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Below ground matters: Urban soil rehabilitation increases tree canopy and speeds establishment

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ABSTRACT

Urban land development frequently destroys soil structure and removes organic matter, limiting tree growth. Soil rehabilitation has potential to improve soil quality but the long-term effectiveness and consequences for tree growth are poorly documented. We evaluated growth, canopy development, and physiological response of five tree species over six years to soil rehabilitation in an experimental site pre-treated to replicate typical land development. A corollary experiment evaluated growth and establishment of three additional species one year after rehabilitation in highly urbanized sites in Arlington County, Virginia. Plot study soil treatments were: typical practice (TP) (10 cm topsoil replaced); enhanced topsoil (ET) (topsoil + rototilling); profile rebuilding (SPR) (compost amendment via subsoiling to 60-cm depth + topsoil + rototilling); and undisturbed (UN) (agricultural land with no pre-treatment). In Arlington, SPR was compared with conventional site preparation (topsoil replacement). Overall, trees grew more rapidly in SPR soils and soil depths immediately below the surface (~15–30 cm) were most affected by SPR, which reduced soil bulk density by between 0.19 and 0.57 Mg m^{-3} compared to nonrehabilitated soils. After six years, both trunk cross-sectional area and canopy area of plot-study trees in SPR soils matched or surpassed those in undisturbed soil for all species except *Quercus bicolor* while canopy area increased by as little as 2% (*Q. bicolor*) to as much as 84% (*U.* 'Morton'). In Arlington, SPR resulted in 77% trunk cross-sectional area growth after one year. Plant and soil water relations may also be altered by rehabilitation, possibly contributing to its potential as a tool for stormwater mitigation. Rehabilitation accelerates establishment and growth of urban trees planted in compacted urban soils indicating that the below-ground environment should be a key component in policy and decision making.

1. Introduction

As global urban land cover continues to increase (Seto et al., 2012), the need to effectively sustain tree canopy on soils disturbed by this land conversion becomes more critical. Tree canopy provides a host of ecosystem services (Bolund and Hunhammar, 1999; Nowak and Dwyer, 2007; Roy et al., 2012), yet urban canopy cover is difficult to establish (Harris, 2007; Roman et al., 2014) and maintain (Nowak and Greenfield, 2012). Consequently, expected environmental and social benefits from tree planting are seldom achieved in highly disturbed sites where tree growth and survival rates are poor.

Urban tree canopy is frequently viewed as a policy tool to improve environmental quality (Chesapeake Executive Council, 2003; Nowak, 2006; McGee et al., 2012). Yet despite such policy efforts, urban canopy cover often does not increase; rather there is evidence of widespread canopy shrinkage (Nowak and Greenfield, 2012). This decline is in large part attributed to land use change (Nowak et al., 2004), but revegetation of developed

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land is also necessary for counteracting these trends. Unfortunately, poor soil quality may be among the most significant limiting factors for optimal tree survival and growth. Both direct disturbance and the disruption of soil development processes are major factors that degrade urban soils (Pavao-Zuckerman, 2008). During the change from rural to urban land uses, soils are typically degraded by processes intended to facilitate building construction, such as vegetation clearing, topsoil removal, grading, and compaction (Randrup and Dralle, 1997). These typical land development practices adversely influence soil physical characteristics desirable for ecosystem service provision (Chen et al., 2014b), and impede tree growth and canopy establishment (Gilbertson and Bradshaw, 1990; Jim, 1998).

As a consequence of this disruption, there is considerable interest in improving the ability of disturbed sites to support tree growth and establishment (Cogger, 2005; Sloan et al., 2012). For planted trees, the establishment period encompasses the first few years after planting and is generally considered a high risk period in terms of tree survival (Harris, 2007), although mortality rates vary widely due to the vagaries of quality control during the planting process (e.g., nursery stock quality, transport and handling, irrigation regimes) and the wide range of vulnerabilities that can exist at urbanized sites (e.g., soil conditions, vandalism, exposure to vehicular collisions, etc.; for examples, see Gilbertson and Bradshaw, 1990; Nowak et al., 1990; Roman and Scatena, 2011). Following establishment, site conditions continue to affect tree growth. Soil compaction hinders tree root exploration of soil (Day and Bassuk, 1994; Kozlowski, 1999; Day et al., 2000) and is associated with significantly reduced canopy dimensions of urban trees (Day and Amateis, 2011). Although the potential of soil compaction to reduce tree canopy is well recognized, quantitative assessments of increased canopy growth resulting from soil management practices that reduce compaction and improve soil quality are scarce. In addition, the organic matter loss associated with land development may impair rebuilding soil physical properties over time because of its essential role in the development of soil structure (Six et al., 2004) and in sustaining water and nutrient supplies (Hillel, 1982), suggesting that a soil rehabilitation technique that both reduces compaction and sets the stage for long-term improvement of soil quality is needed. Such a soil rehabilitation technique would be a novel approach to post-development site preparation, since typical practices are no more than a shallow covering of topsoil. A quantitative analysis of the effects of differing post-land development soil management practices on urban tree canopy development could then inform land development policies and practices.

Local government may rely on tree protection and replacement ordinances for new development to maintain or increase community tree canopy cover. In some instances, increasing tree canopy may be needed to meet regulatory requirements concerning water and air quality. However, policy rarely distinguishes between development practices that employ improved soil protection and rehabilitation and those that do not–even though these factors will likely strongly influence canopy outcomes. Quantifying the effects of soil rehabilitation on tree canopy development would be a useful tool for urban foresters seeking to include the effects of soil quality on the growth potential for urban and landscape trees in management decisions and contribute to effective and equitable policy tools for increasing canopy. Soil restoration is also a recognized component of sustainable practice at the site level [e.g., the voluntary certification standards set forth by the Sustainable Sites Initiative (SITES$^{\mathrm{TM}}$) (Sustainable Sites Initiative, 2014)], but measures of the impact of rehabilitation practices that contribute to soil restoration are needed. The heterogeneous nature of urban landscapes and the impact of fine-scale land management decisions (Mincey et al., 2013) make a strong case for including site-level decisions, such as soil management, in urban tree canopy policy and planning.

Soil improvement usually includes some degree of amendment with organic materials such as compost. Soil organic amendments can improve water holding capacity (Khaleel et al., 1981; Rawls et al., 2003), accelerate C storage (Chen et al., 2013) and increase hydraulic conductivity (Boyle et al., 1989; Martens and Frankenberger, 1992; Pitt et al., 1999; Brown and Cotton, 2011; Chen et al., 2014b). However, many amendment studies focus on surface applications or shallow incorporation of organic amendments (e.g., Cogger, 2005; Sloan et al., 2012), which likely do not address the deeper soil compaction that may be present in urbanized land. In this study we examine the effects on tree establishment and growth of "soil profile rebuilding" (Day et al., 2012), a technique that includes deep incorporation of compost to loosen subsurface soils that are typically compacted during urban development and land use change. We previously reported the effects of this practice on soil properties (Chen et al., 2013, 2014b) and greenhouse gas emissions (Chen et al., 2014a).

