in 2018, with very few differences between samples collected in the different years (Figure 5). Only basal respiration was significantly different between years ($p < 0.01$; Figure 5). Patterns associated with afforestation success (Figure 5), species diversity, and site factors were also similar in both years. There were no significant interactions between years and afforestation success.

DISCUSSION

Our results show a clear link between N and afforestation success. Successful afforestation sites, where planted trees have established an intact closed canopy and where litter is accumulating in an emerging forest floor surface organic horizon had markedly higher pools of total and

T A B L E 3 Soil parameters of N pools measured at across depth intervals (0–100 cm) at study sites

Site	Afforestation success	Depth (cm)	Total N (g m^{-2})	Exchangeable NH$_4^+$ (g N m^{-2})	Exchangeable NO$_3^-$ (g N m^{-2})	Total inorganic N (g N m^{-2})
Alley Pond Park	Low	0–10	120.47 ± 24.04	0.03 ± 0.04	0.23 ± 0.10	0.26 ± 0.11
		10–30	102.03 ± 11.46	0.13 ± 0.18	0.62 ± 0.26	0.65 ± 0.33
Canarsie Park	Low	0–10	46.82 ± 5.04	0.02 ± 0.02	0.45 ± 0.16	0.46 ± 0.17
		10–30	61.32 ± 6.25	0.02 ± 0.05	0.00 ± 0.17	0.02 ± 0.20
		30–70	122.37 ± 23.40	0.17 ± 0.17	−0.91 ± 0.52	−0.74 ± 0.69
Clearview Park	Low	0–10	56.13 ± 3.99	0.06 ± 0.02	0.44 ± 0.11	0.50 ± 0.11
		10–30	47.52 ± 2.21	0.16 ± 0.06	0.57 ± 0.24	0.72 ± 0.29
		30–70	99.33 ± 17.80	0.18 ± 0.06	0.80 ± 0.12	0.98 ± 0.17
		70–90	54.05 ± 8.79	0.67 ± 0.32	0.37 ± 0.04	1.05 ± 0.29
Clove Lakes Park	High	0–10	101.23 ± 18.41	0.06 ± 0.01	1.19 ± 0.26	1.25 ± 0.28
		10–30	131.95 ± 7.59	0.07 ± 0.04	0.84 ± 0.29	0.91 ± 0.28
		30–70	110.90 ± 32.44	0.18 ± 0.07	0.21 ± 0.07	0.39 ± 0.11
		70–90	35.48 ± 3.87	0.11 ± 0.06	0.50 ± 0.47	0.61 ± 0.45
		90–100	16.99 ± 1.60	0.06 ± 0.02	0.06 ± 0.06	0.12 ± 0.09
Conference House Park	High	0–10	78.40 ± 31.39	0.06 ± 0.04	0.92 ± 0.38	0.97 ± 0.42
		10–30	102.98 ± 34.57	0.06 ± 0.04	0.60 ± 0.24	0.76 ± 0.29
		30–70	165.62 ± 41.26	0.13 ± 0.03	2.22 ± 1.76	2.34 ± 1.78
		70–90	55.88 ± 14.11	0.04 ± 0.02	0.65 ± 0.45	0.69 ± 0.43
		90–100	36.75 ± 18.02	0.06 ± 0.05	0.25 ± 0.05	0.32 ± 0.00
Fort Totten Park	High	0–10	132.45 ± 15.50	0.07 ± 0.02	1.72 ± 0.03	1.79 ± 0.01
		10–30	101.04 ± 10.33	0.05 ± 0.01	1.67 ± 0.92	1.72 ± 0.93
		30–70	83.61 ± 13.60	0.07 ± 0.03	0.52 ± 0.07	0.59 ± 0.10
		70–90	37.55 ± 6.08	0.05 ± 0.01	0.16 ± 0.05	0.20 ± 0.06
		90–100	14.69	0.01	0.04	0.05
Marine Park 1	High	0–10	102.56 ± 14.16	0.06 ± 0.01	1.03 ± 0.62	1.09 ± 0.61
		10–30	135.44 ± 14.00	0.07 ± 0.01	0.35 ± 0.06	0.42 ± 0.06
		30–70	121.48 ± 6.31	0.11 ± 0.03	0.69 ± 0.13	0.80 ± 0.13
		70–90	51.65 ± 21.80	0.05 ± 0.01	0.21 ± 0.13	0.26 ± 0.14
		90–100	15.53 ± 1.79	0.01 ± 0.00	0.02 ± 0.02	0.04 ± 0.01
Marine Park 2	High	0–10	104.32 ± 6.90	0.02 ± 0.01	0.50 ± 0.04	0.53 ± 0.05
		10–30	166.18 ± 23.29	−0.03 ± 0.01	0.73 ± 0.12	0.70 ± 0.13
		30–70	278.66 ± 36.45	−0.05 ± 0.03	0.60 ± 0.26	0.55 ± 0.26
		70–90	29.84 ± 2.90	−0.04 ± 0.01	0.13 ± 0.08	0.09 ± 0.08
		90–100	15.31	−0.02	0.07	0.05
Marine Park 3	High	0–10	238.07 ± 46.33	0.03 ± 0.02	1.77 ± 0.37	1.80 ± 0.36
		10–30	441.88 ± 124.89	0.00 ± 0.12	7.00 ± 2.75	7.00 ± 2.87
		30–70	81.96	−0.4	1	0.60
		70–90	21.76	−0.19	0.18	−0.01
		90–100	12.28	−0.09	0.08	−0.02

