Development of Urban Tree Growth Models Based on Site and Soil Characteristics

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Abstract

Trees provide numerous benefits crucial to urban environments, yet poor growing conditions often prevent trees from reaching their genetic potential for growth, longevity, and ecosystem function. To overcome these limitations, greater understanding of tree growth in the urban environment is needed. The goal of this research project was therefore to characterize a broad suite of soil characteristics associated with urban tree plantings and evaluate their suitability for modeling physical dimensions and growth rates of urban trees. A series of observational studies and experiments was conducted on urban soils inhabited by two tree species (*Zelkova serrata* (Thunb.) Mikano and *Quercus phellos* L.) in Washington, DC and one tree species (*Quercus virginiana* Mill.) in Jacksonville, FL – two major metropolitan areas of the eastern United States with contrasting climate and soils.

Characterization of urban soil attributes within cities revealed low variability for some properties (soil texture, pH, and certain plant nutrients with coefficients of variation (CV) below 0.5), but high variability (CV>1.0) for others (nitrate, ammonium, copper, and zinc). This is dependent on the location. These findings suggest that tree planting site evaluations may not require measurements for all soil properties and that representative sampling may be sufficient to accurately characterize most soil properties within a city.

Field assessment of urban tree soils also revealed that conventional measures of soil compaction are difficult to obtain due to obstructions by roots and other foreign objects. To address the critical need for efficient and reliable assessment of soil compaction around urban trees, an experiment was conducted to develop bulk density estimation models for four common soil texture classes using soil strength and soil moisture as predictor variables. These models provided medium (0.42) to high (0.85) coefficients of determination when volumetric water content (VWC) was log transformed, demonstrating that measurements of soil texture, strength, and moisture can provide rapid, reliable assessment of soil compaction.

Tree growth modeling focused on three response variables: canopy projection (CP), canopy volume (CV), and peak-increment-area age (PIA). To calculate PIA, tree-ring analysis was used to determine the age at which maximal trunk diameter growth occurred between transplanting and time of sampling. Because *Q. virginiana* has difficult-to-distinguish growth rings, an intensive tree-ring analysis of cores collected from these trees was conducted. The analysis revealed interseries correlation coefficients of up to 0.66, demonstrating that *Q. virginiana* can be aged with fairly high confidence in an urban setting.

Empirical models developed for all three tree species using the suite of soil and site variables explained 25% – 83% of the observed variability in tree physical dimensions and growth rates. Soil pH was found to be a significant predictor variable for the majority of growth models along with nutrients such as Fe, B, Mn, and Zn, which are also associated with soil alkalinity. Models for PIA possessed the highest coefficient of determination, suggesting that measurements of soil conditions can be used confidently to predict the age at which growth rate subsides in these species. CV and CP were not predicted as well by soil-related variables, presumably because above-ground constraints such as pruning and building encroachment can affect canopy size without necessarily affecting growth rate.

Certain prediction models for all three species included predictor variables with counterintuitive influences on tree growth (e.g., negative influences of soil depth on *Q. phellos* and soil volume on *Q. virginiana*), suggesting that either these urban trees are responding to these variables in a novel manner or that variables unaccounted for in these models (perhaps related to urbanization or high vehicular traffic) are concomitantly influencing tree growth.

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Abbreviations

ANSI	American National Standards Institute
CEC	Cation exchange capacity
cm	Centimeter
CP	Canopy projection
CV	Canopy volume
DBH	Diameter at breast height
FWC	Field water capacity
GWV	Gravimetric water content
LCS	Longer cutout side
m	Meter
MPa	Mega pascal
NAAQS	National Ambient Air Quality Standards
OM	Organic matter
PIA	Peak-area increment age
PWP	Permanent wilting point
SCS	Shorter cutout side
SS	Soluble salts
VIF	Variance Inflation Factor
VOC	Volatile organic compounds
VWC	Volumetric water content
ρ_b	Bulk density
m^2	Square meter
m^3	Cubic meter
ppm	Parts per million
TDR	Time domain reflectometer

Chapter 1: Introduction

Urban trees are frequently planted in unsuitable growing conditions that contribute to high juvenile mortality, suppressed growth rate, and shortened lifespan. As a consequence, trees do not reach their full genetic potential for size and longevity and thus fall short of maximizing their ecological, social, and economic benefits. Although it is well known that soil and site conditions influence tree growth, the relative importance of these variables to tree performance has not been well documented in highly urbanized settings. The effect of these environmental factors on tree growth attenuation over time is particularly relevant given current efforts to expand tree canopy cover in urban areas around the world. Thus the goal of this study was to develop growth prediction models for urban trees that identify growth-influencing soil and site attributes as well as their level of influence on tree growth (Chapter 6). Knowing which environmental factors significantly influence tree development will help urban foresters pursue canopy cover goals efficiently to improve the urban environment and enhance quality of life for citizens.