We evaluated five tree species over six years in response to soil profile rebuilding in comparison with typical development practices and undisturbed agricultural soil at a long-term experimental plot area. Additionally, we measured tree growth and mortality of three additional tree species one year after planting with and without soil profile rebuilding along roadsides and in medians in Arlington County, Virginia. Our objectives were to (1) evaluate whether compaction can be reduced over the long-term in soil damaged by typical land development practices; (2) assess whether soil rehabilitation aids in new tree establishment; and (3) quantify potential gains in tree growth and canopy cover resulting from soil rehabilitation.

2. Methods

2.1. Experiment 1: Experimental plot study

2.1.1. Study site and pre-treatment

The long-term study site, in Montgomery County, Virginia USA (37°12′1.1844″ N, 80°33′48.3768″ W), was historically in agricultural use and planted in pasture grass for 12–15 years before plot installation. Soils were loams, including Shottower loam (fine, kaolinitic, mesic Typic Paleudults) and Slabtown loam (fine-loamy, mixed, mesic Aquic Paleudalfs) (Galbraith and Donovan, 2005). Twenty-four 4.6 × 18.3 m plots were installed in a completely random experimental design (6 replications × 4 soil treatments = 24 plots) as described below.

Prior to treatment installation, all existing vegetation was killed with the herbicide glyphosate. Undisturbed (UN) plots were protected from traffic while all other plots received a scraping and compacting pre-treatment common to current land development practices in the United States. The A horizon (25–30 cm depth) was scraped and stockpiled adjacent to the site on June 19, 2007 and the underlying exposed subsoil was then compacted with eight passes of a 4800 kg sheep's foot vibrating riding compactor to a mean bulk density of 1.95 Mg m^{-3} ($n = 64$, SE = 0.01) at 5–10 cm depth.

2.1.2. Soil treatments

Each experimental plot received one of four soil treatments during August–October 2007: (1) undisturbed (UN) no treatment (and no pre-treatment); (2) typical practice (TP), stockpiled topsoil replaced to a uniform depth of 10 cm; (3) enhanced topsoil (ET), same as TP, but topsoil tilled to approximately 12–15 cm depth to mix its interface with compacted subgrade; and (4) soil profile rebuilding (SPR), 10 cm of composted leaf litter (C/N ratio = 15; pH 7.4) applied to subgrade followed by subsoiling with a backhoe (adapted from a procedure described by Rolf, 1991) to a depth of 60 cm. In this procedure, soil is lifted with the backhoe bucket to approximately 1–2 m and allowed to fall back to ground, serving to mix components and break clods. Clods greater than approximately 30–45 cm in diameter are mechanically fragmented with the backhoe bucket. This method of subsoiling was selected because it can be employed in physically constrained urban sites (road medians, near underground infrastructure, etc.). Subsequent sampling with a push tube and observation using minirhizotrons confirmed the presence of veins of compost consistently reached a depth of 35–60 cm. Finally, 10 cm of stockpiled topsoil was applied and tilled to approximately 12–15 cm depth. The TP treatment represents typical practice employed by contractors to bring a building site to finish grade and prepare it for landscaping. Soil profile rebuilding is a soil rehabilitation technique developed specifically for this study intended to facilitate long-term soil improvement, improve tree growth, and enhance soil C sequestration (Day et al., 2012).

A 0.76-mm thick, 0.6-m deep root barrier (Deep Root Partners, L.P., San Francisco, CA) was installed between adjacent plots in an approximately 0.2-m-wide trench excavated 0.5 m deep to prevent root growth and soil movement from neighboring plots. Approximately 10 cm of barrier was left exposed above ground to prevent root growth over the top of the barrier. All plots were covered with straw erosion control blankets to protect them from rain impact and erosion for the first two years. After this time, the soil surface was kept bare by controlling weeds with periodic application of glyphosate and oxyfluoren + pendimethalin.

2.1.3. Tree species

Five tree species were planted 3.7 m apart in a single row in each plot with in-row position randomly assigned: container-grown (26.5 L) *Acer rubrum* L. and *Quercus bicolor* Willd.; container-grown (11.4 L) *Quercus macrocarpa* Michx.; and bare root *Ulmus* 'Morton' (Accolade®) (*U. japonica* (Rehd.) Sarg. × *U. wilsoniana* Schneid.), and *Prunus* 'First Lady' (*P.* × *incam* Ingram ex R. Olsen & Whittemore 'Okamé' × *P. campanulata* Maximowicz). Container-grown trees were grown in semi-composted 100% pine bark substrate at a nearby research nursery. Bare-root stock was obtained from J. Frank Schmidt & Son Company (Boring, Oregon).

All trees were planted before leaf out in spring 2008. *Q. bicolor* and *A. rubrum* trees were planted between February 28, 2008, and March 10, 2008, into planting holes two times the width of the container. *Ulmus.* 'Morton' and *Prunus* 'First Lady' were planted on March 17, and *Q. macrocarpa* on April 25, 2008, in 70–80 cm diameter holes.

2.1.4. Soil measurements

Soil physical and chemical characteristics were characterized in May and June 2008, approximately 8 months after site preparation by collecting undisturbed soil cores (5-cm D × 5-cm H) at four depths (approximately 2.5–7.5 cm, 15–20 cm, 30–35 cm, and 51–56 cm) at two randomly selected midpoints between trees in each plot. Soil bulk density (ρ_b) was calculated for each core after oven drying at 105 °C to a constant weight and the average of the two cores at each depth calculated for each plot. Particle size analysis (PSA) and carbon/nitrogen ratio (C/N) was determined from composites of the two cores at each depth within a plot. C/N was analyzed with a Vario MAX CNS macro elemental analyzer (Elementar, Hanau, Germany). In June 2012, bulk density was remeasured using the same procedures.

2.1.5. Growth measurements

Tree height and trunk diameter were measured with micro-calipers in two perpendicular directions at 30 cm above the soil surface. Trunk cross-sectional area was calculated as $\pi D_{NS} D_{EW}/4$, where D_{NS} and D_{EW} are the two trunk diameters. Measurements were made immediately after planting in spring 2008, then again at the end of the growing season in late November 2008, and each November thereafter until 2013. Canopy projection area was likewise determined by measuring canopy spread in two perpendicular directions using the farthest reaching branch in each direction on March 21, 2009 (before leaf out, representing the previous year's growth), and on subsequent years in November when trees were in full canopy. Trees were lightly pruned on May 22, 2009, to promote future structure with the exception of the *U.* 'Morton'. For these trees, extremely vigorous shoots were headed back and staked to avoid the possibility of windthrow. In subsequent years, trees were only very lightly pruned to enhance structure as needed.

