RESEARCH ARTICLE

Variability in Urban Soils Influences the Health and Growth of Native Tree Seedlings

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ABSTRACT

Reforesting degraded urban landscapes is important due to the many benefits urban forests provide. Urban soils are highly variable, yet little is known about how this variability in urban soils influences tree seedling performance and survival. We conducted a greenhouse study to assess health, growth, and survival of four native tree species growing in native glacial till, coal ash, urban fill, and sandy clean fill soils collected from urban forest restoration sites in New York City. Using a multifactorial design, nine replicates of silver maple (*Acer saccharinum*), black birch (*Betula lenta*), red oak (*Quercus rubra*), and Canadian serviceberry (*Amelanchier canadensis*) were planted in four urban soil types and one greenhouse mix. We hypothesized that: 1) urban soil type would influence growth, health, and survivorship; 2) each tree species would respond differentially to each soil type; and 3) seedling stress and mortality would be higher for soils with more anthropogenic disturbance. After one growing season, we found that seedlings were less healthy and grew less in soils with a history of greater anthropogenic disturbance. Seedling mortality was low (< 3% overall) except for red oak seedlings in urban fill soil from one location. These results demonstrate that urban soil conditions can impact tree growth and health while supporting high survivorship. Species × soil type interaction for height growth and stress indicate that native tree species may not respond to urban soil conditions consistently. Consequently, matching tree species to soil type could help optimize establishment and growth of urban forest restoration projects.

Keywords: *Acer saccharinum*, *Amelanchier canadensis*, *Betula lenta*, *Quercus rubra*, reforestation

Restoration Recap

- Restoration of native tree species in urban areas may be heavily impacted by the variability inherent in urban soils. Understanding how different species respond to urban soil types is important for successful restoration outcomes.
- We examined the health and growth responses of seedlings of four native tree species to three urban soils compared to native soil. In one growing season we found tree seedlings grown in a wide range of urban soil types had high survival, however over time increased stress could lead to increased seedling mortality.
- Short term outcomes show that fast growing pioneer species, such as silver maple and black birch, grow taller in less disturbed soil types, while slower growing species show no differences in height growth among soil types. To maximize success in a restoration project it is important to choose the correct tree species palette for a given restoration site.

Chicago, Los Angeles, Philadelphia, Detroit, New York City and many other cities in the United States and around the world are engaging in large scale urban greening projects. These planting efforts are motivated by a wide range of documented economic, ecological, and social benefits of urban forests including energy savings, urban heat island mitigation, and restorative benefits for urban residents (Bolund and Hunhammar 1999, Dwyer et al. 1992, Mcpherson et al. 1997, Brack 2002, Davies et al. 2011, Nowak et al. 2013). In many cities, these efforts have moved beyond street and yard tree planting to reforestation and afforestation projects intended to establish urban forest stands comprised of native tree species in urban open space (Oldfield et al. 2013). In New York City (NYC), the MillionTreesNYC program, which started in 2007 has planted one million trees citywide within a 9-year timeframe, half of which were planted as part of reforestation efforts in natural areas. However, there has been little research on the factors influencing the long-term success of these efforts (Oldfield et al. 2013).

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A large body of knowledge exists for successfully managing forests for discrete goals such as timber and biomass in rural areas (Carmean 1978, Burns and Honkala 1990a, 1990b). Over the past two centuries, foresters have created prescriptions for maintaining rural forests, including which species to plant on various soil types and how far apart to plant seedlings to maximize growth and productivity (Marquis et al. 1990, Lindenmayer and Franklin 1997). Although urban foresters have some of the same goals—tree survival, quick establishment of closed canopy forest—more research is still needed on urban ecosystem management across multiple scales (Rowntree 1995) and how aspects of the urban environment could impact and feedback to influence plant survival and health (Oldfield et al. 2014).

Along with other environmental factors, soil condition and nutrient status play an important role in determining tree species composition, health, and growth in rural forests (Eid and Tuhus 2001, Bailey et al. 2004, Stephenson and Mantgem 2011). Like soils in rural forests, urban soils exhibit a high degree of spatial variability, yet they differ from rural soils in that they are generally composed of a matrix of remnant natural soils and human-made materials and are transformed directly or indirectly by human activity. Pouyat et al (2010) point out that urban soils vary depending on historical disturbance, management regime, and the effects of the urban environment. Effland and Pouyat (1997) suggest that urban landscapes contain a continuum of human altered soil bodies intermixed with islands of unaltered natural soil bodies. Anthropogenic impacts on soils include direct alterations such as mixing, importing and exporting material, and contamination from industrial or construction activities (Craul 1992), as well as more indirect consequences from urban pressures such as changes in the nutrient avaliability (Baxter et al. 2002). Studies indicate that urban soils can have the nutrient and physical characteristics that meet necessary requirements for plant growth, but can also have high concentrations of heavy metals and other pollutants and the impact of these contaminants on tree growth and health is uncertain (Pouyat et al. 2010). The influence of the variability among urban soils on plant growth is relatively unknown but important to consider in forest restoration projects. Pavao-Zuckerman (2008) calls for an integrated ecological restoration approach depending on site specific soils knowledge.

The New York City Department of Parks & Recreation (NYC Parks) owns and manages over 30,000 acres of parkland, including almost 5,500 acres of natural forest (NYC Parks 2015). However, most of NYC's present day forests have complex land use histories, involving many of the anthropogenic impacts described above, resulting in a range of forest conditions and opportunities for forest restoration and management. Many of the sites that are targeted for urban reforestation projects often have highly disturbed soils and are dominated by aggressive, exotic invasive plants. Initial establishment and survival of young planted trees in these variable environments is a critical first step in the success of a reforestation project. In cases where soils are not deemed suitable for plant growth, efforts to improve degraded soils in support of urban afforestation projects include removal of damaging debris and soil, adding clean soil (NYC Parks 2014) and/or soil amendments to better support infiltration, decomposition, mineralization, and nutrient retention (Oldfield et al. 2014) and plant growth. However, the relationships between urban soils, the range of amendments, and tree seedling health and survival have not been well characterized.

To ensure that these newly planted forests persist over time and provide the expected benefits to urban environments, we must gain a better understanding of how urban soils affect the growth, health, and survival of the newly planted native trees. This study was designed to investigate the interaction between urban soils representing a range of anthropogenic influence, and several native tree species that are commonly planted in forest restoration projects in NYC. In a controlled greenhouse study, we examined survival and performance of native tree seedlings planted in four NYC urban soil types based on land use history (described below). The soils were collected from the field in areas with existing reforestation projects or the potential for reforestation/afforestation projects, and represent a range of soil nutrient quality and anthropogenic disturbance.