(Continues)

T A B L E 3   (Continued)

Site	Afforestation success	Depth (cm)	Total N (g m^{-2})	Exchangeable NH$_4^+$ (g N m^{-2})	Exchangeable NO$_3^-$ (g N m^{-2})	Total inorganic N (g N m^{-2})
Pelham Bay Park	High	0–10	255.77 ± 57.77	0.27 ± 0.05	1.51 ± 0.26	1.78 ± 0.30
		10–30	451.42 ± 96.44	0.68 ± 0.32	1.95 ± 0.66	2.63 ± 0.96
		30–70	113.39	−0.14	0.02	−0.12
		70–90	36.87	−0.08	−0.02	−0.09
		90–100	15.27	−0.04	2.16	2.13

Note: Means ± SE for one-time measurement of total N, and soil inorganic N (NH$_4^+$ and NO$_3^-$) from 10 MTNYC research sites sampled in 2018.

inorganic N and higher rates of N cycling processes in soil. These results were consistent over 2 years of sampling (Figure 5).

The question that emerges from our results is if increased N availability in the high success afforestation sites is an inherent property of the soil parent materials or if N accumulated as the plant community became established. The sites sampled in this study represent the anthropogenic (e.g., dredged sediments, construction debris, municipal waste) and natural (e.g., glacial till derived from gneiss, granite, and/or schist) parent materials typical of urban soils (Table 1), some of which can have high N content that can facilitate afforestation success. Alternatively, urban soils with other favorable physical or chemical characteristics, for example, texture, water availability, base cation availability, pH, can foster establishment of afforestation communities that then have a high capacity to capture, store, and cycle N from surrounding environments. These plant–soil feedbacks were noticeable in high success sites, and suggest that unfavorable soil characteristics (e.g., presence of construction debris) may have constrained plant community establishment and N accumulation at sites with low afforestation success.

N availability as a driver of ecosystem development

Forest ecosystem growth and development are driven by the availability of essential nutrients. In temperate forest ecosystems, N is most commonly identified as the limiting nutrient (Vitousek & Howarth, 1991). Total soil N is part of the total soil organic matter pool, and therefore, a key indicator of N status (quality and quantity; Knicker, 2011). In the high success sites, total soil N was largely concentrated at the surface (0–10 and 10–30 cm; Table 3) that is expected, as the surface layer (0–30 cm) contains most of the root zone where microbially mediated C and N mineralization takes place.

In the high success sites, the strong difference in N availability between the surface and deeper depths suggests this accumulation was not an inherent difference in the parent materials at the sites. While, it is likely that the less recently disturbed sites (most of the successful sites) were likely to have had more soil profile development and nutrient content than the more highly disturbed sites (most of the low success sites), if parent materials at the high success sites were inherently N rich, we would expect to see differences across the whole profile rather than just at the surface. This suggests that at high success sites plant community development was fostered by some other factor (e.g., texture, water availability or pH) that would enable plant communities to sequester and accumulate N at accelerated rates over time. At the low success sites, unfavorable soil physical and chemical properties probably constrained plant establishment and development. Evidence for this includes the presence of coarse fragments (>2 mm) in the form of construction debris (e.g., concrete), which may have also contributed to noticeably higher pH levels (Table 2) at the low success sites.

Among the high success sites, both Pelham Bay Park and Marine Park 3 had higher soil N concentrations, which is consistent with significantly higher soil C concentrations (Downey et al., 2021), and a more developed canopy and litter layer of trees planted suggesting higher forest productivity. This relationship between C and N cycling supports the idea that strong plant–soil feedbacks drive afforestation success. This pattern is consistent with long-term observations of soil C and N concentrations in successful afforestation plots in an urban park in New York City (Ward et al., 2021). The low success sites with the poorest performance, Alley Pond and Canarsie, had an average of 50% less total soil N than the highest success sites over the 0–30 cm (Table 3). Total soil N values across all low success sites were comparable with open green spaces (e.g., lawns, gardens, grassy areas) in the city (Raciti et al., 2012).
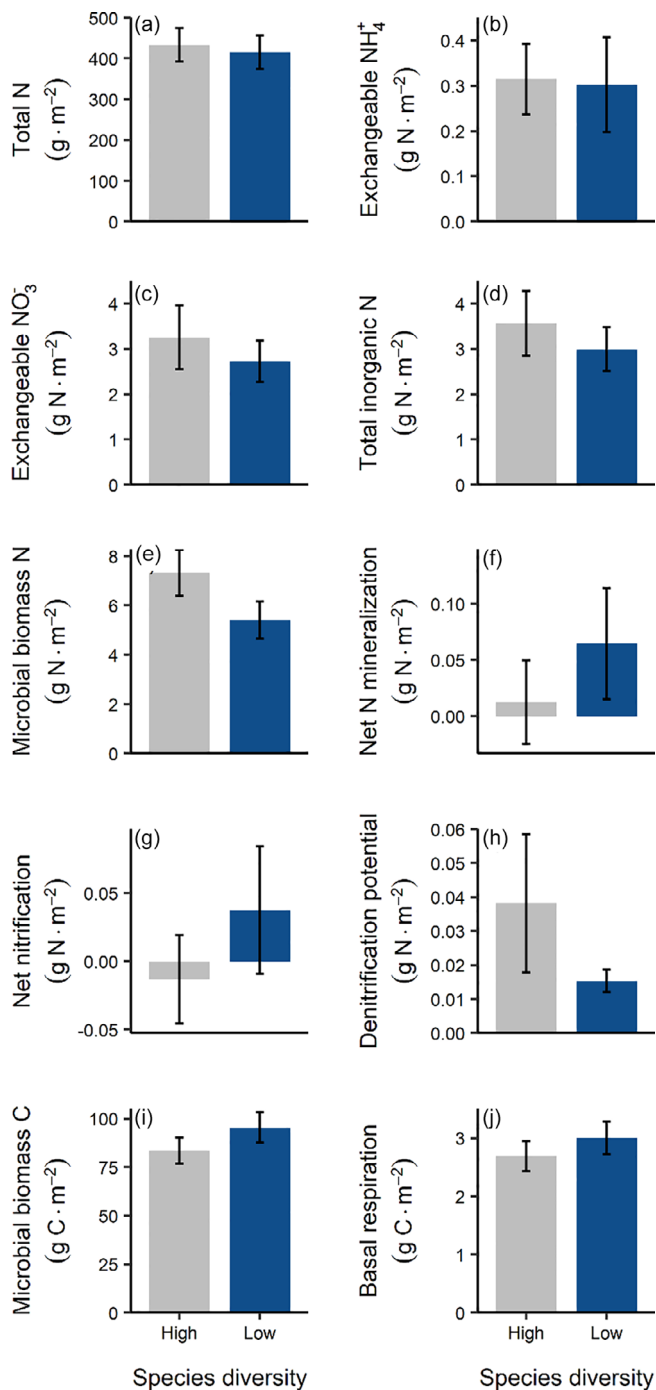
FIGURE 4 (a–j) Whole-core comparison of soil parameters between high and low species diversity subplots (high diversity, $n = 36$; low diversity, $n = 35$). Error bars represent $\pm$ SE. Bars with asterisks are significantly different: *$p < 0.1$; **significant at $p < 0.05$; ***significant at $p < 0.01$; ****significant at $p < 0.001$