In this study, growth prediction models were developed based on thirty soil-related site attributes. A wide range of variables was purposefully chosen for modeling because it is not known which variables (or which interactions of variables) are most important to development of trees in highly urbanized environments. These attributes were first evaluated for their variability within two metropolitan areas of contrasting soils and climate, while also exploring the reliability and practicality of their field measurement techniques (Chapter 3). One of these soil attributes, soil compaction, was found to be difficult to be measured via conventional soil core extraction method due to soil obstructions oftentimes found in urban planting pits. This resulted in a study to develop models for different soil types using easily measure soil strength and moisture data – because soil texture, soil moisture, and soil strength are related – to estimate bulk density so that practitioners might have a) a reliable measure of soil compaction and b) a reproducible measure that is comparable across studies (Chapter 4).

Modeling tree growth rate requires a reliable measure of annual growth increment. One way of measuring tree growth rate is by analyzing annual trunk ring widths, which provides more reliable information than trunk diameter and age alone. Tree ring analysis has been used frequently for studying rural trees, yet has received limited attention for urban tree study. Although these techniques have great potential for studying urban trees, there are inherent challenges to applying these methods in urban environments, particularly for trees growing in highly-variable street-side settings and mild climates at middle latitudes. One of the species selected for the overall modeling study, *Quercus virginiana* growing in Florida, was found to be difficult to analyze because its growth rings lacked readily discernable growth rings boundaries. To address this challenge and shed light on urban tree ring analysis, a dendrochronological study was conducted on *Q. virginiana* and is presented in Chapter 5.

The primary thrust of this comprehensive study was the development of growth models for three common urban tree species using a broad suite of soil-related variables (Chapter 6). Soil-related characteristics were chosen for modeling tree growth because they affect every tree, can be modified prior to tree planting, and have been shown to be growth limiting in most urban settings. By knowing the effect of these crucial site characteristics on particular tree species, it would be possible to better design planting sites for long-term tree growth and benefit provision. Modeling efforts in this study took two approaches: (1) complex modeling to evaluate the full explanatory power of the sampled independent variables, and (2) simplified modeling with a sub-set of these variables that significantly affect tree growth, yet are not expensive, laborious, or technically complex and therefore accessible to most municipalities. Currently, many resources are used to plant trees without knowing whether the trees will survive or whether they will reach their anticipated size. Trees may die prematurely or even outgrow their site. In either case, the tree would have to be removed and replaced long before the tree’s potential is reached. This does not improve urban canopy cover and is therefore inefficient and unsustainable.

Chapter 2: Literature Review

The goal of this research endeavor is to evaluate the explanatory power of specific soil properties for urban tree growth and to develop models based on these variables to predict tree growth metrics such as canopy size. The following sections address the importance of trees -especially in the urban environment- for the long list of benefits they provide, the notion of using canopy cover goals to ensure provision of these benefits, and the difficulties of reaching these goals due to unsuitable planting designs and the resulting lack of resources required for tree development. In addition, existing tree growth models are discussed although no tree-growth model, to my knowledge, involves soil variables despite the fact that they are essential to a tree's health and longevity.

Urban tree benefits and their relationship to tree characteristics and site conditions

Trees provide a wide range of benefits that are essential to the existence of the world and its habitants. Many ecological, socioeconomic, and aesthetic benefits are provided by urban trees such as atmospheric carbon reduction (Nowak 1993), wildlife habitat provision (Calder et al. 2008; Dwyer et al. 1992), water quality improvement (Nowak 2005), water infiltration as well as soil quality improvement (Bartens et al. 2008), stormwater management enhancement (Calder et al. 2008; Cermák et al. 2000; Hinckley et al. 1994; Meinzer et al. 2005; Simpson 2000; Thomas 2000), and temperature moderation (Heisler et al. 1995). Trees also increase property values (Martin et al. 1989), reduce crime (Kuo and Sullivan 2001), shorten recovery times of hospital patients (Ulrich 1984), lower energy costs (Dwyer et al. 1992; Heisler 1986), and reduce noise pollution (Fang and Ling 2003). To help quantifying the benefits provided by urban trees, monetary values can be placed on ecosystem-service functions as well as other benefits provided by trees. For example, the urban forest in Chicago was estimated to have removed almost 6,000 metric tons or $9 million dollars' worth of air pollutants during 1991 (McPherson et al. 1997). However, most benefits are proportional to leaf area (McPherson et al. 1998; Nowak and Dwyer 2007; Nowak 1994a) and therefore health, size, species, and age of a tree.