2.1.6. Physiological measurements

For all treatments, we measured chlorophyll fluorescence and chlorophyll content index for all species during the first two years after planting and photosynthesis rate and leaf water potential for *A. rubrum* and *Q. bicolor* trees only. Measurements for chlorophyll content index (Minolta SPAD 502, Spectrum Technologies, Plainfield, Illinois) were made on all species using two sun-exposed leaves per tree on July 11, 2008, September 20, 2008, and August 14, 2009. Chlorophyll fluorescence measurements were obtained from all species after sun-exposed leaves (one per plant) were dark-adapted for 20 min prior to measurement of the maximum photochemical efficiency of photosystem II (Fv/Fm) on September 21, 2008, and August 18, 2009. Photosynthesis rate was measured for *A. rubrum* and *Q. bicolor* trees on one randomly chosen sun-exposed leaf from the outer canopy (3–7 nodes from twig apex) using a portable gas exchange analyzer (Li-6400, Li-cor Biosciences, Lincoln, Nebraska) on May 27, 2008, September 13, 2008, and September 2, 2009. Leaf water potential (ψleaf) was measured on one randomly selected leaf (3–7 nodes from twig apex) every two hours beginning at 0600 HR and ending at 2000 HR using a pressure chamber (Model 600 Pressure Chamber Instrument, PMS Instrument Co., Albany, Oregon, USA) on July 19, 2008, October 1, 2008, and August 15, 2009. Data were plotted for each individual replication and the area under the curve (hereafter referred to as integrated whole day water stress; I-Ψ) was calculated using the trapezoidal rule (Zill, 1985).

2.2. Experiment 2: Arlington study

2.2.1. Study site

The study was conducted in Arlington, Virginia, USA where 25 plots were located along two main roads, South Walter Reed Drive near its intersection with South Four Mile Run Drive (38.847046, −77.094800) and North George Mason Drive beginning at the intersection of 15th Street and continuing to the intersection with Lee Highway (38.895427, −77.133510). Each plot consisted of an unpaved area in a center median or alongside the road created as a part of a city traffic calming project. Arlington is located in the Fall Zone (Coastal Plain cappings over Piedmont) physiographic region of Virginia and has a temperate climate, with an average annual temperature of 13.17 °C, and average annual rainfall 1085 mm.

Site soils are classified as urban land complex but may retain some characteristics of the pre-development soils (Effland and Pouyat, 1997) which likely include Sassafras series (Fine-loamy, siliceous, semiactive, mesic Typic Hapludults) and Neabsco series (Fine-loamy, siliceous, semiactive, mesic Typic Fragiudults) at the Walter Reed plots, and Glenelg series (Fine-loamy, mixed, semiactive, mesic Typic Hapludults) at the George Mason plots. The Sassafras series is well drained with moderate to high saturated hydraulic conductivity (K_{sat}) and loamy fluviomarine sediment parent material. The Neabsco series is very deep and moderately well drained. Particle size analysis at 0–15 cm indicated soils were sandy loams while deeper horizons were loams or sandy clay loams.

2.2.2. Experimental design and plot placement

Tree species and locations were selected by the Arlington Division of Transportation, with *Ginkgo biloba* L. being planted in the medians along N George Mason Drive, *Quercus coccinea* Muenchh in streetside plantings on N George Mason Drive, and *Cercidiphylum japonicum* Siebold & Zucc. in streetside plantings on S Walter Reed Drive. Treatments were then randomly assigned to plots resulting in 13 control plots and 12 SPR plots. Fifteen of the plots were either parallel parking spaces or left-turn lanes, and were under pavement prior to their conversion to sidewalk "bump-out" tree pits or median plantings. The remaining 10 plots were not previously under pavement and were either on hillsides near intersections, in existing tree planting areas, or separated from the street by the sidewalk. All plots were within 5 m of the road.

2.2.3. Soil treatments

Plots were prepared by a contractor with either soil profile rebuilding (SPR) as described in Experiment 1 (note that contractor did not fully meet specifications, see *Results* below) or left as prepared with the standard site preparation method used by Arlington County Parks and Recreation (control), where approximately 15 cm topsoil (sandy loam, pH of 5.5–6.5, minimum organic content of 1%, and free of debris >1.3 cm) is placed over existing subsoil to bring the soil up to curb grade.

2.2.4. Tree planting

All plots were planted with one of the three tree species in October 2012 with existing soil as backfill, each plot had between 1 and 4 trees (total 25 plots and 36 trees). Trees were balled and burlapped and approximately 60 mm trunk diameter at 15 cm above the root ball. Trees were not staked and 10 cm of shredded hardwood bark mulch was applied around the trees in a 1.2 m diameter ring. The remainder of the plot surface was turf. Because the SPR treatment disturbed surrounding soil and sod, new sod was installed after tree planting.

2.2.5. Tree growth

Trunk diameter, canopy, and height were measured in March 2013 and February 2014 representing size at planting and after one growing season. Trunk diameter was measured at 15 cm, 30 cm and 130 cm from ground level, corresponding to caliper and diameter at breast height measurements common in the forestry and horticulture professions. Height was measured with a Vertex III hypsometer (Haglöf, Långsele, Sweden). Canopy was calculated by measuring crown width in two dimensions and height of lowest branch. Individual trees in plots with more than one tree were treated as subsamples.

2.2.6. Infiltration measurements

Infiltration, as near-saturated hydraulic conductivity (K_{near}) of the soil matrix (Zhang, 1997), was measured using a mini disk tension infiltrometer (Decagon Devices, Inc., Pullman, Washington) with 2 cm tension at approximately 1 m from trees in each plot on May 15–16, 2014. Turf was trimmed at soil level and three measurements (treated as subsamples) were taken at each plot.

2.2.7. Soil temperature

Temperature sensors (Hobo® Tidbit v2, Onset, Bourne, Massachusetts) were installed 20 cm below the soil surface in the center of each plot but at least 1 m from the nearest tree on June 24–26, 2013, and logged temperature readings (±0.2 °C) every 15 min until they were removed on June 21, 2014.

2.2.8. Soil sample collection

Soils were sampled for total C, aggregate stability, bulk density and aggregate-associated C on November 1–3 and 25, 2013. Soil cores were obtained with a JMC Environmentalist's Subsoil Probe (ESP; Clements Associates, Inc, Newton, Iowa). This instrument was driven into the soil manually with a slide hammer, and penetrated the soil to a depth of 92.8 cm. Cores were removed by jacking the sampling tube out of the ground resulting in a continuous core 2.9 cm in diameter. As an artifact of core extraction, the soil sample can become slightly compressed. To adjust for this, the amount of sample compression was measured for every 15 cm that the sampler was advanced into the ground, the last interval being 17.8 cm. In some instances, rocks blocked the opening of the sampler, falsely indicating high compression for a section of the sample. Samples were retaken in such cases. Compression of each 15 or 17.8 cm section was calculated and recorded as a percentage. Cores were kept on ice during transport and then stored at 4 °C for later processing for analysis of particle size distribution, aggregate stability, total C and aggregate associated C.

In addition, four soil cores (5-cm D × 5-cm H) were taken from each plot with a slide hammer at approximately 5–10 cm, 20–25 cm, 42.5–47.5 cm, and 72.5–77.5 cm and used for analysis of ρ_b and K_{sat}. Some depths at some plots could not be sampled due to excessive stones resulting in only 83 of the 96 planned samples being collected. The presence of stones was not treatment related and these samples were treated as missing data.

2.2.9. Soil sample analysis

Compression percentages recorded in the field were used to separate the samples into 4 depth increments corresponding to 0–15, 15–30, 30–60 and 60–90 cm depths in the field. Particle size distribution was analyzed from these segments from 8 plots representative of the range of soils included in the study.