In this greenhouse study, we hypothesized that: 1) Urban soil type would influence growth, health, and survivorship of native tree species currently used in NYC Parks' reforestation projects; 2) Seedlings of different species would exhibit different relative growth, health, and survivorship characteristics in and across soil types; and 3) More degraded and disturbed soil types would negatively influence tree survival and health.

Methods

Soil Collection and Analysis

To test the variability of urban soils on tree seedling survival and health we collected soils from 12 sites within NYC parks (Figure 1) with either existing or planned reforestation projects, and used one greenhouse soil as a control. Sites were selected to ensure a range of urban soil conditions, following common types of soils found in NYC Parks (NYC Parks 2014). Three sites were selected for soil collection within the following four general soil categories:

1. **Native Glacial Till:** This category is representative of the native forest soil in the northeastern United States. It is typically an acidic well-drained sandy loam or loam. Pockets of mature native forest exist on glacial till soil in New York City parks, and are dominated by native trees, shrubs, and understory. This soil type

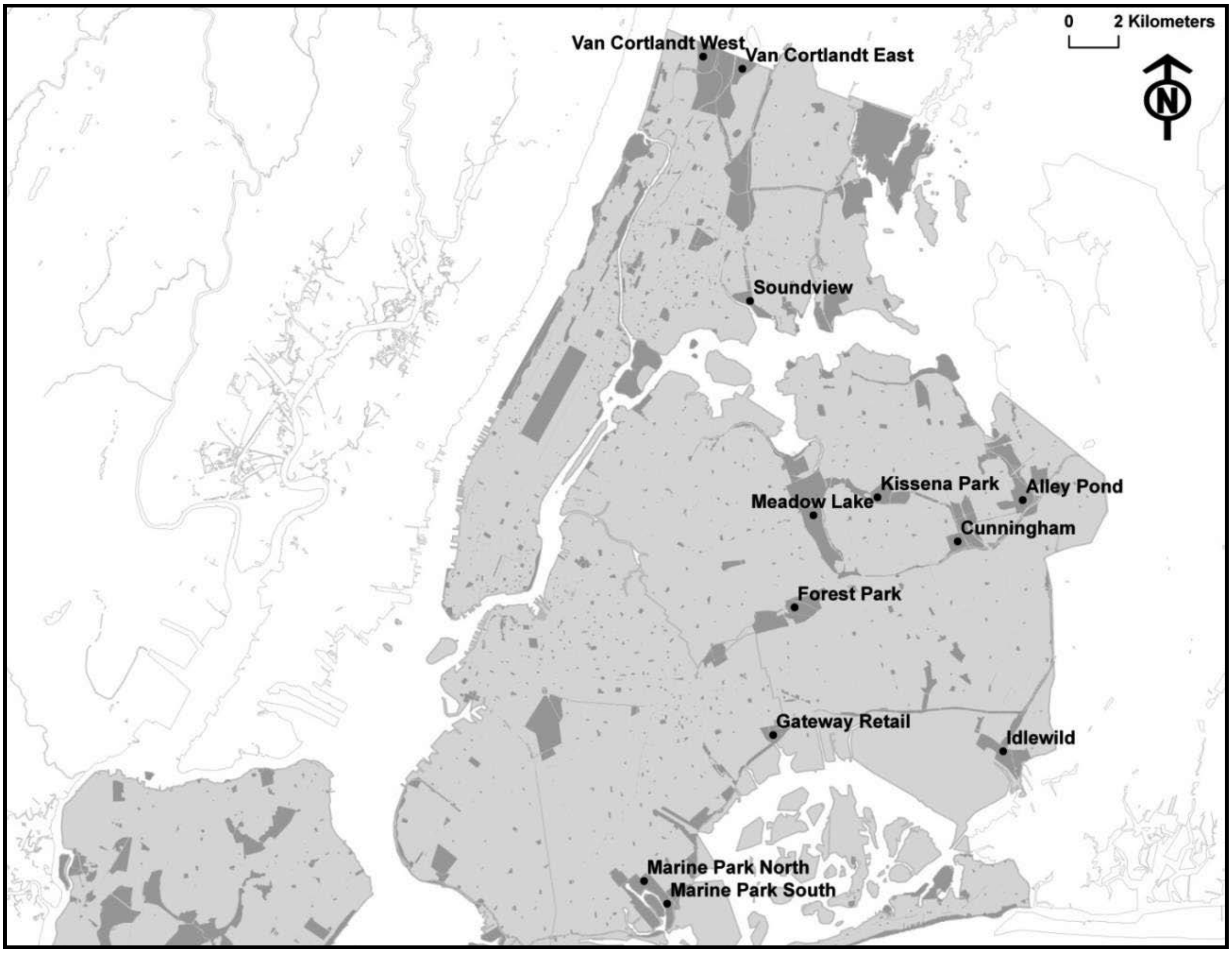

Figure 1. Location of soil collection sites in New York City, NY, USA. NYC is represented in light grey; NYC Parks Department properties are represented in dark grey. Soil collection sites are labeled.

is generally classified as being suitable for vegetative growth and commonly supports native species. Sites were selected based on park manager knowledge and field observations.

2. **Coal Ash:** During the 19th and 20th centuries, coal ash from heating homes was dumped into regulated and unregulated locations throughout New York City. Many of NYC Parks' current reforestation sites fall on old coal ash dumps that became city parkland. Historic maps were used to identify these sites (City of New York 1936).
3. **Clean Fill:** This soil originates from excavation projects, and is placed over degraded urban fill at afforestation sites. Clean fill is thought to be sandy soil without an invasive seed bank that is free of contamination and low in plant available nutrients. Observations from past restoration projects in NYC suggest increased tree mortality and stunted growth on this soil type. Sites were selected based on park manager knowledge and field observations.
4. **Urban Fill:** NYC Parks owns over 1,000 acres of filled land. The urban fill soil on these sites is usually native

Table 1. Methods for soil analysis used in this study.

Analysis	Method	Description	Citation
Texture	—	Hydrometer	Ashworth et al. 2001
pH	4Cla2a1	1:1 soil to DDI	Rebecca 2004
Soluble Salt	4F1a	1:2 soil to DDI	Rebecca 2004
%SOM	4H2	LOI @550 C	Rebecca 2004
CEC	5A1	NHOAC extract @pH 7	Rebecca 2004
Plant Available Elements	Modified Morgan	NHOAC extract @pH 4.8	Rebecca 2004

soil mixed with anthropogenic waste, such as construction and demolition debris, and/or household trash from regulated or unregulated dumping. Urban fill soil is known to be highly variable, often has a high pH, and is thought to be the most degraded of these soil categories. Sites were selected based on park manager knowledge and field observations.