Because large, healthy trees generally possess a bigger canopy and greater total leaf area, they typically provide greater benefits than small or unhealthy trees. For example, mature *Platanus acerfolia* may intercept more than 22 times the volume of precipitation compared to small *Jacaranda mimosifolia* from a 25-year storm or more than 38-fold annually (Xiao and McPherson 2003). Thus large trees can have an immense influence on stormwater management through runoff reduction. Similarly, larger street trees can make a significantly higher contribution to the aesthetic value of a street (up to 8 fold) compared to yard trees based on a survey in Delaware, OH (Schroeder and Cannon 1987). However, large trees not only provide a greater degree of benefits, they are more cost effective because their life expectancy-and thus longevity of ecological, aesthetic, and social benefits provided- is greater than for small or medium-sized trees (Geiger 2004).

In addition to tree size, species type also plays a significant role when it comes to benefits provided by trees. *Fraxinus* plantations have been found to take up more sodium and nitrate while potassium, calcium, and magnesium are added to the system compared to a *Betula* plantation and a *Pinus-Quercus-Betula* forest (Neal 2002). On a more general basis, deciduous trees differ in levels of functions they provide compared to coniferous trees. Conifers provide certain benefits year-round due to their evergreen foliage whereas similar functions in deciduous trees are typically limited to the growing season. In addition, leaf area indices of conifers can be higher than those of deciduous trees (Gower and Norman 1991; Karlik and Winer 2001) because their shape is most often excurrent whereas most angiosperms have decurrent form (Harris et al. 1992) and thus larger canopy projection. Because conifers can provide certain benefits year-round, they are often recommended for enhancing airborne particulate matter removal (McPherson et al. 1994). Thus, both species type as well as tree physical dimensions must be known in order to accurately predict ecosystem services provided by urban trees.

A tree's size and ecological function are products of its genetics and its environment. In the urban environment, below-ground site conditions (such as soil compaction and restricted rooting space) can have a strong influence on eventual tree size attainment. Thus environmental influences must be understood to accurately project tree size potential in urban settings. Urban soils are an essential contributor to the survival and longevity of trees and thus their provision of benefits yet tree species vary in their tolerance to environmental factors, including soil characteristics. Soil environments of urban trees can vary greatly in terms of available rooting space as well as soil chemical and physical properties (De Kimpe and Morel 2000; Jim 1998a), all of which have been found to influence tree growth (see Chapter 3 as well as Day and Amateis in review; Grabosky and Gilman 2004; Kent et al. 2006; Lindsey and Bassuk 1992; Misra and Gibbons 1996; Sands et al. 1979; Soane 1990; Thompson et al. 1987; Masle and Passioura 1987 .

Thus tree growth and health- as depend on soil chemical and physical properties- can vary greatly within an urban area due to the high soil variability commonly found in urban soils. Similarly, the level of benefits provided by urban trees can vary to a large extent. In addition, urbanization continues to impair the environment through, for example, increases in airborne pollutants, as well as pollutant-loaded runoff into streams. Thus a sustainable urban forest counteract some of these harms is ever more important.

Urban tree canopy cover goals

The urban population is projected to increase worldwide (Grimm et al. 2008). This continuing change in land use is associated with decreases in vegetation cover and increases in pollution loading to the atmosphere through anthropogenic activities. A decrease in open space, including horticultural and agricultural land as well as recreational areas such as parks and playgrounds has been shown in Merseyside, UK. Land use change for 11 residential areas resulted in a significant increase (>7%) in impervious area (e.g. buildings, pavement) while green space was decreasing (>5%) over a 25-year period (Pauleit et al. 2005). Urbanization and its effect on water quality can be particularly detrimental to water quality, as has been seen in the Chesapeake Bay Watershed of the eastern United States which has increased total nitrogen and phosphorus contents as well as low dissolved oxygen with overall "poor to degraded water quality"(Wazniak et al. 2007). However, over the past decades, encouraged by the passing of the Clean Water Act in 1972, the Chesapeake Bay Watershed, as well as other ecological systems, have gained much attention leading to a slow improvement of their quality. One way of assuring and improving ecological quality as well as quality of life within the urban environment is a sustainable (stable) urban tree canopy cover.