Saturated hydraulic conductivity (K_{sat}) of the 5-cm soil cores was measured in the lab in January 2014 using the constant head method described in Klute and Dirksen (2003). Five of the 83 cores were not measured due to rocks protruding beyond the end of the aluminum sleeve. After cores were measured for K_{sat}, samples were oven dried for 24 h at 105 °C and weighed. Bulk density was calculated in both the $\rho_{\text{fine-earth}}$ (density of the soil between rock fragments in the sample) and ρ_{hybrid} (density of the soil without the mass of rock fragments but with the entire sample volume) forms described by Throop et al. (2012), although rock volume was calculated from the mass of washed separated rocks (assumed particle density of 2.65 g/cm^3), instead of being measured by displacement. The ρ_{hybrid} bulk density was used for estimation of areal C densities, because the density of the soil when rocks are considered voids accurately accounts for the proportion of the soil-rock matrix that can contribute to soil C, while $\rho_{\text{fine-earth}}$ is used for discussion of changes in bulk density, as the density of the fine-earth fraction is most related to root growth restriction.

Aggregate size distribution was determined from samples extracted from each of the four layers in the deep continuous cores described above using the wet sieving methods described in Six et al. (1998). 50 g (±0.02 g) samples were placed on 2 mm sieves and slaked by being rapidly submerged in deionized water. Samples were allowed to equilibrate for 5 min, then the sieve was moved up and down for 50 strokes (counting both the up stroke and the down stroke) within 2 min. Material remaining on the sieve was then washed into labeled aluminum pans. Water and material that had passed though the sieve was then poured onto a 250 μm sieve and sieved for 50 strokes. Material left on the sieve was washed into a labeled pan and the water and remaining material were poured onto a 53 μm sieve, and the process above repeated. Samples were dried at 55 °C for 24 h or until all water had evaporated from the pans. Sample weights were recorded and soil mean weight diameter was calculated according to this equation:

$$\mathrm{MWD} = (\mathrm{M} > 2000\ \ \mu\mathrm{m} \times 5) + (\mathrm{M250\text{-}2000}\ \ \mu\mathrm{m} \times 1.125)$$
$$+ (\mathrm{M53\text{-}2000}\ \ \mu\mathrm{m} \times 0.151) + (M < 53\ \ \mu\mathrm{m} \times 0.0265)$$

Aggregate fractions were corrected for rock and sand content according to Denef et al. (2001) Fractions were ground and dry-sieved to separate rocks, a subsample of the aggregates was placed in sodium hexametaphosphate solution and shaken overnight, and washed through a 53 μm sieve. Material remaining on the sieve was oven-dried and weighed.

Total C analysis was performed using dry combustion on an Elementar Variomacro CN Analyzer (Elementar Analysensysteme GmbH, Hanau, Germany), all C was assumed to be organic. Soil core segments were broken apart by hand, mixed, and air-dried before a subsample was ground to be analyzed for total C. After sand corrections were done on aggregate fractions, the ground aggregate fraction samples were also analyzed for aggregate-associated C using the same CN analyzer. One segment contained lumps of coal and was not included in soil C calculations. Soil C for 90–100 cm depth was extrapolated based on the C at the 60–90 cm depth to calculate total soil organic C to a 1 m depth.

2.2.10. *Statistical analysis*

For Experiment 1, soils and physiological data were analyzed via ANOVA in SAS v. 9.2 (SAS Institute, Inc., Cary, North Carolina) followed by mean separation procedures as noted. Multi-year growth data were analyzed with PROC GLIMMIX and repeated measures analysis in SAS v. 9.2 (SAS Institute, Inc., Cary, North Carolina). In Experiment 2, two-sample *t*-tests were used to analyze differences in soil characteristics between treatments. For tree growth, GLM was used to check for interactions of treatment and species due to the unbalanced design. In both experiments, species were analyzed separately.

3. Results

3.1. *Experiment 1: Experimental plot study*

3.1.1. *Soil characteristics*

Surface soil (2.5–7.5 cm) ρ_b 5 yrs after treatment installation was similar across all treatments (Table 1), although measurements at 8 months had indicated SPR and ET (treatments that included tillage) had slightly lower densities. Treatment effects on ρ_b were most pronounced at 15–20 cm depth, below the added topsoil layer, where SPR had the lowest density, followed by undisturbed soils. For the most part, treatment did not significantly affect ρ_b below 30 cm.

Soil pH ranged from 5.1 to 5.8 except in SPR plots, which were slightly higher (6.3–7.1) presumably due to the addition of compost (pH 7.4). Likewise, C/N ratio was relatively consistent (9.7–10.3 in the upper 20 cm of soil) and decreased with depth, although SPR elevated C/N ratio slightly.

3.1.2. *Tree growth and survival*

Tree survival was 100% with the exception of one SPR red maple that was destroyed by a severe wind storm in July 2012. After six growing seasons, trunk cross-sectional area had increased more rapidly in trees planted in the SPR plots for all species except *Q. bicolor*, where undisturbed plots resulted in larger trees (Fig. 1). Canopy projection area followed a similar pattern, although there was more variability and differences could not always be attributed to treatments (Fig. 2). Trees planted in TP plots were universally smaller in both trunk diameter and canopy than those planted in SPR plots, although in some cases (*Q. bicolor*) differences were slight or statistical evidence was weak (*A. rubrum* and *Q. bicolor*; $p > 0.05$). In the case of *A. rubrum* this can be partly attributed to the death of one of the SPR replicates.

3.1.3. *Physiological measurements*

Soil treatments had no significant effect on mean I-Ψ in the first or second year for either *A. rubrum* or *Q. bicolor* except for *A. rubrum* in 2009 when water stress was greater in the SPR and ET treatments (Table 2). Likewise, photosynthesis rates for all treatments of both *A. rubrum* and *Q. bicolor* were low (as might be expected post-transplant) and, for the most part, not significantly different (Table 2). However, in September 2008 *Q. bicolor* photosynthesis rates in SPR plots were noticeably higher than in other treatments. Treatment did not affect chlorophyll content index or fluorescence for any species.

3.2. *Experiment 2: Arlington study*

3.2.1. *Tree growth*

Even after only one growing season, trees planted in SPR plots in Arlington had a 77% greater average increase in cross-sectional area measured at 15 cm above ground level than trees in control plots (Fig. 3). This pattern was also observed within species, although there were too few experimental units with *G. biloba* to perform statistical tests. At 30 cm and 1.30 m, no differences were observed, likely because of both the small magnitude of increase and high variability due to branching below the measuring point in these young trees. Likewise, there was no evidence of differences in height gain or crown volume increase attributable to treatment.

3.2.2. *Soil characteristics*

During soil analysis, no compost was observed at soil depths below 35 cm. Because soil below 30–35 cm was essentially undisturbed due to improper installation, analyses are focused at the 15–30 cm depth. At 15–30 cm depth, ρ_b was significantly lower in SPR plots than in control plots while macro-aggregate-associated C was greater for both the 250–2000 μm and the >2000 μm

Table 1

Mean soil bulk density at four depths in soils that were not disturbed (UN, undisturbed), or subjected to typical land development practice and then not tilled (TP, typical practice), tilled (ET, enhanced topsoil), or rehabilitated with subsoiling and compost additions (SPR, soil profile rebuilding) 8 months and 5 years after installation. Numbers in parentheses indicate standard errors of the mean ($n = 6$). Letters indicate differences within each depth at $a = 0.05$ via Fisher's protected LSD.