The fact that potential net N mineralization and nitrification were not significantly higher in high success sites, and the high correlations between microbial biomass C and N content and processes, support the idea that strong plant–soil feedbacks drive afforestation

success (Table 6). Mineralization, which is the dominant source of N for plant growth, results from a net balance between N that microbial communities produce (mineralize) and consume (immobilize), and is therefore strongly tied to the C cycle (Hart et al., 1994). While potential net nitrification was not significantly higher in the high success sites, these sites had lower pools of NH_4^+ and higher pools of NO_3^-, suggesting higher rates of nitrification, which consumes NH_4^+ and produces NO_3^- (Kaye & Hart, 1997; Kuzyakov & Xu, 2013; Vitousek et al., 1979; Zak et al., 1990). This is evidenced by the strong positive relationship between NO_3^- and net nitrification (Table 6). The higher pools of NH_4^+ at the low success sites may also be a product of low plant uptake at these sites. A further possibility is that bulk N deposition could be contributing to NH_4^+ pools at the low success sites, which were all within close proximity of high-traffic roads that were likely to enhance N precipitation from fossil fuel combustion (Bettez & Groffman, 2013; Decina et al., 2017; Fenn et al., 2018).

Upper surface (0–10 cm) layer values for soil inorganic N pools, net N mineralization and nitrification, and microbial biomass N (Table 4) were comparable with a similar MTNYC afforestation study (Pierre et al., 2016) conducted using the same methods applied in this study. Total inorganic N and microbial biomass N were also similar to those found in other urban forest sites (e.g., Pelham Bay) in the NYC metropolitan area (Zhu & Carreiro, 2004b), but net N mineralization and nitrification were lower (Zhu & Carreiro, 2004a). These microbial transformations were also low compared with other eastern urban forests (Enloe et al., 2015; Trammell et al., 2017). However, microbial biomass C and N were similar to southeastern urban oak and pine stands studied by Enloe et al. (2015).

Microbial activity at some of the sites may have been affected by management activities or other site-specific factors. Marine Park 3 site had very high NO_3^- pools and microbial biomass C compared with other afforestation sites in this and other studies in NYC (Oldfield et al., 2014; Pierre et al., 2016). Undocumented mulch and/or compost application may have played a role at this site (Downey et al., 2021). The Fort Totten site had notably high basal respiration (CO_2 production) that may have been caused by large quantities of woody and leaf litter and a well developed herbaceous layer at this site (Appendix S2: Figure S1). This positive effect of litter quality and species richness on microbial activity has been observed in other temperate urban forests (Melliger et al., 2017). High nitrification rates at the Fort Totten site may also be driven by high litter input (Table 4).