5. **Greenhouse Soil Mixture:** This is a moderately acidic greenhouse soil mix containing top soil (50%), sterile peat (35%), and perlite (15%). The NYC Parks Greenbelt Native Plant Center uses this mix as the soil for native seed propagation. The tree seedlings used in this experiment were also propagated in this mixture.

To identify locations where these soil types may exist in the field, we interviewed park managers with first-hand knowledge on the soil history and site conditions across NYC parks, and referenced historic maps of parks when they existed. However, detailed historic maps of disturbance (historic dumping) were not always available. Visual assessment during field visits confirmed that each soil collection site fell into the intended category.

In June 2012, approximately 115 L of topsoil (from the top 25 cm) was collected from within a 200 m² area considered representative for each site. Vegetation was present at each site, indicating it was suitable for plant growth. At each site, the soil was placed in a large container, homogenized and not sterilized or given any further treatment after collection. One sample of homogenized soil per site was analyzed for physical and chemical properties. See Table 1 for a full list of soil analysis methods used in this study.

Tree Species

We selected four native tree species that are commonly used in reforestation projects within New York City: silver maple (*Acer saccharinum*), black birch (*Betula lenta*), red oak (*Quercus rubra*), and Canadian serviceberry (*Amalanchier canadensis*). Seedlings of each species were propagated and grown by the NYC Parks Greenbelt Native Plant Center. For this study, all individuals were grown from seed collected in NYC, with the exception of the Canadian serviceberry, which was collected in Cheesequake State Park, NJ. All seedlings were grown from seed in a greenhouse potting soil mix in containers for 2 years (2–0 planting stock). In June 2012 we randomly chose 117 seedlings of each species, transplanting nine replicates of each species into one-gallon pots containing each of the thirteen soils (n = 468). During the transplant, effort was made to remove the existing soil around each seedlings root by massaging the root ball and brushing off loose soil to allow for direct contact with the new field soil. Once transplanted, all seedlings were placed in a greenhouse and grown under natural light and watered to field capacity twice weekly. Air temperature in the greenhouse was generally kept close to ambient conditions, and averaged 7°C in the winter and 25°C in the summer months.

Growth and Stress Measurements

Within 48 hours of transplanting, the total height and stem caliper (taken just above the root collar) of each seedling was recorded. At the end of the growing season (October 2012), the number of surviving seedlings was recorded and the same measurements were made, as well as leaf discoloration and chlorophyll fluorescence.

Physiologically, one of the most pronounced effects of incipient stress is a reduction in net photosynthesis. This response is observed following a variety of stressors including dehydration, flooding, freezing, ozone, herbicides, competition, disease, insects, and deficiencies in ectomycorrhizal development and N fertilization (Carter and Knapp 2001). To assess whether any of the soils being tested were having an adverse impact on the health of the trees, we measured chlorophyll fluorescence using a portable fluorescence spectrometer (Handy PEA (Plant Efficiency Analyzer), Hansatech Instruments Ltd., England, United Kingdom). Chlorophyll fluorescence measurements taken on dark-adapted leaves can be used to estimate overall photosynthetic capacity and photosynthetic efficiency. We used a 30-minute dark adaptation time on three leaves from each seedling, after which samples were illuminated using a 3000 μmol photons m^{-2} s^{-1} LED to fully reduce electron acceptors in photosystem II (Mohammed et al., 1995). Leaves were fully expanded and selected from three different sides of the seedling canopy whenever possible. Leaves were measured while still attached to the tree. We used the Handy PEA software to calculate Performance Index (PI) and Fv/Fm values following the O–J–I–P test described in Strasser et al. (1995). We then incorporated the average PI and Fv/Fm value from each seedling into the final health calculations described below.

Leaf discoloration is a symptom of abiotic stress such as winter desiccation, drought, or nutrient deficiencies and imbalances (Zoettl et al. 1989, McQuattie and Schier 2000, Randolph 2013). In this study, leaf discoloration was assessed by making an ocular estimate by the same person of the percent total leaf tissue with color change using the following classes: Class 1 = 0% discoloration; Class 2 = 1–25% discoloration; Class 3 = 26–50% discoloration; Class 4 = 51–75% discoloration; and Class 5 = 76–100% discoloration.

Statistical Analysis

To compare seedling health across all soils and species, we created a single tree stress rating variable using z-scores. This method allows for a comprehensive and detailed assessment of seedling condition (Pontius and Hallett 2014). All measured physiological variables (diameter growth, height growth, discoloration, PI, and Fv/Fm) were standardized using the entire range of observed values to

Table 2. Soil characteristics from 12 field soils collected at different sites in New York City, NY and one Greenhouse mix. Each field soil was categorized as part of one urban soil type (coal ash, urban fill, clean fill, native till). Mean height growth and seedling stress are averaged for nine replicates of four native tree seedlings grown in each of the soil sites. Negative seedling stress values indicate healthier trees. Soil nutrients and heavy metals are shown in parts per million (mg kg^{-1}). Significant differences (Tukey's HSD) between soil types were determined by ANOVA and are marked with lowercase letters, non-significant differences between means are not marked. *Mean value for soil type.