	Bulk density (Mg m^{-3})							
	Soil depth (cm)							
	2.5–7.5		15–20		31–36		51–56	
	8 mos	5 yrs	8 mos	5 yrs	8 mos	5 yrs	8 mos	5 yrs
UN	1.52 (0.04)a	1.43 (0.02)	1.65 (0.02)b	1.61 (0.02)ab	1.69 (0.03)	1.72 (0.02)	1.62 (0.08)	1.70 (0.02)b
TP	1.51 (0.02)a	1.38 (0.07)	1.91 (0.03)a	1.76 (0.04)a	1.76 (0.02)	1.76 (0.03)	1.77 (0.03)	1.67 (0.02)b
ET	1.39 (0.06)b	1.44 (0.03)	1.84 (0.04)a	1.68 (0.04)a	1.69 (0.03)	1.72 (0.02)	1.76 (0.01)	1.68 (0.01)b
SPR	1.28 (0.03)c	1.33 (0.02)	1.34 (0.05)c	1.49 (0.09)b	1.68 (0.06)	1.79 (0.03)	1.75 (0.01)	1.76 (0.02)a

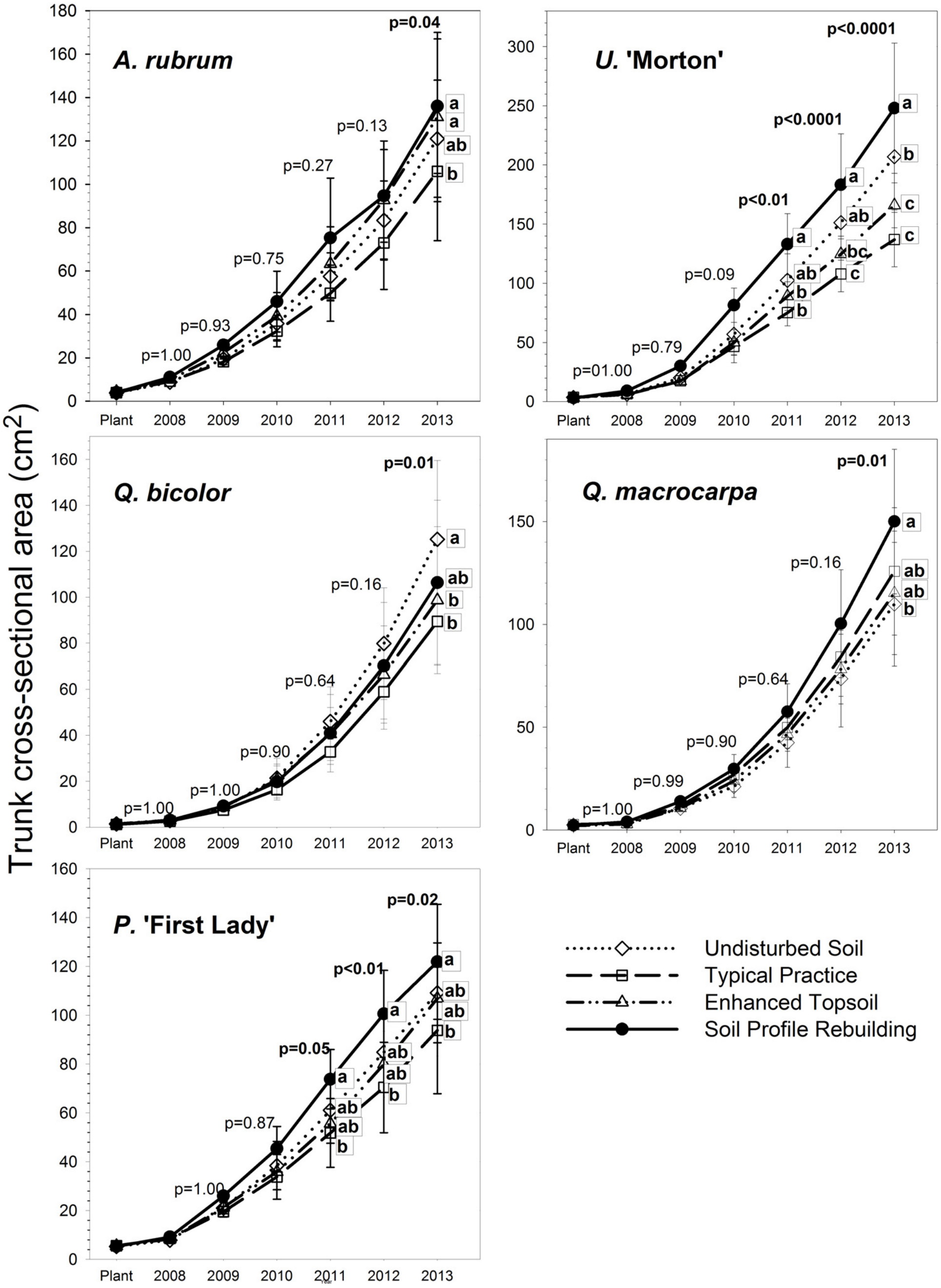

Fig. 1. Mean trunk cross-sectional area of five tree species at 30 cm above ground level over 6 growing seasons in Experiment 1 (plot study). Overall *p*-values are from repeated measures analysis. Error bars indicate standard errors of the means, letters indicate means different at $\alpha = 0.05$ "sliced" by year.

size classes (Table 3). Aggregate-associated C in micro-aggregates (<250 μm) was not affected by treatment. Mean aggregate weight diameter (MWD) was used to represent aggregate size distribution (Van Bavel, 1950), but we found no differences in MWD among treatments after one year. In spite of the compost addition associated with SPR, total soil organic C stocks were not statistically different between SPR and control plots. This may be due in part to the heterogeneous nature of the SPR-treated soil vs. the vertical core based sampling scheme employed (Table 3).

3.2.3. *Saturated and near-saturated hydraulic conductivity*

Surface soils and surface treatments were similar and no differences in infiltration as measured by K_{near} were observed, with an overall mean K_{near} of 2.75 cm h^{-1} (SE 0.39). At all depths, K_{sat} was generally high, but more importantly K_{sat} was highly variable and there were no differences attributable to treatment. Rates varied from zero or near zero to well over 200 cm h^{-1} due to the heterogeneous configuration that is typical of highly disturbed soils.