Interestingly, Marine Park 2 site had the highest rates of net nitrification, but much smaller pools of NO_3^- than most

TABLE 4 Soil parameters of microbial N processes measured at across depth intervals (0–100 cm) at study sites

Site	Afforestation success	Depth (cm)	Microbial biomass N (g N m^{-2})	Net N mineralization (g N m^{-2})	Net nitrification (g N m^{-2})	Denitrification potential (g N m^{-2})
Alley Pond Park	Low	0–10	0.93 ± 0.18	−0.01 ± 0.01	−0.02 ± 0.01	0.03 ± 0.01
		10–30	1.59 ± 0.60	0.05 ± 0.03	0.01 ± 0.01	0.00 ± 0.00
Canarsie Park	Low	0–10	0.06 ± 0.06	0.00 ± 0.01	−0.01 ± 0.01	−0.00 ± 0.00
		10–30	2.25 ± 1.82	0.01 ± 0.02	−0.02 ± 0.01	−0.00 ± 0.00
		30–70	9.56 ± 5.52	0.01 ± 0.03	−0.03 ± 0.03	0.00 ± 0.00
Clearview Park	Low	0–10	0.88 ± 0.31	−0.00 ± 0.01	0.00 ± 0.01	0.01 ± 0.00
		10–30	0.72 ± 0.31	−0.00 ± 0.01	−0.00 ± 0.00	0.00 ± 0.00
		30–70	0.77 ± 0.16	0.00 ± 0.03	−0.03 ± 0.01	−0.00 ± 0.00
		70–90	1.51 ± 0.53	0.06 ± 0.06	−0.02 ± 0.00	0.00 ± 0.00
Clove Lakes Park	High	0–10	3.12 ± 0.34	0.03 ± 0.03	0.03 ± 0.02	0.02 ± 0.01
		10–30	2.62 ± 1.31	−0.00 ± 0.01	0.00 ± 0.01	0.01 ± 0.01
		30–70	0.87 ± 0.41	−0.01 ± 0.02	0.00 ± 0.01	−0.00 ± 0.00
		70–90	0.52 ± 0.18	−0.06 ± 0.05	−0.05 ± 0.05	−0.00 ± 0.00
		90–100	0.62 ± 0.55	−0.01 ± 0.01	−0.01 ± 0.01	−0.00 ± 0.00
Conference House Park	High	0–10	2.80 ± 0.89	0.11 ± 0.05	0.03 ± 0.03	0.02 ± 0.00
		10–30	1.33 ± 0.82	0.02 ± 0.00	0.02 ± 0.00	0.00 ± 0.00
		30–70	0.67 ± 0.03	−0.19 ± 0.18	−0.18 ± 0.18	0.00 ± 0.00
		70–90	0.16 ± 0.10	−0.06 ± 0.04	−0.06 ± 0.04	0.00 ± 0.00
		90–100	0.04 ± 0.05	−0.03 ± 0.00	−0.03 ± 0.01	0.00 ± 0.00
Fort Totten Park	High	0–10	4.61 ± 0.09	0.02 ± 0.00	0.02 ± 0.00	0.02 ± 0.00
		10–30	3.06 ± 1.96	0.11 ± 0.03	0.11 ± 0.02	0.00 ± 0.00
		30–70	0.51 ± 0.13	0.03 ± 0.03	0.03 ± 0.03	−0.00 ± 0.00
		70–90	0.33 ± 0.04	−0.01 ± 0.01	−0.00 ± 0.01	−0.00 ± 0.00
		90–100	0.06	0	0.00	0
Marine Park 1	High	0–10	1.23 ± 0.60	−0.02 ± 0.04	−0.03 ± 0.04	0.01 ± 0.00
		10–30	0.56 ± 0.09	0.02 ± 0.00	0.01 ± 0.00	0.00 ± 0.00
		30–70	0.85 ± 0.22	−0.00 ± 0.02	−0.01 ± 0.01	−0.00 ± 0.00
		70–90	0.36 ± 0.20	0.01 ± 0.02	0.01 ± 0.02	0.00 ± 0.00
		90–100	0.11 ± 0.04	0.00 ± 0.00	0.00 ± 0.00	−0.00 ± 0.00
Marine Park 2	High	0–10	1.44 ± 0.42	0.02 ± 0.03	0.01 ± 0.03	0.01 ± 0.00
		10–30	1.67 ± 0.73	0.07 ± 0.04	0.06 ± 0.04	0.00 ± 0.00
		30–70	1.45 ± 1.00	0.08 ± 0.02	0.07 ± 0.02	0.00 ± 0.00
		70–90	1.24 ± 0.30	0.03 ± 0.03	0.02 ± 0.03	−0.00 ± 0.00
		90–100	0.7	−0.01	−0.01	0.00
Marine Park 3	High	0–10	4.37 ± 0.77	−0.00 ± 0.02	−0.01 ± 0.01	0.04 ± 0.01
		10–30	8.86 ± 2.38	0.11 ± 0.21	0.11 ± 0.20	−0.01 ± 0.01
		30–70	1.94	0.03	0.00	0.00
		70–90	0.7	0.02	0.01	0.00
		90–100	0.2	0.01	0.00	−0.04

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T A B L E 4 (Continued)

Site	Afforestation success	Depth (cm)	Microbial biomass N (g N m^{-2})	Net N mineralization (g N m^{-2})	Net nitrification (g N m^{-2})	Denitrification potential (g N m^{-2})
Pelham Bay Park	High	0–10	4.42 ± 1.22	-0.01 ± 0.04	0.01 ± 0.04	0.02 ± 0.01
		10–30	4.35 ± 1.71	0.02 ± 0.03	0.05 ± 0.04	0.10 ± 0.09
		30–70	-0.59	-0.04	-0.08	0.00
		70–90	-0.32	-0.02	-0.04	0.00
		90–100	-0.26	-0.24	-0.26	0.00

Note: Means ± SE for one-time measurement of microbial biomass N content, potential net N mineralization and nitrification, and denitrification potential from 10 MTNYC research sites sampled in 2018.

sites (Tables 3 and 4). These patterns, which were consistent across both sampling years, suggest potential for high hydrologic NO_3^- losses at this site (Table 3). Falxa-Raymond et al. (2014) observed high ^{15}N foliar enrichment in planted trees species at this site—an indication of low NO_3^- assimilation (nitrate reductase activity)—and attributed these patterns to high N leaching. These losses are a concern in forest ecosystems, as they reduce availability of a limiting nutrient and can cause eutrophication in receiving waters (Galloway et al., 2004). High nitrification is often associated with site disturbance (Bormann & Likens, 1979; Vitousek et al., 1979) and urban forests are subject to a wide range of stressors inherent to cities that can disrupt soil–plant–microbial interactions and stimulate nitrification (Bai et al., 2015; Bednova et al., 2018; Bulbovas et al., 2020).