Soil Type* Soil Site	USDA Soil Series (Type)	pH	SOM	CEC	Sand	Mg	Al	Pb	As	Cr	Zn	P	K	Ca	Mn	Height Growth	Seedling Stress
	(%)	cmol kg^{-1}	(%)	(ppm)												cm	z-score
Coal Ash*		6.6	11.7	11.6	69.0	125.3	22.8	303.1	6.6	77.5	307.5	7.6	48.4	1837.4	5.2	6.76^{a}	–0.11^{bc}
Meadow Lake	Mosholu (MuA)	7.1	6.1	7.97	61.0	158.0	15.8	634.0	11.3	83	610.9	4.4	75.7	1052.3	5.8	5.25	0.03
Van Cortlandt East	Mosholu (MuA)	7.3	18.4	21.46	73.0	125.4	10.1	182.0	5.3	120	181.9	13.3	48.9	3817.3	8.2	5.58	0.21
Van Cortlandt West	Mosholu (MuA)	5.3	10.6	5.24	73.0	92.4	42.5	93.4	3.1	30	129.6	5.1	20.7	642.5	1.6	9.47	–0.57
Urban Fill*		**6.93**	**9.73**	**6.76**	**73.7**	**264.0**	**15.2**	**41.9**	**3.93**	**37.67**	**66.7**	**6.1**	**56.7**	**642.7**	**1.1**	**4.12^{b}**	**0.28^{c}**
Idlewild	Secaucus (SeA)	6.1	15.3	10.52	86.0	603.2	3.8	34.4	1.0	19	55.6	6.9	99.8	808.1	0.9	4.41	0.49
Marine Park South	Gravessand (GOB)	6.9	6.6	5.54	67.0	75.1	13.2	35.9	5.4	34	72.1	5.4	37.5	723.1	1.8	5.06	0.32
Soundview	LaGuardia (LaBs)	7.8	7.3	4.22	68.0	113.6	28.7	55.5	5.4	60	72.2	6.0	33.0	396.9	0.8	2.91	0.03
Clean Fill*		**7.6**	**3.5**	**4.8**	**79.0**	**127.1**	**45.9**	**163.4**	**5.3**	**73.0**	**441.9**	**3.5**	**13.9**	**493.0**	**2.3**	**3.29^{b}**	**0.37^{c}**
Marine Park North	Breeze (BzA)	7.8	1.8	4.09	71.0	65.7	103.3	236.8	5.5	124	138.2	4.0	22.5	456.8	4.1	1.63	0.81
Gateway Retail	Big Apple (BiA)	7.1	7.8	6.89	71.0	254.7	27.0	239.6	9.4	44	1141.1	2.7	13.9	707.0	1.3	5.97	–0.11
Kissena Park	Big Apple (BiAn)	8.0	0.8	3.3	95.0	60.8	7.5	13.9	0.9	51	46.4	3.9	5.4	315.4	1.5	2.29	0.41
Native Till*		**6.2**	**8.9**	**13.8**	**70.7**	**222.4**	**20.8**	**107.1**	**18.2**	**39.3**	**150.0**	**6.4**	**85.8**	**2106.3**	**54.3**	**7.27^{a}**	**–0.40^{a}**
Alley Pond	Charlton (ChB)	6.3	6.7	8.6	71.0	287.0	5.9	62.6	13.0	44	98.1	9.5	93.1	954.1	0.8	6.14	–0.19
Cunnigham	Charlton (ChAs)	6.8	10.2	21.32	68.0	98.7	10.6	231.5	35.2	40	248.9	8.7	53.3	3832.6	4.9	8.03	–0.51
Forest Park	Charlton (ChBs)	5.5	9.8	11.6	73.0	281.5	45.8	27.2	6.3	34	102.9	1.2	111.0	1532.3	157.3	7.67	–0.51
Greenhouse Soil	**NA**	**6.9**	**13.2**	**5.66**	**87.0**	**59.0**	**6.0**	**81.0**	**2.2**	**19**	**120.4**	**5.0**	**28.0**	**780.0**	**1.3**	**5.66^{ab}**	**–0.25^{ab}**

create z-scores (Green 1979). Standardized scores for each variable are then inverted if necessary so that they all scale from healthy (low z-score) to stressed (high z-score), and then averaged to capture overall condition in one continuous stress index variable for each seedling. This final stress variable represents a synthesis value of all measured physiological variables. Seedling height growth was calculated by taking the last height measurement and subtracting the initial height measurement.

Our seedlings were planted in a multifactorial design with tree species and soil type as the main effects. There were four tree species and five soil types included in the analyses. To analyze the effects of soil, species, and soil × species interactions on seedling height growth and stress z-score, we use generalized linear mixed models with replicate included as a random effect. Tukey-Kramer groupings for least squares means were used to determine significance among individual soil and species combinations. One-way ANOVAs were conducted to compare the effect of soil type on tree growth and seedling stress by species. Linear regressions were used to test for relationships between individual soil characteristics and seedling height growth or seedling stress. Differences with $p < 0.05$ were accepted as statistically significant. All data were analyzed in JMP 11.0.0 (SAS Institute Inc. Cary, NC, USA, 2011).

Results

Soil Characteristics

After the soils were collected, we compared each site location to the USDA Natural Resources Conservation Service soil survey maps published after the completion of our study (Table 2; USDA 2014). All soils were characterized either as Sandy Loam or Loamy Sand. We found that soil series were consistent in all native till and coal ash soils, and while the urban fill and clean fill soils contained several soil series, they were all described as containing human transported materials. All coal ash soils were classified as Mosholu sandy loam (MuA, *Sandy, mixed, mesic Aquic Udorthents*), containing a mixture of coal combustion bottom ash and unburned coal on anthropogenic landscapes. The native till soils were all classified within the Charlton series (ChB, ChAs, ChBs, *loamy, mixed, active, mesic Typic Dystrudepts*), described as well drained loamy soils. The three urban fill soils were classified as different series: Secaucus artificial fine sandy loam (SeA, *Loamy-skeletal, mixed, superactive, nonacid, mesic Oxyaquic Udorthents*); Gravessand and Oldmill coarse sand (GOB, *Sandy-skeletal, mixed, hyperthermic Typic Udorthents*); and LaGuardia artificial coarse sandy loam (LaBs, *Loamy-skeletal, mixed, superactive, nonacid, mesic Typic Udorthents*). All three soil series were described as containing human transported material including household garbage, construction debris, and other discarded materials and occurring on anthropogenic landscapes. Clean fill soils were classified as two series: Big Apple series (BiA, BiAn, *Mixed, mesic Typic Udipsamments*), described as forming in a thick mantle of anthropotransported soil material from dredging activities in coastal waterways and rivers; and Breeze series (BzA, *Mixed, mesic Typic Udipsamments*), also described as forming in a thick mantle of sandy anthropotransported soil materials intermingled with demolished construction debris. In the case of soil series BzA at Marine Park North, the USDA soil survey field work could have been conducted prior to the clean fill being deposited at the site during spring 2012. These USDA soil series classifications confirm that the categories described by park managers are relatively consistent for native till and coal ash soils, and become more variable for urban fill and clean fill soil types.

Results from laboratory testing of each composite soil sample show a large range in soil properties across the 12 urban soils, but soil categories were not significantly different from each other in nutrient and elemental analysis. However, we are limited by a small sample number for soil analysis (n = 13). Soil pH ranged from 5.3 to 8.0 (Table 2), with clean fill soil being most alkaline on average (mean pH = 7.6) and native till soils being the most acidic (mean pH = 6.2). However, variation in soil pH within soil type was sometimes as great as between soil types. For example, there was as much variation in physical and chemical properties of coal ash soils as there was between coal ash and any other soil type. Disturbed urban soils can be more alkaline than native soils due to the weathering of concrete in construction debris, but this is highly site specific depending on land use history (Pavao-Zuckerman 2008). Soil organic matter (SOM) did not differ significantly between the soil types. On average, SOM was the highest in the greenhouse mix (13.2%), followed by coal ash soils (11.7%) and lowest in clean fill soils (3.5%), with native till and urban fill intermediate (Table 2). Plant available micronutrient and heavy metal concentrations were not significantly different between soil types. Heavy metal toxicity in the soil can have direct impacts on leaf discoloration, photosynthesis, and plant growth, however the bioavailability of heavy metals is a complex reaction between CEC, pH, plant root tissue, and species specific reactions (Reichman 2002) vary making it hard to draw direct links between our soil results and tree seedling growth and stress. However, we did find several of our urban soil sites to have higher levels of lead (Meadow Lake–Coal Ash) and zinc (Gateway Retail–Clean Fill) (Table 2).