In an effort to conserve and augment urban tree canopy cover, many municipalities develop tree preservation as well as canopy conservation ordinances. The goal of a tree preservation ordinance is to preserve trees on private as well as public land during construction, identify appropriate new tree plantings, and provide maintenance of preserved trees after construction (MNSTAC 1995). One such ordinance has been developed for the City of Lake Forest, MN, called the tree preservation and landscaping ordinance. Besides the mentioned focus, the city also included tree preservations to support environmental functions such as decreasing erosion and stormwater runoff (City Council of Lake Forest 2010). Canopy conservation ordinances focus on the conservation of existing trees during the development of properties. Raleigh, NC, for example, adopted such ordinance as part of their zoning code. Their ordinance requires that a certain number of trees are to be conserved when areas larger than two acres are to be developed. For example, they specified that 15% of the land area should be covered with tree canopy in low-density residential districts (City of Raleigh 2009). However, other incentives have been developed over the years to encourage municipalities to improve their tree planting and maintenance programs to optimize benefits provided by urban trees.

One such incentive is the Tree City USA® program sponsored by the Arbor Day Foundation, the USDA Forest Service, and the National Association of State Foresters. The Tree City USA® program provides direction and assistance to improve urban forestry programs. Tree City USA® can be a status symbol and therefore attract educated residents, businesses, as well as tourism. In addition, the "status" Tree City USA® shows that a municipality offers engagement, enthusiasm, and success and is a supportive fact when allocating financial assistance. Many Tree City USA® communities, such as the City of Miami, FL or the City of Alexandria, VA, have included canopy cover goals in their city master plans. The City of Miami, Florida's master plan, for example, states that the city-wide canopy cover should reach 30% by 2020 (Miami Green Commission 2009). The City of Alexandria, VA, Tree City USA since 1982, developed an urban forestry master plan in the late 2000s (Kincannon and Blakeley no date) which follows the canopy cover recommendation by American Forests (American Forests 2006) and sets an urban canopy cover goal of 40%. In addition, the City's master plan recommends to plant 400 additional trees per year on all types of public lands especially school grounds. Canopy cover goals, such as those by American Forests, a nonprofit conservation organization, have been widely used as they aid to maintain a minimum threshold of urban canopy cover to help meet environmental goals as well as quality of life. Besides supporting tree planting programs and improving the status of a municipality through community involvement, tree canopy cover can play a big role to improve nonattainment areas for airborne pollutants such as ozone or fine particle matter. The Environmental Protection Agency (EPA) identified nonattainment areas for these pollutants for Virginia such as Arlington, Fairfax, and Prince William County. Increasing tree canopy cover to help improve air quality would be extremely important in these areas because their air quality does not meet the National Ambient Air Quality Standards (NAAQS) (see EPA 2010 for more information on NAAQSs).

However, setting canopy goals requires knowledge of the current status of the urban forest as well as the functions the urban forest should provide. Moreover, canopy cover planning must account for environmental constraints to tree growth rate and longevity. Because urban soil conditions are often poor and can vary greatly, capacity to augment canopy cover can be vastly overestimated, particularly in dense urban centers. In addition, one may not know what the prevailing soil quality and below-ground constraints are and whether a particular tree species' needs are met. Thus the longevity and health of urban trees may be jeopardized from the start and the accomplishment of canopy goals may be difficult.

Urban tree conditions and needs

Over the 20th century we gained much knowledge on forest trees, such as growth predictions of forest trees, economic impacts, and long-term economic forecasting, but this knowledge often does not translate well to urban areas because of extreme differences between forest and urban environments. Urban trees, as opposed to rural trees, are most often exposed to a rather hostile environment. Air quality as well as soil quality is generally impaired due to anthropogenic activities, such as vehicular traffic and industrialized manufacturing. Even climate is altered from rural conditions to a warmer climate with less solar radiation and humidity yet more clouds and precipitation (Heidt and Neef 2008). Changes in climate in combination with factors such as vandalism and disease infestations as well as poor soil quality impair the structure and function of the urban forest. Thus, life expectancy of urban trees is generally low compared to their counterparts in the rural environment (Nowak et al. 2004; Nowak et al. 1990; Roman 2006). This low life span and high mortality significantly influences the integrity of the urban forest and the level and range of benefits these urban trees can provide and indicates the need for attention and management urban trees deserve.

Although urban trees are known to provide many ecological, economical, and social benefits, such as improving the urban climate, providing aesthetic value, and increasing tourism, little attention has been given to the conditions urban trees are expected to thrive in. Many urban trees are planted in unsuitable conditions and thus doomed to failure.