N losses can also occur through denitrification, the microbial process that converts NO_3^- to gaseous forms (NO, N$_2$O, and N$_2$; Robertson & Groffman, 2015). Denitrification potential was not significantly different between high and low success sites, suggesting that all these sites have a capacity for N removal by this process. Because denitrification is an anaerobic process, sites with high water content (e.g., forest riparian zones) often have higher denitrification potential. Therefore, it is not surprising that denitrification was highest at Pelham Bay—a hydric site with high C (Table 5) and N content (Table 3; Fang et al., 2015, Wallace et al., 2018). Given the proximity of this site to coastal waters, the potential for denitrification is important because this process prevents NO_3^- transport to coastal ecosystems where it is a prime cause of eutrophication (Conley et al., 2009; Rosenzweig et al., 2018).

Canarsie and Alley Pond had the lowest N content and were the least successful of our study sites; nearly all trees and shrubs planted at these two sites did not survive (Cook et al., in progress; Downey et al., 2021). As a result, both sites were replanted after the first two years of poor survivorship (Cook et al., in progress; Downey et al., 2021). The Canarsie site had noticeable signs of mowing in some plots, and other plots were overgrown with Mugwort (*Artemisia*

vulgaris; Appendix S2: Figure S3). Similarly, Clearview was heavily overgrown with Mugwort (*Artemisia vulgaris*; Appendix S2: Figure S3) and showed evidence of active dumping (Cook et al., in progress; Downey et al., 2021). Preplanting site preparation at some sites may have also involved herbicide application and removal of woody invasive tree species, such as *Acer platanoides*, which is common in restoration efforts (Simmons et al., 2016). Management activities and intensity can clearly cause disturbances that change ecological trajectories, that in turn, change soil conditions and microbial processes (Johnson & Handel, 2019).

C and N patterns of tree species diversity treatments

There were no significant differences between high and low diversity plots for any soil parameters at the whole-core or 0–30 cm level, 10 years after plot establishment. The lack of a diversity effect was consistent across sites, which exhibited widely varying total soil N and C content (Downey et al., 2021). These results are consistent with other afforestation studies that found that soil microbial activity is much less affected by diversity treatments than by soil amendments (i.e., compost and mulch), at least in the early phases (<10 years) of establishment (Oldfield et al., 2014; Pierre et al., 2016; Ward et al., 2021).

It is likely that diversity effects on soil microbial activity may emerge over time in these afforestation plots as trees mature, as there is well documented evidence that plant species diversity is a factor that can influence soil microbial activity (Chen et al., 2019). Stand composition is known to exert a strong control on C and N through litter quality (Zhu and Carreiro 2004) and species-specific N characteristics have varying effects on individual N processes (Lovett et al., 2004). These effects are likely to have taken time to develop and become expressed against the background of preafforestation site conditions. For example, Falxa-Raymond et al. (2014) found significant differences

T A B L E 5 Soil parameters of C microbial processes and pools measured at across depth intervals (0–100 cm) at study sites