Seedling Survival and Growth

Overall seedling survival after one growing season was high, with 100% survival for all tree seedlings grown in native till, greenhouse mix, and coal ash soils, 97% survival in clean fill, and 90% survival in urban fill. Across all soil types, silver maple had the highest survival rate at 100%,

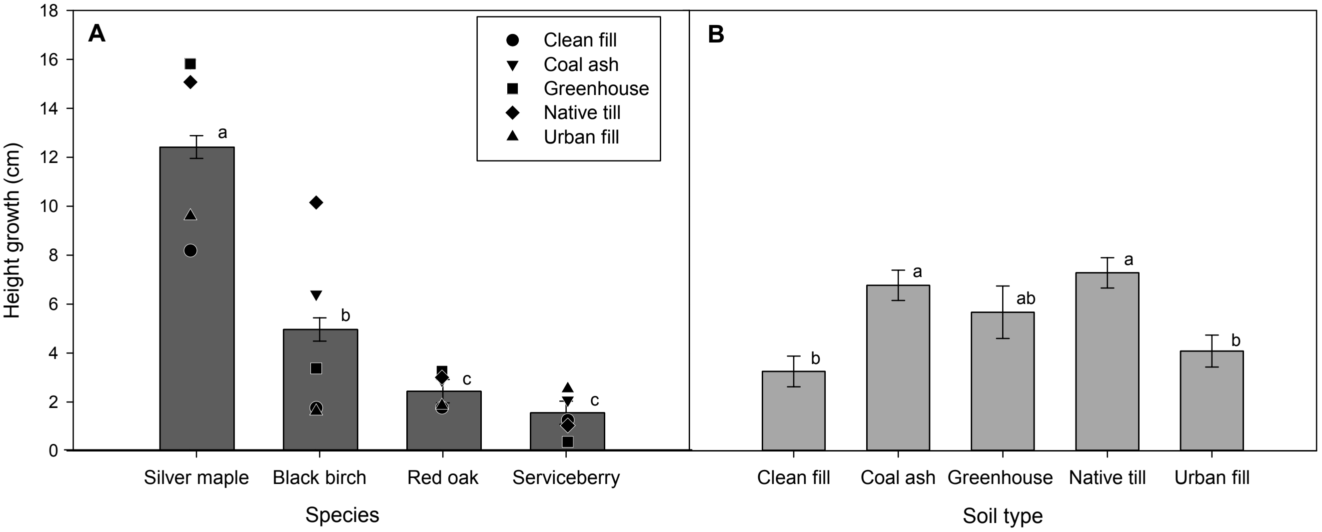

Figure 2. Mean height growth (±SE) after one growing season of four tree species grown in four different urban soil types and a greenhouse soil mix. Panel A shows significant differences in mean height between species (df = 3, F = 110.09, $p < 0.0001$). Panel B shows significant differences in tree seedling growth between the different urban soil types (df = 4, F = 7.3, $p < 0.0001$). Within each figure, values not connected by the same letter are significantly different. In Figure 2A, symbols represent mean height growth of each soil type within a species. Silver maple grew the tallest among all species, and had the greatest growth in the greenhouse mix, native till and coal ash soil and significantly less growth in urban fill and clean fill. Black birch grew the tallest in native till, coal ash and the greenhouse mix and significantly worse in urban fill and coal ash. Red Oak and Serviceberry had the least amount of growth and had no significant differences in growth between soil type (but did among soil collection location).

followed by 98% of serviceberry, 96% survival of black birch and 95% survival of red oak. However, some specific species × soil site combinations had lower survival rates in clean fill and urban fill soils. Idlewild urban fill had the poorest survival rates overall, with 44% of the red oak, 66% of the black birch and 88% of the serviceberry surviving. Serviceberry survival in Marine Park South urban fill was 88%. Among the clean fill soils, Marine Park North soil had 88% survival of red oak, and Gateway Retail soil had 77% survival of black birch.

Overall, tree seedling height growth varied significantly between species and across soil types (Figure 2A, Table 3), with trees growing significantly taller in native till, greenhouse, and coal ash soils than clean fill and urban fill soils (Figure 2B). Silver maple seedlings had significantly more height growth than all other species, with a mean increase of 12.42 cm. Black birch had significantly greater height growth than red oak and serviceberry with a mean increase of 4.96 cm, while red oak averaged 2.44 cm height growth and serviceberry averaged 1.57 cm (Figure 2A). It is not surprising that silver maple and black birch had greater height growth overall, as these are faster growing pioneer species. We also found a significant soil type × species interaction effect on seedling height growth (Figure 2A, Table 3,) reflecting that species did not show the same patterns of growth across the different soil types (Figure 2A). For example, silver maple and black birch showed significantly greater height growth when grown in native till soils compared to urban fill and clean fill soils, however serviceberry and red oak showed no significant height differences across all soil types. It may take longer for this soil type × species interaction to impact height growth in slower growing species.

By regressing individual soil properties against average seedling height growth, we found that lower pH was significantly correlated to greater height growth ($R^2 = -0.59$, $p = 0.002$). We did not find any other significant relationships between soil characteristics and seedling performance, but were limited by a low number of soil measurements.

Plant Stress Z-score

Using our standardized metric for tree seedling stress for each tree, we found that across all species, seedling stress was significantly different between soil types. Seedlings were found to be under greater stress in urban fill and clean fill soils compared to native till, coal ash, and greenhouse mix soils (Figure 3). We also found a significant soil type × species interaction effect for plant stress (Table 3). Black birch showed the greatest range in seedling stress across soils, while serviceberry had the smallest range of stress scores. All species had significantly higher stress in clean fill compared to native till soils, and all species except for serviceberry were significantly more stressed in urban fill compared to native till soils. Red oak and serviceberry are slower growing species, which did not show significant differences in height growth across the soil types, but they did show significant differences in seedling stress across the soil types. Seedlings grown in the greenhouse mix were

Table 3. Generalized linear mixed model results for height growth (cm) and seedling stress (z-score) for four species of trees grown different urban soil types.

	Height Growth		Seedling Stress (z-score)	
	F	*p*-value	F	*p*-value
Soil Type	16.24	< 0.001	39.2992	< 0.0001
Species	127.3368	< 0.001	0.182	0.9086
Species*Soil Type	5.7836	< 0.001	2.3151	0.0072

*Degrees of freedom for the model include (Soil Type = 4, Species = 3, Species * Soil Type = 12).

generally less stressed than those in urban fill or clean fill soils, but not always less stressed than seedlings grown in native till and coal ash soils (Figure 3).