Urban Tree Mortality and Longevity

One hindrance to reaching canopy cover goals is simply the high mortality of urban trees. Early tree mortality in Berkeley/SanFrancisco, CA, has been found to be ca. 20% per year with the main reasons being physical damage through poor staking techniques, vandalism, and traffic injury (Nowak et al. 1990). Trees located in areas with high unemployment rates as well as trees in areas of high-density land use (apartment buildings and public greenspace) can experience higher mortality rates, which suggests that lower funds for tree care as indicated by lower income (Nowak et al. 1990) may result in poorer site quality, tree care, and maintenance. Similarly, analyses for Baltimore, MD, revealed that two of the main reasons for tree mortality are poor tree health and adjacent land use (Nowak et al. 2004). Younger trees often experience high mortality during pre-establishment period (about 7%), which could be counteracted by adequate management, such as watering and fertilization. High density land use resulted in higher mortality as well as poor site quality. Based on mortality and natality rates, canopy cover in Baltimore, MD, is projected to decrease over the next century (Nowak et al. 2004). Street trees in Philadelphia may experience a mortality rate of 56% less than a decade after planting, depending on cutout area and sidewalk conditions (Roman 2006). It becomes clear that knowing the site conditions and providing the tree with a suitable below ground environment could significantly improve tree survival, especially in the early years.

In addition to high mortality in the early years of a tree's life, urban tree life expectancy is also generally short. Foster and Blaine (1978) identified the average survival rate for trees planted in sidewalk cutouts in Boston, MA, to be only 10 years with soil disturbance through construction works, water stress, and physical damage by cars often followed by fungal infections as the main contributors to tree death. Although lifespan estimations by Nowak et al. (2004) exceed those by Foster and Blaine by five years, it becomes clear that the expected lifespan of urban trees is far from their genetic potential. In addition, these high mortality rates and short lifespan of urban trees show that many planted trees will not provide the range and magnitude of benefits they genetically could provide. Many problems with urban tree health result from unsuitable soil conditions.

Urban Soils and their (Un)suitability

Urban soils often possess physical and chemical properties unsuitable for trees to grow to their potential. Urban soils are generally too shallow to support trees with adequate moisture, nutrients, rooting space and anchorage (Jim 1998a). In addition, urban soils are generally of poor structure and highly compacted hindering root growth even more (Jim 1998a). Soil organic matter and soil chemical properties such as microbial biomass N, extractable phosphorus and potassium are often low in newer urban areas (Scharenbroch et al. 2005). In addition, high variability of urban soils (De Kimpe and Morel 2000; Jim 1998b) can make tree management very difficult because a) general knowledge about the prevailing conditions may not be sufficient for designing adequate tree plantings and b) soil measurements representative of the prevailing conditions may be difficult due to the amount of measurements needed to incorporate the high variability. However, many (below-ground) factors have been identified to influence tree growth, which should justify their consideration in planning and management of urban forests.

Available Soil Volume

Soil volume and cutout size (exposed soil surface area) have been found to influence urban tree growth, although these effects can vary by species and region (Grabosky and Gilman 2004; Day and Amateis in review). Kent et al. (2006) evaluated the conditions of various tree species, including *Acer rubrum*, *Magnolia grandiflora*, and *Quercus virginiana*, growing in varying soil volumes in a major parking lot in Orlando, FL. They found a significant effect of soil volume on tree conditions. Trees growing in less than 2.8 m^3 of soil were more likely to be in poor condition or have died prematurely. On the other hand, the majority of trees growing in at least 28 m^3 of soil and all trees growing in a minimum of 42 m^3 of soil were in good condition.

The influence of available soil volume on tree growth and health has resulted in soil volume recommendations of 0.3 m^3/m^2 crown projection (CP) (Lindsey and Bassuk 1992) or more (Vrecenak and Herrington 1984; Helliwell 1986). Although these recommendations are impractically high for many urban landscapes and are based on tree water demand rather than tree growth, it becomes clear that most conventional tree planting sites, such as sidewalk tree pits or parking lot islands, offer insufficient soil volume to support long-term tree growth. In addition these sidewalk tree pits are surrounded by compacted soil to meet engineering standards for road and sidewalk construction or are lined with concrete to prevent sidewalk heaving by roots (Figure 2.1).

Figure 2.1 A bad example of a street tree planting; downtown Blacksburg, VA. The root ball has been trimmed to accommodate for a utility box, the planting pit is very small thus providing only little soil for the tree and the planting pit is aligned with concrete to contain the roots. The growing condition for this tree is poor jeopardizing the survival potential of the tree.