Site	Afforestation success	Depth (cm)	Total C[a] (C m^{-2})	Microbial biomass C (g C m^{-2})	Basal respiration (g C m^{-2})
Alley Pond Park	High	0–10	1.91 ± 0.21	13.77 ± 0.91	0.36 ± 0.05
		10–30	2.44 ± 0.33	17.49 ± 2.50	0.67 ± 0.05
Canarsie Park	High	0–10	0.94 ± 0.05	13.92 ± 0.98	0.96 ± 0.08
		10–30	1.65 ± 0.23	19.47 ± 1.12	1.07 ± 0.05
		30–70	4.23 ± 0.36	40.19 ± 10.94	2.00 ± 0.43
Clearview Park	High	0–10	0.75 ± 0.06	15.31 ± 2.54	0.39 ± 0.00
		10–30	0.58 ± 0.06	19.86 ± 2.72	0.54 ± 0.03
		30–70	1.01 ± 0.20	35.68 ± 3.64	1.35 ± 0.17
		70–90	0.61 ± 0.06	20.87 ± 1.02	0.67 ± 0.05
Clove Lakes Park	High	0–10	1.63 ± 0.28	38.00 ± 6.53	0.68 ± 0.02
		10–30	2.01 ± 0.18	27.10 ± 3.91	0.71 ± 0.07
		30–70	1.42 ± 0.62	34.45 ± 5.76	1.18 ± 0.10
		70–90	0.32 ± 0.07	15.02 ± 1.38	0.60 ± 0.05
		90–100	0.10 ± 0.02	8.40 ± 1.19	0.33 ± 0.05
Conference House Park	High	0–10	1.16 ± 0.39	30.63 ± 1.96	0.77 ± 0.15
		10–30	1.83 ± 0.55	24.54 ± 11.13	0.57 ± 0.04
		30–70	2.45 ± 0.71	28.75 ± 4.81	1.13 ± 0.15
		70–90	0.82 ± 0.47	15.28 ± 0.96	0.50 ± 0.03
		90–100	0.58 ± 0.49	5.40 ± 1.19	0.21 ± 0.03
Fort Totten Park	High	0–10	2.15 ± 0.27	22.73 ± 0.76	2.60 ± 0.22
		10–30	2.08 ± 0.24	25.92 ± 6.69	2.17 ± 0.47
		30–70	1.30 ± 0.39	30.19 ± 0.45	2.64 ± 0.35
		70–90	0.43 ± 0.11	13.76 ± 0.85	0.89 ± 0.25
		90–100	0.22 ± 0.04	6.67	0.34
Marine Park 1	High	0–10	1.70 ± 0.18	11.14 ± 2.38	0.43 ± 0.05
		10–30	2.77 ± 0.37	15.07 ± 2.57	0.53 ± 0.04
		30–70	1.79 ± 0.24	28.94 ± 2.24	1.05 ± 0.01
		70–90	0.72 ± 0.39	15.30 ± 1.63	0.54 ± 0.04
		90–100	0.09 ± 0.01	10.10 ± 1.37	0.43 ± 0.04
Marine Park 2	High	0–10	1.62 ± 0.09	26.08 ± 4.05	0.64 ± 0.02
		10–30	3.14 ± 0.31	28.83 ± 7.45	0.73 ± 0.06
		30–70	4.06 ± 0.94	27.07 ± 3.95	1.05 ± 0.07
		70–90	0.17 ± 0.03	10.06 ± 1.42	0.53 ± 0.04
		90–100	0.06 ± 0.01	8.39	0.37
Marine Park 3	High	0–10	4.64 ± 0.51	54.11 ± 13.11	0.88 ± 0.16
		10–30	8.54 ± 1.60	79.54 ± 20.74	1.55 ± 0.49
		30–70	2.05	15.64	0.65
		70–90	0.11	7.84	0.31
		90–100	0.06	7.13	0.27
Pelham Bay Park	High	0–10	3.34 ± 0.47	53.80 ± 9.03	0.87 ± 0.21
		10–30	4.80 ± 0.66	60.30 ± 10.07	0.92 ± 0.20

(Continues)

TABLE 5 (Continued)

Site	Afforestation success	Depth (cm)	Total C[a] (C m^{-2})	Microbial biomass C (g C m^{-2})	Basal respiration (g C m^{-2})
		30–70	0.85 ± 0.22	26.83	0.91
		70–90	0.38 ± 0.17	13.93	0.47
		90–100	0.18	12.44	0.49

Note: Means ± SE for one-time measurement of total C, microbial biomass C, and basal respiration from 10 MTNYC research sites sampled in 2018.
[a]Total soil C was obtained from Downey et al. (2021).

TABLE 6 Whole-core Pearson correlation results between all soil parameters across all study sites

Test variables	Microbial biomass C[a]	Basal respiration[a]	Exchangeable NO$_3^{-b}$	Exchangeable NH$_4^+$	Total inorganic N	Microbial biomass N	Net N mineralization[b]	Net nitrification	Denitrification potential	Total N
Microbial biomass C	1									
Respiration	0.36	1								
Exchangeable NO$_3^-$	0.53****	0.15	1							
Exchangeable NH$_4^+$	0.22	0.07	0.13	1						
Total inorganic N	0.55****	0.16	0.99****	0.28	1					
Microbial biomass N	0.59****	0.26	0.59****	0.21	0.61****	1				
Net N mineralization	−0.07	0.05	−0.37	−0.19	−0.38*	0.04	1			
Net nitrification	0.01	0.09	−0.29	−0.11	−0.3	0.11	0.94****	1		
Denitrification potential	−0.03	−0.15	0.09	0.21	0.12	0.08	−0.04	−0.01	1	
Total N	0.67****	0.06	0.65****	0.2	0.66****	0.56****	−0.01	0.1	0.26	1

Significant at *$p < 0.1$; **$p < 0.05$; $p < 0.01$; ****$p < 0.001$.
[a]Microbial biomass C and respiration ($p = 0.11$).
[b]Net N mineralization and NO$_3^-$ ($p = 0.10$).

in nitrate reductase activity and foliage δ^{15}N between planted species of *A. canadensis* and *P. serotina* at Clove Lakes, Alley Pond, and Marine Park 2. Those differences appeared to be driven by site history, suggesting that site physical, chemical, and biological characteristics are stronger determinants of N concentrations than the characteristics of the planted species. Intraspecies and interspecies dynamics can also have different functional impacts depending on the desired outcome (e.g., biomass vs. productivity; Jiang et al., 2008). In urban afforestation, it is possible that species diversity, distribution, and growth result in different ecosystem functions depending on afforestation goals (e.g., increased biodiversity). Oldfield et al. (2016) found that tree species composition had less effect on site performance than species-specific effects in urban afforestation, concluding that competition between individuals of the same species at the plot level may be an overlooked factor.