Because we had only one bulk homogenized sample to characterize each soil, we were limited in our ability to detect soil mechanisms driving the patterns in seedling health and growth. Soils with the lowest pH values generally supported high seedling survival and growth. By regressing individual soil properties against average seedling health and height growth, we also found that low soil pH was significantly correlated with increased height growth ($p = 0.002$, $R^2 = 0.58$), but not significantly correlated with plant stress.

Discussion

While studies have shown that heterogeneity is common in urban soils (Pouyat and McDonnell 1991, Effland and Pouyat 1997, Hope et al. 2005), this variability has not been studied in the context of the large scale reforestation and afforestation plantings being implemented within urban landscapes. Our results show that variation in seedling survival, growth, and overall stress could be linked to the disturbance and heterogeneity commonly found in urban soils. We found that native tree growth and health were negatively impacted by more disturbed soil types. However, after one growing season in a greenhouse environment, seedling mortality was low and seedling growth and health in some urban soils (native till and coal ash) was greater than in the greenhouse mix soil. Overall seedling mortality across all urban soil types was 3%, which is slightly higher than a recent field study showing only 1% tree mortality in one reforestation project after one growing season (Oldfield et al. 2015). However, the trees planted in that study were much larger than our two-year-old seedlings, which may impact tree survival. While urban soils are often viewed as having low fertility (Craul 1999), our results suggest that even highly altered urban soils (clean fill and urban fill) may still provide an opportunity for tree seedling survival and growth. However, variability in urban soil types can significantly influence seedling performance and stress outcomes.

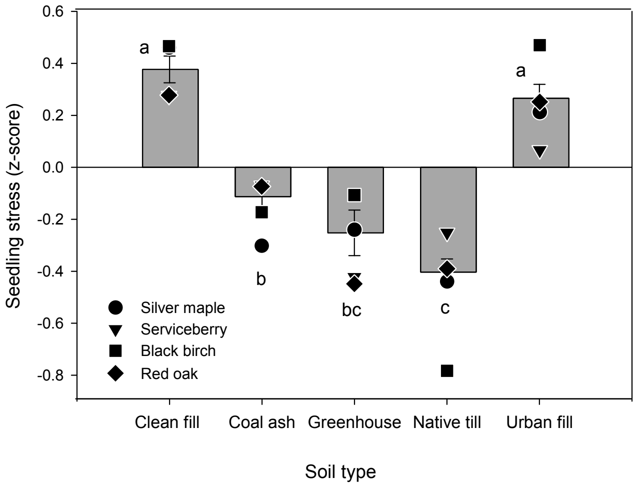

Figure 3. Mean plant stress z-score (± SE) after one growing season of four tree species grown in four different urban soil types and one greenhouse soil mix. Soil types not connected by the same letter have significantly different average seedling stress (df = 4, F = 38.6, $p < 0.0001$). Average seedling stress for each species in each soil type is represented by a different symbol.

Most urban landscapes have been altered to some degree, and characterizing the conditions at the site, including specific soil properties, should be considered prior to starting a large forest restoration project. Using our park managers' suggestions, historical knowledge, and field observations of the soil conditions, we were relatively successful in categorizing broad manager soil types into USDA mapped soil series. Despite the fact that the soil series were similar within each urban soil type, differences in chemical and physical characteristics reveal that variation within soil categories can be as great as variation between soil types. For example, clean fill soils are assumed to be sandy, and while Kissena Park clean fill did have the sandiest soil (95% sand), the other clean fill soils had sand content similar to soils in other categories. However, variation in seedling growth and stress was just as great within greenhouse mix soil replicates as it was within other soil types.

Assumptions about urban soil chemistry were also challenged; native till soils were generally acidic, but not always more acidic than other urban soils (e.g., coal ash), suggesting that soil properties can be unique to each urban site and visual characterizations of the soil and historical knowledge may now always be correct in estimating tree seedling outcomes. It is difficult to draw conclusions about the effects of specific soil properties on seedling performance, given our low sample size used to characterize each soil. More comprehensive characterization of diffuse and incorporated debris and their impacts on soil quality are needed to understand exactly why these urban fill and clean fill soils may have a negative impact on native tree seedling survival, growth and stress.

Field observations can help us interpret both soil characteristics and seedling performance results. For example, during soil collection at Idlewild Park (an urban fill site) we observed high levels of household garbage, discarded tires, broken glass, and other waste incorporated into the soil. Trees planted in this soil experienced the highest mortality and the surviving trees showed high seedling stress with patterns of mortality mirroring the stress of each species. Red oak had the highest mortality and stress, followed by black birch, serviceberry, and silver maple, indicating high stress may lead to mortality, and that properties within that soil are impacting seedling outcomes. At that site, a visual estimate of the altered soil could have been a good predictor of tree planting outcomes.

In restoration projects, success is measured in a variety of ways (SER 2004), including establishment of native vegetation structure, and continued growth and survival of native species (Ruiz-Jaen and Aide 2005). In NYC, height growth of planted trees is used as an indicator of success in both establishment of a native forest and in reducing the threat of fast-growing, shade intolerant exotic invasive plant species. Variation in height across the species in our study reflects expected growth habits for these native trees, with silver maple and black birch gaining the most height in one season, followed by red oak and serviceberry. Silver maple and black birch are fast growing pioneer species and known to be easily established from seed or transplants (Geyer et al. 2010). In addition to having the greatest amount of height growth, silver maple was the only tree species with 100% survival across all soil types. The widespread success of silver maple suggests that it could be successful even when planted in sites with evidence of anthropogenic inputs and dumped debris incorporated into the soil. Planting fast-growing species first on reforestation sites with clean fill or urban fill could increase shade and provide an opportunity for slower growing later successional species, such as red oak, which could be planted later or allowed to establish naturally. However, the significant interaction (species × soil type) for stress suggests that other indicators of plant stress (e.g., leaf discoloration) could be important to consider in addition to height when monitoring individual seedling success at a restoration site. Extended research and monitoring throughout a number of growing seasons is needed to determine whether differences in height growth lead to improved forest structure and reduction of invasive species, or if trade-offs exist with belowground growth (Searle et al. 2012) that would impact the long term success of a forest restoration project.