3.2.4. *Soil temperature*

Overall, soil temperature appeared to be very slightly buffered by SPR, although the plots used in this study were too variable in terms of sun exposure to provide overall statistical evidence to document this. Consequently, as a case study, we compared temperature data from two plots that were well matched in terms of proximity, closeness to pavement, and solar exposure during the

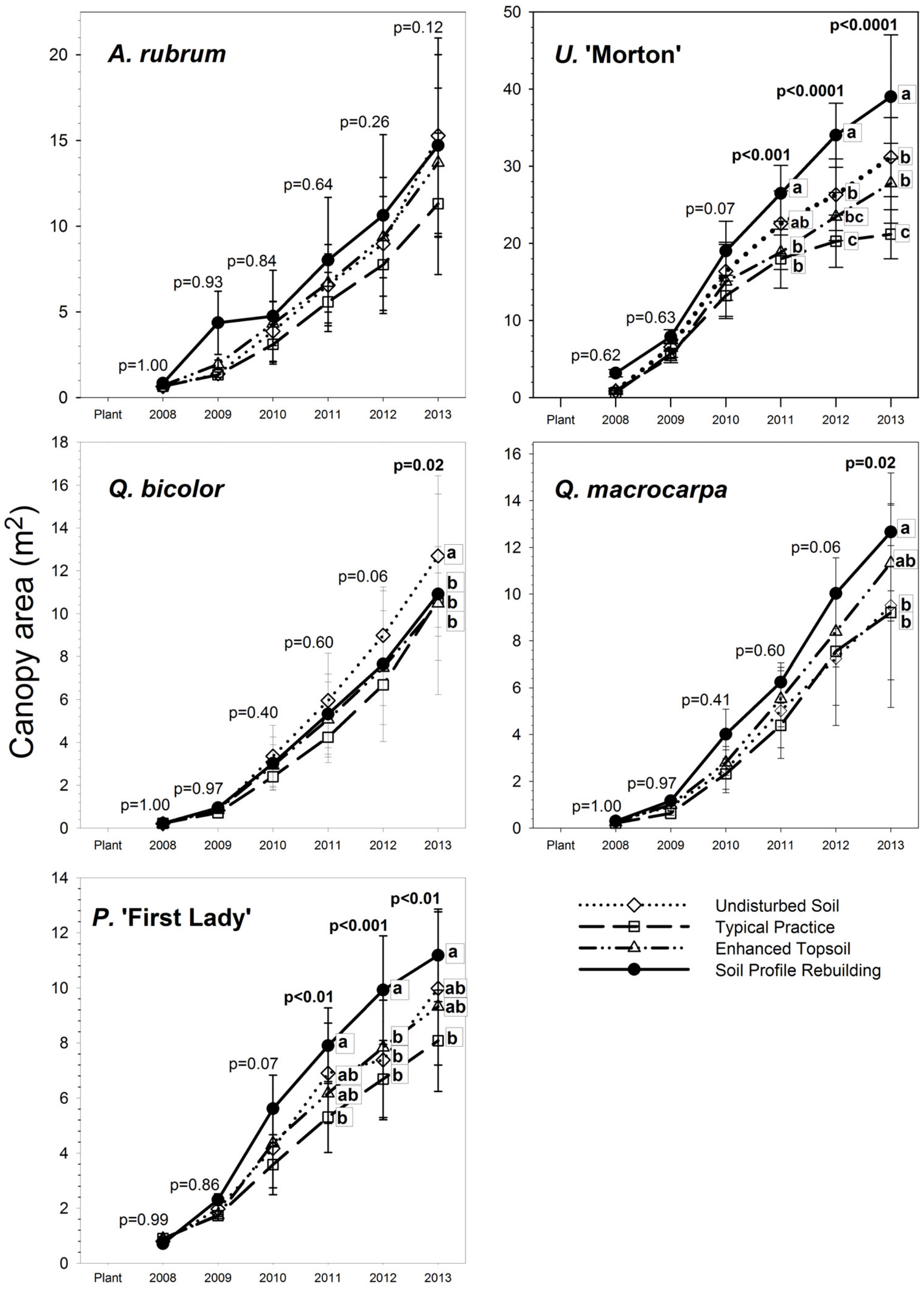

Fig. 2. Mean canopy area of five tree species over 6 growing seasons in Experiment 1 (plot study). Overall p-values are from repeated measures analysis. Error bars indicate standard errors of the means, letters indicate means different at $\alpha = 0.05$ "sliced" by year.

month of September. Maximum/minimum temperatures recorded over the entire study period in the plots were 31.7/0.3 °C and 31.4/0.8 °C for control and SPR plots respectively indicating an extremely slight buffering of temperature by SPR. Maximum temperatures for both treatments occurred on July 19, 2013 at 6 PM and the minimum on January 31, 2014 for the SPR plot and on February 1 and 2, 2014 for the control. Mean diurnal temperature range was 2.04 °C (SE 0.11) for controls and 1.84 °C (SE 0.10) for SPR. One sensor was disturbed by installation of an electrical box soon after it was placed, and was found within 1 cm of the surface. The maximum and minimum temperatures recorded by that sensor were 48.9 °C (July 19) and −2.2 °C (January 30) indicating the magnitude of temperature extremes possible near the surface.

4. Discussion

Overall, establishment was enhanced by SPR as evidenced by increased first year trunk growth in the Arlington study and a similar response over the six years of the plot study. In the plot study, species considered slower to establish (*Q. bicolor* and *Q. macrocarpa*) did not begin to display treatment differences until after two or three growing seasons, while more rapidly establishing species began to demonstrate different growth rates after one growing season. This may explain why *A. rubrum* experienced greater water deficit in ET and SPR treatments after one year, while *Q. bicolor* showed no such effect. Chen et al. (2014b) found that SPR resulted in lower bulk soil water contents than other treatments, which may have contributed to this effect. Differences in water deficit were not

Table 2

Mean integrated whole day water stress (I-Y) and photosynthesis (Ps) of *A. rubrum* and *Q. bicolor* transplanted in spring 2008 into soils that were not disturbed (UN, undisturbed), or subjected to typical land development practice and then not tilled (TP, typical practice), tilled (ET, enhanced topsoil), or rehabilitated with subsoiling and compost additions (SPR, soil profile rebuilding). Parentheses indicate standard errors of the mean ($n = 6$). Mean comparisons are within a day and species (within columns) at $a = 0.05$ via Fisher's protected LSD at $P < 0.10$.

	Integrated whole day water stress (I-Ψ)					
	Jul 19, 2008		Oct 1, 2008		Aug 15, 2009	
	A. rubrum	*Q. bicolor*	*A. rubrum*	*Q. bicolor*	*A. rubrum*	*Q. bicolor*
UN	135.9 (3.9)	89.1 (12.6)	92.2 (4.1)	131.9 (4.9)	98.5 (3.4)b	158.5 (5.2)
TP	144.5 (7.9)	111.2 (8.7)	91.6 (3.3)	131.4 (4.6)	98.9 (3.0)b	169.9 (7.2)
ET	141.8 (4.5)	103.4 (7.4)	92.0 (3.3)	131.5 (4.7)	109.3 (1.7)a	161.5 (5.0)
SPR	137.7 (6.8)	108.7 (6.7)	84.8 (4.2)	123.1 (7.1)	115.8 (3.4)a	170.4 (6.0)