Soil Physical Conditions

Compaction is a common problem for urban trees surrounded by hardscape because the underlying soil must be compacted to provide high load-bearing capacities to prevent pavement failure (Grabosky and Bassuk 1995; Alberty et al. 1984; Pan and Bassuk 1985). As a result, root growth, hydration, and aeration are hindered. Soil compaction as well as bulk density is buffered by soil organic matter (Soane 1990). Soil organic matter not only improves soil physical properties such as soil strength, soil structure, porosity, and water holding capacity, it also nourishes soil microorganisms and thus plants (Brady and Weil 2002d). However, urban soils often lack organic matter because top soil is generally removed during building and road construction (Alberty et al. 1984). This low soil organic matter content then results in low or no organic-matter decomposition and thus insufficient plant nutrients (Jim 1998a).

Soil Chemical Conditions

Nutrient levels within the urban environment can be quite different from the rural environment through atmospheric nutrient deposition as well as lack of organic matter. Nitrate and phosphorus can be elevated through deposition which likely influence biodiversity and thus performance of urban ecosystems (Power and Collins 2010). On the other hand, as mentioned earlier, nutrient levels may be low due to a lack of organic matter and the resulting decrease in mineralization of nutrients available to trees (Jim 1998a). This may greatly influence tree development because nutrients such as nitrogen, phosphorus, potassium, calcium, and magnesium are essential to plant growth since they are constituents of many organic compounds and integral to metabolic processes such as photosynthesis and respiration (Finck 1991; Mengel and Kirkby 2001; Pallardy 2008). Nitrogen has been found to positively correlate with urban site quality within regions, but little variation has been demonstrated between urban landscapes regionally (Scharenbroch and Lloyd 2006).

Available soil nutrients oftentimes depend on soil pH. Soil alkalinity can cause deficiencies of micronutrients such as boron, copper, iron, manganese, and zinc in many tree species (Mengel and Kirkby 2001). Although most trees are adapted to low pH (<7), urban soils are often alkaline (Scharenbroch et al. 2005) due to the use of concrete and other calcareous materials in buildings and sidewalks (Jim 1998b). As a result, tree species and cultivars tolerant of alkaline soils are often recommended for urban plantings (Appleton and Chaplin 2001; Bassuk et al. 2003).

Much work has been done to identify the (soil) factors that influence tree growth and survival. Cutout size and soil volume, as well as soil pH, available soil nutrients, and soil organic matter may influence tree growth significantly. Yet soil properties can vary greatly among and within cities. Standardized protocols to measure these tree-growth-influencing soil variables and produce reliable and comparable data are still lacking. It is also unclear how these variables influence tree growth and there is therefore a lack of tree growth models that take these tree-growth-influencing factors into account to confidently predict tree growth and the suitability of an urban tree planting design. The following section gives an overview of the urban tree growth models that have been developed.

Urban tree growth models

To reach canopy cover goals, many municipalities use general guidelines of eventual tree crown dimensions for common urban tree species. However, these guidelines are generally not research-based, but rather based on anecdotal observations of trees growing in parks or other settings that do not represent conditions in highly urbanized sites. These documents can be acquired from various sources such as the Virginia Nursery and Landscape Association (VNLA) (no date) or the Chicago Botanic Garden (no date) as well as Michael Dirr's 'Manual of Woody Landscape Plants' (Dirr 1998) or Appleton and Chaplin's 'The New York/Mid-Atlantic Gardener's Book of Lists' (Appleton and Chaplin 2001). These publications are useful guidelines because they give general information about the species' potential to reach certain sizes at maturity; *Acer sacchrum*, for example, has an 'estimated' crown spread of 4.8-6.1 m at age 20. However, these guidelines do not take impoverished urban site conditions into account and thus the potential of a tree actually reaching the 'estimated' size may be slim. This average may over- or even underestimate the eventual tree size depending on the particular site. Either scenario, however, may lead to tree removal and replacements rather than long-term canopy cover and the associated provision of benefits. To confidently predict tree growth, empirical growth-prediction modeling is necessary that incorporate the variability found in urban settings.

Many growth-prediction models have been developed for the rural environment to estimate above-ground biomass to maximize timber production. However, these models are not easily, if at all, transferable to the urban environment (Peper and McPherson 1998). Many of these models have wide prediction ranges, ca. 100-200%, (McHale et al. 2009) which shows the need for prediction models that focus on urban street trees to allow for confident management of healthy urban forests.