Coupled C–N cycling as driver of N dynamics

A major question that emerges from our results is if higher N availability at the high success sites is an inherent property of the soil parent materials at these sites, or if some other factor (e.g., texture, water holding capacity, base cation availability, or pH) fostered development of the plant community that then was able to sequester and accumulate N over time. Several lines of evidence suggest that the differences that we observed were not a function of the inherent N richness of soil parent materials. First, symptoms of N richness were much more marked in surface soils than at depth at high success sites. If parent materials were inherently N rich, effects would probably be obvious at depth. Second, if high N availability at high success sites were driven by inherently N rich parent
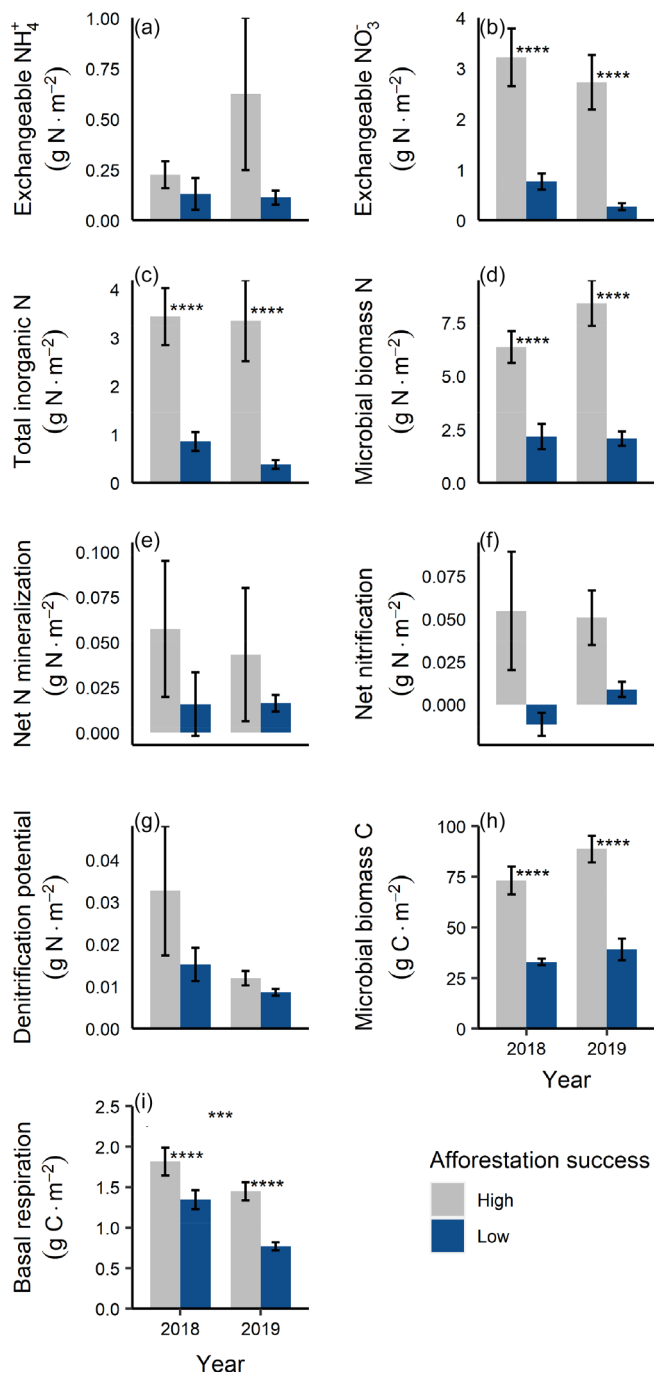
FIGURE 5 (a–i) Whole-core comparison of soil parameters between high and low afforestation success and 2018–2019 sampling years across sites (sites, $n = 10$; sites, $n = 10$). Error bars represent $\pm$ SE. Bars with asterisks are significantly different: *$p < 0.1$; **significant at $p < 0.05$; ***significant at $p < 0.01$; ****significant at $p < 0.001$

materials, we would expect both mineralization and nitrification (which is particularly sensitive to N enrichment), to be high, as in sites that have received fertilizer or high rates of atmospheric deposition (Aber et al., 1989; Venterea et al., 2004). We did not observe significant effects on mineralization, nitrification or denitrification

potential at the whole-core or 0–30 cm level (Figure 3; Table 4), all of which are tightly coupled to the C cycle as well as to N richness (Hart et al., 1994).

Finally, the strong correlations between N cycling processes and microbial biomass C and N content and soil respiration, also suggest a strong link to the C cycle, which is driven by the plant community (Table 6). Forest ecosystems with high above and belowground productivity have higher levels of microbial biomass and activity and tight coupling of C and N cycling and sequestration (Knicker, 2011). In this study, sites with higher microbial biomass C and N and soil respiration, had also developed a closed canopy and leaf litter layer (Tables 4 and 5). This coupling varies with plant litter quality (Scott & Binkley, 1997) and root turnover that have been shown to contribute significantly to the accumulation of detritus (dead organic material), which in turn influences decomposition and mineralization rates (Bowden et al., 1993).

The idea that a soil factor (e.g., texture, water holding capacity, base cation availability, or pH) underlies the development of differences in N cycling in high and low success afforestation sites is based on the premise that these factors establish a successful trajectory for the development of a healthy plant community that then goes on to absorb and retain nutrients from surrounding environments. In forest ecology, differences in tree composition develop along gradients of soil texture and lead to differences in N cycling due to adaptations to moisture stress associated with coarse-textured soils (Pastor et al., 1984, Pastor & Post, 1986). This points to the importance of plant–soil feedbacks, where soil properties (e.g., texture) determine water availability, primary production, and N uptake by plants, which facilitates accumulation of N in soil pools.