	Ps (μmol CO_2 m^{-2} s^{-1})					
	May 27, 2008		September 13, 2008		Sept 2, 2009	
	A. rubrum	*Q. bicolor*	*A. rubrum*	*Q. bicolor*	*A. rubrum*	*Q. bicolor*
UN	4.78 (1.63)	4.17 (0.72)	11.86 (0.81)	12.58 (0.80)c	10.31 (0.65)	16.28 (0.90)
TP	5.78 (1.15)	4.15 (0.38)	12.66 (1.86)	15.77 (0.86)b	10.64 (1.58)	17.67 (1.25)
ET	4.77 (0.84)	3.77 (0.45)	12.88 (0.50)	15.50 (0.81)b	11.02 (1.73)	15.72 (1.13)
SPR	5.80 (0.64)	3.82 (0.53)	13.14 (2.02)	19.51 (0.88)a	10.41 (0.74)	19.78 (0.87)

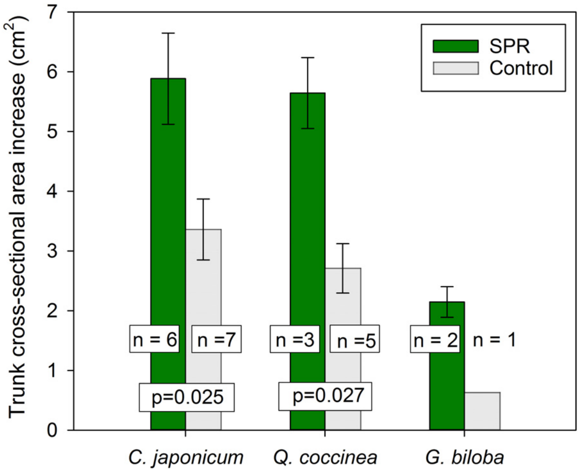

Fig. 3. Mean increase in trunk cross sectional area at 15 cm above ground level for trees planted in street medians or along the roadside prepared with either soil profile rebuilding or topsoil replacement (controls) after one growing season in Experiment 2 (Arlington study). Growth values for individual trees within plots with >1 tree were treated as subsamples, as treatment was assigned at the plot level. Overall *p*-value = 0.007.

biologically significant, but do suggest that more exploration of the water relations of the plant soil system may be warranted.

Overall, soil rehabilitation speeds growth and canopy development of planted trees compared to conventional practices. In the Arlington study, increased growth was only measurable in trunk measurements at 15 cm, as might be expected since the establishment period is usually characterized by root regeneration and minimal shoot growth (Harris, 2007). With the exception of *Q. bicolor*, long term canopy development was strongly affected by soil treatment, indicating that soil conditions should be considered whenever tree planting is used as a policy tool to address urban tree canopy cover. The clear effect of available soil volume on canopy development has been demonstrated (Grabosky and Gilman, 2004; Day and Amateis, 2011) but this study supports efforts to include soil quality in decision making as well. Trunk size is well correlated with whole tree biomass (McHale et al., 2009), and trunk measurements likewise showed a strong soil treatment effect that did not dissipate over time. The plot study pre-treatment mimicking land development practices is really a base level for development-associated soil disruption. Many sites will have lower quality fill material and be subjected to significantly more grading resulting in deeper and more severe compaction. Consequently, the net effects of SPR could be greater in many situations.

Soil organic amendments are commonly recommended for improving highly disturbed urban soils and are particularly recommended for reducing soil compaction (Cogger, 2005; Sæbø and Ferrini, 2006; Larney and Angers, 2012; Sloan et al., 2012). While organic soil amendments immediately decrease ρ_b through a bulk dilution of mineral soil with organic material (Bassuk and Rivenshield, 2007; Loper et al., 2010), the persistence of this effect has been questioned. In the Arlington study, the small decreases in ρ_b were likely due to this dilution effect, as aggregate formation usually takes longer than the 13 months between installation and sampling (Wick et al., 2009a). The soil rehabilitation procedure under study here differs from typical agricultural amendment (surface application followed by shallow tillage) in three ways: (1) compost incorporation is accomplished with a backhoe leading to much coarser mixing than tillage; (2) compost is incorporated into the subsoil, to 60 cm in some cases; and (3) tree planting is part of the rehabilitation practice based on the premise that roots will have access to newly opened soil channels resulting from compost incorporation and root activity will facilitate movement of C into more stable pools (Chen et al., 2013). Compost incorporation into deeper soil layers is important in urban settings where cut and fill grading practices during land development may result in multiple compacted soil lifts. Furthermore, even though subsurface soils may be highly disturbed during initial urbanization, they are less likely than surface soils to be subjected to either ongoing human impacts or plant root influences as these may be unlikely to penetrate highly compacted soil regions (Day et al., 2000). This reduced surface interaction, however, also contributes to the higher proportion of C in stable pools (i.e., physically or chemically protected) found in deeper soils (Lorenz et al., 2011). Nonetheless, addressing soil compaction with coarse insertion of compost well below the soil surface may have significant benefits because it opens up these soil regions to root penetration and thus ongoing C storage (Chen et al., 2013), greater hydraulic conductivity (Chen et al., 2014b), and greater rooting space to support tree growth and potentially increase tree stability—without excessive disruption of aggregates, especially macroaggregates. However, in this study treatments did not always successfully reach the intended soil depth, emphasizing the difficulty of achieving rehabilitation of compacted subsoils.

In the fully replicated plot study, observation through minirhizotrons installed for another experiment immediately after

Table 3

Soil bulk density, soil organic C, and aggregate-associated C (standard errors of the means in parenthesis) measured at four depths in soil profile rebuilding (SPR) and control plots in Arlington, Virginia 13 months after treatment installation. Data for 90–100 cm depth is estimated based on 60–90 cm.

Depth (cm)	Bulk density ($Mg\,m^{-3}$)		Total C density ($kg\,C\,m^{-2}$)		Sand-free aggregate-associated C ($g\,C\,g^{-1}$ aggregate)					
					<250 μm		2000–250 μm		>2000 μm	
	SPR	CON	SPR	CON	SPR	CON	SPR	CON	SPR	CON
0–15	1.22 (0.08)	1.30 (0.07)	3.61 (0.49)	3.12 (0.44)	2.43×10^{-2} (3.7×10^{-3})	3.18×10^{-2} (7.7×10^{-3})	1.1×10^{-1} (2.4×10^{-2})	7.24×10^{-2} (1.3×10^{-2})	4.08×10^{-2} (4.9×10^{-3})	4.35×10^{-2} (4.7×10^{-3})
15–30	1.25 (0.08)$^{+}$	1.44 (0.05)$^{+}$	1.89 (0.33)	1.77 (0.35)	1.84×10^{-2} (2.6×10^{-3})	1.61×10^{-2} (5.1×10^{-3})	1.17×10^{-1} (3.0×10^{-2})*	5.16×10^{-2} (1.5×10^{-2})*	1.05×10^{-1} (3.3×10^{-2})§	2.81×10^{-2} (8.8×10^{-3})§
30–60	1.49 (0.06)	1.38 (0.09)	2.52 (0.35)	1.98 (0.32)	1.16×10^{-2} (1.7×10^{-3})	1.16×10^{-2} (2.4×10^{-3})	5.24×10^{-2} (1.1×10^{-2})	3.68×10^{-2} (9.7×10^{-3})	5.34×10^{-2} (2.7×10^{-2})	8.5×10^{-3} (2.4×10^{-3})
60–90	1.51 (0.07)	1.53 (0.03)	0.56 (0.17)	0.79 (0.19)	4.28×10^{-3} (1.4×10^{-3})	1.06×10^{-2} (5.9×10^{-3})	1.50×10^{-2} (9.3×10^{-3})	2.40×10^{-2} (1.1×10^{-2})	2.13×10^{-2} (1.3×10^{-2})	1.04×10^{-2} ($n = 1$)
90–100 (estimated)			0.18 (0.06)	0.26 (0.07)						
Total C density to 1 m			7.90 (1.29)	8.25 (0.59)						

$^{+}$ $p = 0.064$.