Urban tree growth models (Summary table 2.1) include:

a) Tree growth models based on tree parameters
b) Tree growth models based on resource requirements by trees
c) Models of urban tree physical dimensions and ecological functions

Tree growth models based on tree parameters

Starting in the late 1980s and still today, researchers have sought to develop models to predict urban forest biomass from metrics of existing trees. Vrecenak et al. (1989) evaluated 50-80 tree species including *Acer rubrum*, *A. saccharinum*, *A. saccharum*, and different *Fraxinus* and *Tilia* species in Central New Jersey to develop growth ratio indices (average yearly growth). Variables used for this analysis were house setback, presence or absence of competition, amount of open space between the sidewalk and the curb surrounding the tree, and percent permeable surface beneath the crown. They found significant linear relationships with site factors explaining a maximum of 14% of the variation in average yearly growth.

Nowak (1996) developed regression equations to predict leaf area and leaf biomass of urban trees from readily obtained tree measurements. They focused on common open-grown park tree species, such as *Ulmus americana*, *Fraxinus pennsylvanica*, *Gleditsia triacanthos*, and *Acer platanoides.* Fifty-four small to medium-sized trees were sampled. Tree height, diameter at breast height (DBH), height to base of live crown, crown width, crown volume, and sample leaf area data were used for model development. For the trees sampled, crown parameters were found to be more reliable predictors for leaf area and leaf biomass (R^2>0.90) then DBH (R^2<0.65). Two years later, in 1998, Nowak and Crane developed UFORE (The Urban Forest Effects Model), which has since been incorporated into the urban forest assessment software, i-Tree Eco. Part of UFORE quantified the forest structure including leaf area and leaf biomass of an urban forest. The models use vegetation data as well as local meteorological and pollution-concentration data and have been utilized to quantify the urban forest structure for a number of cities, such as Baltimore, MD, Atlanta, GA, and New York City. However, it is unclear what type and quality of data were used to develop the initial model.

Banks et al. (1999) used survey data to determine the relationship between species, crown health, diameter at crown break, age, crown diameter and tree height to estimate growth and canopy dimensions of 340 street tree species in Canberra Australia. They assumed sigmoidal growth curves and used regression analysis to determine that total height of the trees was well correlated with age and other parameters of interest and the model was significant with a coefficient of determination of 0.54. Peper at al. (2001a, b) evaluated 12 species, including *Zelkova serrata*, *Platanus* x *acerifolia* and *A. saccarinum,* in Modesto, CA as well as 16 species, including *Ficus macrocarpa*, *Jacaranda mimosifolia*, and *Magnolia grandiflora*, in Santa Monica, CA. Their goal was to develop prediction models for DBH based on age, as well as for tree height, crown diameter, crown height, and leaf area based on DBH. Logarithmic regression models were used for all variables except leaf area predictions for which a nonlinear exponential model was used. They found strong correlation between total height, crown diameter, and leaf area with DBH (R^2>0.70) for many species and weaker correlations between crown height and DBH.

Larsen and Kristoffersen (2002) used tree age to develop prediction models for tree height, trunk height, crown base height, DBH, and crown radii for 251 urban and 80 nursery tree within the *Tilia* genus, including *T. cordata* and *T. europaea*. Regression analysis showed quadratic relationships between age and size variables with coefficients of determinations of >0.9. Taking into account the results of their project with the short life span of most urban trees (Foster and Blaine 1978; Nowak et al. 2004), the authors conclude that "within the actual life span of urban trees, it will be difficult to obtain the expected architectural and aesthetic function" (Larsen and Kristoffersen 2002). Stoffberg et al. (2008) studied the relationships of tree age to tree height and crown dimensions for *Combretum erythrophyllum*, *Sersia lancea*, and *Searsia pendulina*, three indigenous species to the City of Tshwane, South Africa, where the study was conducted. Seventy to 105 trees per species were evaluated. Tree height and crown dimensions were regressed on age. Growth models resulted in a coefficient of determination of 0.54 to 0.74. Although different tree growth models have been developed, even for the urban environment, only a few have focused on growth-influencing resources.

Tree growth models based on resource requirements by trees

In addition to estimating tree biomass based on tree parameters, such as DBH, tree growth can also be estimated based on the resources a tree needs. Lindsay and

Bassuk (1992) developed models that predict how much soil is needed by an urban tree in order to provide soil water sufficient for its growth. They calculated water losses of trees based on their relationship to pan evaporation. A 20% adjustment ratio of pan evaporation to tree transpiration was used in addition to crown and climate characteristics. They determined a soil volume of 0.3 m^3/m^2 canopy projection to be necessary to support tree growth, or more general, 5 m^3 of available soil for a medium-sized tree (Lindsey and Bassuk 1992). Other study results (Helliwell 1986; Vrecenak and Herrington 1984) suggest that 0.3 m^3 available soil volume per m^2 crown projection may be considered a minimum threshold for volume to support tree growth. Besides estimating tree growth for the sake of knowing its size, tree size can be estimated to predict the functions or benefits a tree can provide.

