Urban Forestry & Urban Greening 16 (2016) 25–35

Contents lists available at ScienceDirect

Urban Forestry & Urban Greening

journal homepage: www.elsevier.com/locate/ufug

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

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ARTICLE INFO

Article history:
Received 10 November 2015
Received in revised form 21 January 2016
Accepted 21 January 2016
Available online 26 January 2016

Keywords:
Compost
Land development
Organic amendments
Soil carbon
Soil compaction
Subsoil
Soil remediation
Soil temperature
Tillage

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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http://dx.doi.org/10.1016/j.ufug.2016.01.004
1618-8667/

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^{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