* $p = 0.071$.

§ $p = 0.087$.

treatment installation confirmed that compost had reached 60 cm depth in most, but not all locations. In the Arlington study, soil sampling clearly indicated that compost incorporation had not been achieved to the specified depth. This indicates that in spite of being provided with a written specification (Day et al., 2012), several teleconference and face-to-face meetings with the project management team, and periodic site visits during installation, the contractor did not install the SPR treatment to the depth mandated in the specification (i.e., that the backhoe bucket did not penetrate to the full 60 cm). The method explored here is novel, and it seems that ensuring that the contractor installed SPR to the unusually great depth of 60 cm was more difficult than expected. Because of the novelty of the SPR soil treatment, testing for contractor compliance after installation by extracting samples with a push tube could be helpful. In addition, the idea of site preparation, as opposed to planting hole preparation, was novel to contractors and additional effort may be required to clearly communicate that SPR is to be applied to the entire soil area, not just where trees are to be planted.

The greatest reductions in ρ_b from SPR vs. conventional practice in both studies were seen at soil depths where conventional practice (TP and CON) resulted in highly compacted soils *and* the SPR subsoil disruption was fully implemented, at approximately 15–30 cm depth. These differences persisted after 5 years, possibly due to the minimal disruption of aggregates in comparison to traditional tillage, root exploration, and the eventual protection of macroaggregates by organic matter additions (Grosbellet et al., 2011), although these were not measured in this study. The slightly greater ρ_b found near the bottom of the SPR treatment in some cases may have been caused by the movement of the backhoe bucket during installation. In the Arlington study, SPR resulted in increased macroaggregate-associated C after only one year, confirming findings from an earlier analysis of soil aggregates in the plot study (Chen et al., 2014b). Chen et al. (2014a,b) reported higher macro-aggregate-associated C concentrations in SPR treated soil at 15–30 cm depth than in simulated development four years after the installation of SPR. We observed this same effect after only 13 months in this study. We saw no differences in MWD among treatments after one year; similarly, Chen et al. (2014b) found no differences after four and five years. Increases in macro-aggregate-associated C imply that C storage in the soil is increasing; however, although mean C density of SPR plots was higher in Arlington, the difference was not significant. Because the subsoil is loosened and disturbed during installation, some existing organic C is likely to be lost (Wick et al., 2009b; Chen et al., 2014b), explaining the increase in the macro-aggregate associated C and lack of change in total organic C.

Contractors sometimes employ the ET treatment to reduce the abrupt soil interface that can result from laying topsoil over a compacted subgrade. This tillage reduced ρ_b in surface soil at 8 months, but this effect did not persist at 5 years. A similar pattern was seen in SPR, which also included surface tillage, although overall ρ_b was lower, likely due to some incorporation of residual compost. Tillage results in both reduced labile and recalcitrant C pools and disrupts soil aggregates (Haynes, 2005; Chen et al., 2013), reflecting long-term costs that outweigh any benefit garnered from short term reductions in soil density for urban tree planting.

The lack of differences in hydraulic conductivity of surface soils in Arlington was expected, since surface treatments were virtually identical in SPR and control plots. Because measurements of K_{near} were made under tension and do not represent flow in large macropores (Beven and Germann, 2013), K_{near} and K_{sat} are not directly comparable. Chen et al.'s (2014b) earlier study found K_{sat} was nearly 10 times higher than the typical practice at depths of 10–40 cm, the depth range most affected by SPR. Thus, we expected that differences in K_{sat} would occur at the 15–30 cm depth, where compost was incorporated. That no effect was detectable may be due to the core method we used to measure K_{sat}. Because K_{sat} is scale- dependent and SPR results in heterogeneous subsoil with soil clods interspersed with veins of compost, differences may have been evident if K_{sat} had been measured in situ, or on a larger scale, where larger cracks or water paths may have had more influence. We used the core method because of the difficulty of conducting in situ measurements in dispersed urban plots.

As root growth is known to begin at soil temperatures around 4 °C for some species (Kuhns et al., 1985), and 12 °C for others species including *Q. coccinea* (Harris et al., 1995), we tested whether there was a difference in the amount of time that in the paired temperature plots spent above 12 °C: the difference was approximately 45 min over the course of a year and of no biological consequence. Root growth is known to stop in the fall when soil temperatures reach 6–8 °C (Harris et al., 1995). By these criteria, the root growth growing season was shifted by one day later by SPR; again not of biological significance. The slight buffering of soil temperature we observed in SPR plots may be due to decreased thermal conductivity of amended soil due to more air filled pores and increased water holding capacity, which could raise the amended soil's specific heat capacity (Gupta et al., 1977).

5. Conclusions

We assessed the response of eight commonly planted urban tree species to soil rehabilitation. Using a controlled plot study as well as a designed experiment at an urban site, this work demonstrates that consideration of below-ground conditions is critical to development of strategies to increase urban tree canopy cover through tree planting. Soil rehabilitation that includes deep incorporation of compost such as soil profile rebuilding is a viable means to improve establishment and increase growth rates of planted trees in disturbed, urbanized soils. Response magnitude may be even greater when soils are more severely compacted.

Decreases in soil bulk density resulting from SPR persist over time. In addition, C sequestration rates for the soil/plant system are increased on several fronts: more aggregate-associated C, more soil C at depth; and greater net primary productivity of the site. Although there may be a very slight buffering of soil temperature in rehabilitated soils, this effect is likely site specific and was not of sufficient magnitude to meaningfully alter the below-ground growing season.

In addition to reducing soil compaction and increasing tree growth, soil rehabilitation shows potential for improving stormwater capture of urban forests, although more data are needed in more diverse planting situations to clearly quantify this effect. While other studies have established that SPR enhances K_{sat}, we were unable to replicate this finding in our field study in Arlington, Virginia. However, this may serve more as an indicator of the heterogeneity of disturbed soils and the deliberate heterogeneity created by compost incorporation in SPR, rather than a clear statement of the effect of SPR on K_{sat}. In such situations in situ field measurements that capture conductivity characteristics of the bulk soil and its larger scale characteristics such as root paths, cracks, or clods are valuable. The faster establishment of transplanted trees and decreases in subsoil density found in these studies can allow for more water to be captured and stored than in typical urban soil. Although tree physiological measurements did not reveal strong differences in stress between treatments, trees in SPR plots were able to exploit the improved below-ground conditions and establish more quickly. Faster tree establishment means faster returns on investment for municipalities using trees and soil for ecosystem service provision.

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