Although this study was carried out in a greenhouse over the course of a single growing season, the results indicate the ability of each species to establish in soils from reforestation sites. The predictive nature of short-term greenhouse studies on the future success of field plantings is highlighted by work in the phytoremediation field where a technique called phyto-recurrent selection is used to identify specific clones that are best suited for planting in contaminated sites (Zalesny et al. 2007). When restoration projects are installed in areas with soils that have a history of intense anthropogenic disturbance, there may be costly consequences to ignoring species-soil interactions. In fact, a modified phyto-recurrent selection technique may be a useful tool for screening species to be planted on sites like these. However, the greenhouse setting allows for regular watering, and managers must consider that trees planted in reforestation projects in the field will not receive the same level of maintenance and will face competition for light and nutrients. The native growth conditions and environmental tolerances of each species in this study would likely cause differences in their performance in an urban reforestation site compared to the greenhouse. For example, silver maple generally grows on moist alluvial soils, and so it may have benefitted from the regular watering in our greenhouse experiment. On dry upland sites, silver maple generally cannot compete with other tree species (Burns and Honkala 1990b). Black birch is the most shade intolerant species in our study, and it may not be suitable for reforestation projects near existing tree canopy where there is not adequate light (Burns and Honkala 1990b).

While research on urban soil properties and processes has been growing (White and McDonnell 1988, Pouyat and McDonnell 1991, Goldman et al. 1995, Jim 1998, Zhu and Carreiro 1999 and 2004, Baxter et al. 2002, Groffman et al. 2006, Oldfield et al., 2014), little attention has been paid to the physiological response and performance of plants on urban soils (Cadenasso et al. 2007; but see Falxa-Raymond et al. 2014, Oldfield et al. 2015). Our study directly connects variation in urban soils with native tree seedling growth and stress. Our species × soil type interaction for height and stress indicate species may not all respond to the urban soil conditions the same way, and careful matching of species to soil would be needed if a goal of the forest restoration project is a quickly established forest canopy. Over time, we expect the observed relationships between urban soil and tree seedling growth to continue, and we hypothesize that the differences in stress after the first growing season will lead to increasing differences in height growth across soil types during subsequent years. More long-term experiments are needed to further explore these effects, as some effects of soil nutrients on plant stress may take multiple growing seasons to appear. More research is also needed to describe the mechanisms driving the differences in native seedling performance across soil types and to see if the same patterns persist over time in the field. A greater understanding of urban soils and their ability to support native forests will help natural resource managers initiate more successful restoration projects and make informed management decisions to help overcome challenges faced in urban afforestation and restoration.

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References

Ashworth, J., D. Keyes, R. Kirk and R. Lessard. 2001. Standard procedure in the hydrometer method for particle size analysis. *Communications in Soil Science and Plant Analysis* 32:633–642.

Bailey, S.W., S.B. Horsley, R.P. Long and R.A. Hallett. 2004. Influence of edaphic factors on sugar maple nutrition and health on the Allegheny Plateau. *Soil Science Society of America Journal* 68:243–252.

Baxter, J.W., S.T.A. Pickett, J. Dighton and M.M. Carreiro. 2002. Nitrogen and phosphorus availability in oak forest stands exposed to contrasting anthropogenic impacts. *Soil Biology & Biochemistry* 34:623–633.

Bolund, P. and S. Hunhammar. 1999. Ecosystem services in urban areas. *Ecological Economics* 29:293–301.

Brack, C.L. 2002. Pollution mitigation and carbon sequestration by an urban forest. *Environmental Pollution* 116 Supplement: S195–200.

Burns, R.M. and B.H. Honkala. 1990a. Silvics of North America: Conifers. Page 1383 in: *Silvics of North America Agriculture Handbook* 654. Forest Service, United States Department of Agriculture, Washington, DC.

Burns, R.M. and B.H. Honkala. 1990b. Silvics of North America: Hardwoods. Page 877 in *Silvics of North America Agriculture Handbook* 654. Forest Service, United Stated Department of Agriculture, Washington, DC.

Carmean, W.H. 1978. Site index curves for northern hardwoods in northern Wisconsin and Upper Michigan. U.S. Department of Agriculture Forest Service Research Paper. NC-160, 16 p. North Central Forest Experimental Station, St. Paul, Minnesota.

Carter, G. and A. Knapp. 2001. Leaf optical properties in higher plants: Linking spectral characteristics to stress and chlorophyll concentration. *American Journal of Botany* 88:677–684.

Cadenasso, M.L., S.T.A. Pickett, M.J. McDonnell and R.V. Pouyat. 2007. Forest vegetation along an urban–rural gradient in the New York City metropolitan area: Patterns and relationships to ecosystem processes. *Transactions of the Linnean Society* NY 10:79–99.

City of New York, Department of Parks Topographical Division. 1936. Topographical Map of Van Courtlandt Park.

Craul, P.J. 1992. *Urban Soil in Landscape Design*. New York, NY: John Wiley & Sons.

Davies, Z.G, J.L. Edmondson, A. Heinemeyer, J.R. Leake and K.J. Gaston. 2011. Mapping an urban ecosystem service: quantifying above-ground carbon storage at a city-wide scale. *Journal of Applied Ecology* 48:1125–1134.

Dwyer, J., E.G. Mcpherson, H. Schroeder and R. Rowntree. 1992. Assessing the benefits and costs of the urban forest. *Journal of Arboriculture* 18:227–234.

Effland, W. and R.V. Pouyat. 1997. The genesis, classification, and mapping of soils in urban areas. *Urban Ecosystems* 1:217–228.

Eid, T. and E. Tuhus. 2001. Models for individual tree mortality in Norway. *Forest Ecology and Managment* 154:69–84.

Falxa-Raymond, N., M.I. Palmer, T. McPhearson and K.L. Griffin. 2014. Foliar nitrogen characteristics of four tree species planted in New York City reforestation sites. *Urban Ecosystems* 17:807–824.

Geyer, W.A., J. Dickerson, J.M. Row and L. Acer. 2010. Plant Fact Sheet for Silver Maple (*Acer saccharinum* L.). USDA NRCS Plant Materials Center, Manhattan, KS.

Green, R. 1979. *Sampling Design and Statistical Methods for Environmental Biologists*. New York, NY: Wiley Press.

Goldman, M.B., P.M. Groffman, R.V. Pouyat, M.J. Mcdonnell and S.T.A. Pickett. 1995. CH_4 uptake and N availability in forest soils along an urban to rural gradient. *Soil Biology and Biochemistry* 27:281–286.

Groffman, P.M., R.V. Pouyat, M.L. Cadenasso, W.C. Zipperer, K. Szlavecz, I.D. Yesilonis, L.E. Band and G.S. Brush. 2006. Land use context and natural soil controls on plant community composition and soil nitrogen and carbon dynamics in urban and rural forests. *Forestry Ecology and Management* 236:177–192.

Hope, D., W. Zhu, C. Gries, J. Oleson, J. Kaye, N. Grimm and L. Baker. 2005. Spatial variation in soil inorganic nitrogen across an arid urban ecosystem. *Urban Ecosystems* 8:251–273.

Jim, C.Y. 1998. Soil characteristics and management in an urban park in Hong Kong. *Environmental Management* 22:683–695.