While these dynamics of site conditions, plant growth, and the development of N cycling are well studied in natural forest stands (Amundson & Jenny, 1997; Pastor et al., 1982), their importance in urban (or other) afforestation contexts has not been explored. Urban soils have diverse parent materials that can have complex influences on plant growth and the development of nutrient cycling processes over time (Bulbovas et al., 2020; Groffman et al., 2006). Many urban soils contain construction debris or other waste materials, dredging and extensive modification of natural land for urban land-use has created completely new parent materials, and soil formation processes are often highly altered in urban conditions resulting in the presence of novel soil horizons (Huot et al., 2017; NYC Soil Survey Staff, 2005). As described in the Methods section, these factors were evident in our low success sites, where soil physical (coarse debris) and chemical (high pH) conditions were likely to have restricted root access to nutrients, limiting plant establishment and development. Huot et al. (2017) found

functional differences between human-altered and human-transported (HAHT) soils in urban parks that contained earthy material or sediments (e.g., loamy fill or sandy dredged material), and those that were dominated by anthropogenic materials. Among our low success sites, the Alley Pond and Canarsie sites had a greater degree of human-transported material with construction debris, while the Clearview site has a greater contribution of naturally derived material.

Implications for urban afforestation

These findings underscore the importance of soil conditions and nutrient status in supporting microbial processes critical to ecosystem development in urban afforestation sites. Urban soil heterogeneity—the wide range of parent material—is a prime driver of variability in plant community composition and long-term afforestation success, yet site-specific soil factors are often overlooked in ecological restoration planning and implementation (Pavao-Zuckerman, 2008). In addition to inherent soil qualities, land-use history and past management are important sources of soil heterogeneity that need to be considered in restoration projects (Pouyat et al., 2010). Our results suggest that this consideration needs to include factors that influence plant establishment and growth and the development of plant–soil feedbacks. For example, if afforestation success is driven simply by N availability, then additions of fertilizer should improve results. However, our results suggest that a variety of soil factors, and plant–soil feedbacks also have to be considered and managed for afforestation success (Smith et al., 2021).

Future afforestation efforts need to develop site-specific strategies that assess soil properties and nutrient availability prior to planting and integrate this soil ecological knowledge into best management practices. Integrating site-specific soil ecological knowledge prior to planting in afforestation efforts would eliminate the additional costs and site disturbance associated with replanting that was required at our sites with low afforestation success. Our results over a two-year period show that rates of C and N cycling are closely linked to afforestation success (Figure 5). This suggests that more intensive restoration techniques including top-soil replacement in highly disturbed sites may improve afforestation outcomes (Heneghan et al., 2008). Several studies have found soil amendments (e.g., compost) can facilitate changes in soil moisture, decomposition, mineralization, and nutrient concentrations in urban afforestation projects (Oldfield et al., 2014, 2016, Pierre et al., 2016, Ward et al., 2021). However, it will be a challenge to apply amendments at the scale needed for afforestation projects that aim to have regional-scale effects on climate or C sequestration. The land needed for large-scale afforestation projects, such as MTNYC, will increasingly force managers to plant in sites with diverse and often suboptimal soil properties. Understanding site-specific soil properties will be essential for optimally managing sites to avoid negative environmental effects that can occur with extensive use of amendments.

Tree species diversity treatments did not have a strong effect on nutrient pools and processes in this study, which indicates that soil controls have a stronger impact on these pools and processes than species diversity, at least in the short term. It is also important to note that the comparison of diversity effects here, two versus six species, is limited. Long-term monitoring of afforested sites is needed to document how soil ecological processes and microbial communities respond to forest stand development and exposure to changing environmental conditions (e.g., climate, N deposition) in the long term. Soil conditions are highly variable in urban ecosystems, and further research on the role of detritus from planted species in creating plant–soil relationships that drive nutrient cycling is needed to inform urban afforestation efforts to grow sustainable and resilient urban forests.

CONCLUSION

Research in urban ecosystems has developed rapidly over the last 30 years and is notable for its ability to shed light on both basic and applied science questions (Groffman et al., 2017; McPhearson et al., 2016). The results here further our understanding of basic plant–soil–microbial interactions that have been elucidated in natural forests (Pastor et al., 1984) and provide information relevant to urban afforestation projects that aim to provide important ecosystem services across the globe. Ongoing research in urban ecology that focuses on this basic-applied science nexus is likely to continue to produce important, convergent research findings (Gropp, 2016).

Afforestation projects often have ambitious goals to provide ecosystem services over large scales, for example, climate modification, C sequestration. The land needed for large-scale afforestation projects, such as MTNYC, will increasingly force managers to plant in sites with suboptimal soil properties. Achieving afforestation goals without the use of expensive and/or potentially environmentally damaging amendments and disturbances will need to incorporate understanding of how inherent site conditions and soil physical and chemical characteristics influence the establishment of plant communities that can capture and sequester N, provide the organic input (e.g., detritus) that drives the development of microbial nutrient cycling processes, and generate plant–soil feedbacks over time. There

is a clear need for consideration of how factors inherent to the sites facilitate the development of these soil–plant synergies (Smith et al., 2020).

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data (Mejia, 2021) are available in the EDI Data Portal at: https://doi.org/10.6073/pasta/e809965ea4a597355e03f5b9cc293993.

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