Lindenmayer, D.B. and J.F. Franklin. 1997. Managing Stand Structure as Part of Ecologically Sustainable Forest Management in Australian Mountain Ash Forests. *Conservation Biology* 11:1053–1068.

Marquis, D.A., R.L. Ernst and S. Stout. 1990. Prescribing Silviculture Treatments in Hardwood Stands of the Alleghenies. USDA Forest Service General Technical Report NE-96. Northeastern Forest Experiment Station, Radnor, Pennsylvania, USA.

McPherson, E.G., D. Nowak, G. Heilser, S. Grimmond, C. Souch, R. Grant and R. Rowntree. 1997. Quantifying urban forest structure, function, and value: The Chicago Urban Forest Climate Project. *Urban Ecosystems* 1:49–61.

McQuattie, C.J. and G.A. Schier. 2000. Response of sugar maple (*Acer saccharum*) seedlings to manganese. *Canadian Journal of Forest Restoration* 30:456–467.

Mohammed, G.H., W.D. Binder and S.L. Gillies. 1995. Chlorophyll fluorescence: A review of its practical forestry applications and instrumentation. *Scandavian Journal of Forest Restoration* 10:383–410.

New York City Department of Parks and Recreation. 2014. Guidelines for Urban Reforestation. Available at www.nycgovparks.org/pagefiles/84/guidelines-to-urban-forest-restoration.pdf (Accessed 12 January 2015).

New York City Department of Parks and Recreation. 2015. About NYC Parks. Available at: www.nycgovparks.org/about (Accessed 5 February 2015).

Nowak, D., R.E. Hoehn, A.R. Bodine, D.E. Crane, J.F. Dwyer, V. Bonnewell and G. Watson. 2013. Urban Trees and Forests of the Chicago Region. Resource Bulletin. NRS-84. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station.

Oldfield, E.E., R. Warren, A.J. Felson and M.A. Bradford. 2013. FORUM: Challenges and future directions in urban afforestation. *Journal of Applied Ecology* 50:1169–1177.

Oldfield, E.E., A.J. Felson, S.Wood, R. Hallett, M.S. Strickland and M. Bradford. 2014. Positive effects of afforestation efforts on the health of urban soils. *Forest Ecology and Managment* 313:266–273.

Oldfield, E.E., A.J. Felson, D.S.N. Auyeung, T.W. Crowther, N.F. Sonti, Y. Harada, D.S. Maynard, N.W. Sokol, M.S. Ashton, R.J. Warren, R.A. Hallett and M.A. Bradford. 2015. Growing the urban forest: Tree performance in response to biotic and abiotic land management. *Restoration Ecology* doi: 10.1111/rec.12230.

Pavao-Zuckerman, M.A. 2008. The Nature of Urban Soils and Their Role in Ecological Restoration in Cities. *Restoration Ecology* 16: 642–649.

Pontius, J. and R. Hallett. 2014. Comprehensive methods for earlier detection and monitoring of forest decline. *Forest Science* 60:1156–1163.

Pouyat, R.V. and M.J. McDonnell. 1991. Heavy metal accumulation in forest soils along an urban-rural gradient in southeastern New York. *Water, Air and Soil Pollution* 57:797–807.

Pouyat, R.V., K. Szlavecz, I.D. Yesilonis, P.M. Groffman and K. Schwarz. 2010. Chemical, physical, and biological characteristics of urban soils. In J. Aitkenhead-Peterson and A. Volder (eds) *Urban Ecosystem Ecology: Agronomy Monograph 55*. Madison, WI: American Society of Agronomy, Inc., Crop Science Society of America, Inc., Soil Science Soceity of America, Inc.

Rejmánek, M. and D. M. Richardson. 1996. What Attributes Make Some Plant Species More Invasive? *Ecology* 77:1655–61.

Rebecca, B. 2004. Soil Survey Methods Manual. Soil Survey Investigations Report. No 42 Natural Resources Conservation Services.

Ruiz-Jaen, M.C. and T. Mitchell Aide. 2005. Restoration Success: How Is It Being Measured? *Restoration Ecology* 13:569–577.

Reichman SM. 2002. The responses of plants to metal toxicity: A review focusing on copper, manganese and zinc. Australian Minerals & Energy Environment Foundation. Available from: www.plantstress.com/Articles/toxicity_i/Metal_toxicity.pdf. Accessed 2015 December 18.

Rowntree, R.A. 1995. Toward Ecosystem Management: Shifts in the Core and Context of Urban Forest Ecology. Pages 661–675 in G. Bradley (ed) *Urban Forest Landscapes Integrating MultiDicipliary Perspectives.* Seattle, WA: University of Washington Press.

Sanderson, E. 2009. *Mannahatta: A Natural History of New York City.* New York, NY: Harry N. Abrams, Inc .Searle, S.Y., M.H. Turnbull, N.T. Boelman, W.S. Schuster, D. Yakir and K.L. Griffin. 2012. Urban environment of New York City promotes growth in northern red oak seedlings. *Tree Physiology* 32:389–400.

SER (Society for Ecological RestorationInternational Science & Policy Working Group. 2004. The SER International Primer on Ecological Restoration (available from www.ser.org) accessed in December 2015. Society for Ecological Restoration International, Tucson, Arizona.

Soil Survey Staff, USDA, Natural Resources Conservation Service, United States Department of Agriculture. Web Soil Survey. websoilsurvey.nrcs.usda.gov. (Accessed 27 October 2014).

Stephenson, N. and P. Van Mantgem. 2011. Causes and implications of the correlation between forest productivity and tree mortality rates. *Ecological Monographs* 81:527–555.

Strasser, R., A. Srivastava and Govindjee. 1995. Polyphasic chlorophyll a fluorescence transient in plants and cyanobacteria. *Photochemistry and Photobiology* 61:32–42.

White, C.S. and M.J. McDonnell. 1988. Nitrogen cycling processes and soil characteristics in an urban versus rural forest. *Biogeochemistry* 5:243–262.

Zalesny, R.S., A.H. Wiese and R.B. Hall. 2007. Choosing tree genotypes for phytoremediation of landfill leachate using phytorecurrent selection. *International Journal of Phytoremediation* 9:513–530.

Zhu, W. and M.M. Carreiro. 1999. Chemoautotrophic nitrification in acidic soils in forests along an urban-rural transect. *Soil Biology and Biochemistry* 31:1091–1100.

Zhu, W. and M.M. Carreiro. 2004 Temporal and Spatial Variations in Nitrogen Cycling in Deciduous Forest Ecosystems Along an Urban-Rural Gradient. *Soil Biology and Biochemistry* 36:266–278.

Zoettl, H.W., R.F. Huettl, S. Fink, G.H. Tomlinson and J. Wisniewski. 1989. Nutritional disturbances and histological changes in declining forests. *Water, Air & Soil Pollution* 48:87–109.

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