Models of urban tree physical dimensions and ecological functions

Ecosystem services, such as carbon sequestration or pollutant removal from soil or water, are important functions of trees, especially in the urban environment. Estimating the monetary worth of these benefits is a useful tool for evaluating the value of the urban forest. Based on the value of the ecological contributions urban trees provide, management and maintenance of urban trees may be better justified. Besides estimating above-ground biomass, the UFORE model also estimates the ecological contributions a tree makes Nowak and Crane (1998). For example, this model estimates annual carbon sequestration and pollution removal as well as volatile organic compound (VOC) emissions by trees and shrubs. Species leaf biomass (calculated by another module of UFORE) is multiplied by genera-specific emission factors from the literature to calculate emission levels a tree exudes. Carbon storage is estimated by calculating the above-ground biomass of a tree (78% of total biomass) and carbon sequestration over time includes average diameter growth. Air pollution removal (ozone, sulfur dioxide, nitrogen dioxide, and carbon monoxide) is estimated by incorporating pollutant flux, deposition velocity, canopy resistance, and other (climate and tree) factors in the equation.

Using these models, Nowak and Crane estimated for the year 1994 that urban trees in New York City provided ecological benefits through pollutant removal with a value of $10 million, those in Atlanta, GA, of $6 million and urban trees in Baltimore, MD, provided $3 million worth of benefits. More than 10 other cities have been analyzed using UFORE. They found wide-ranging tree densities (22.5-275.8 trees/ha) with percent canopy cover of 8.9 to 36.7% (Nowak et al. 2008), which indicates generally different levels of benefits provides by these urban forests. However, most estimates of tree functions by UFORE are based on the underlying model for leaf area. Thus if this model is inaccurate, all estimates would be inaccurate. Confident tree growth/leaf area estimations are therefore highly desirable. McHale et al. (2009) estimated the carbon storage capacity of nine tree species, including *Fraxinus pennsylvanica* and *Gleditsia triacanthos*, in Fort Collins, CO. They used DBH as well as crown volume, the latter estimated via LIDAR, to compare biomass predictions from allometric relationships developed for urban areas to predictions from allometirc equations from traditional forests and found that most equations from the literature misestimated by about 100% (McHale et al. 2009).

It becomes clear that, although these models are very informative and useful in urban forest planning and management, they fail to incorporate soil characteristics despite the fact that tree growth, health, and longevity have been proven to be significantly influenced by a variety of soil factors.

Literature synthesis

Trees are an important component of the urban environment. Trees provide many benefits such as cleaner soil, water, and air, shade and related temperature modifications and other valuable benefits. Urban trees are therefore an essential factor that counteract (anthropogenic) pollution and improves the quality of living. Many municipalities define canopy goals to be reached within a certain time period, e.g. 20 years, to improve and further sustain these benefits. Urban tree growth models would be a useful tool to determine the growth of a particular tree and its future contribution to urban canopy cover. However, there are no urban tree growth models available that incorporate soil characteristics despite the fact that the urban soil is the single most tree-growth influencing factor that a) affects all trees and b) can be evaluated prior to tree planting. One factor making adequate urban soil evaluations difficult is the high variability of soil characteristics found within cities. In addition, tree requirements and tolerances to soil conditions are not only expected to differ by tree species, but also by climate region and general soil texture.

To help fill these gaps in our knowledge about urban trees, my objectives were therefore to evaluate soil properties for variability across and between cities as well as the reliability and practicality of the measurements, to determine which soil variables influence tree growth significantly, and to develop urban growth prediction models based on these soil properties for three common urban tree species growing in two generally different climatic regions and original soil texture classes.

Table 2.1 Overview of urban tree prediction models from the literature

TREE SPECIES (# PER SPECIES)	LOCATION	RESPONSES	PREDICTORS	CITATION
Combretum erythrophyllum (105) *Searcia lancea* (107) *Searcia pendulina* (70)	City of Tshwane, South Africa	Tree height crown dimensions	age	(Stoffberg et al., 2008)
Acer rubrum *Acer saccharinum* *Acer saccharum* *Fraxinus sp.* *Gleditsia triacanthos* *Platanus* x *acerifolia* *Quercus palustris* *Tilia* sp. (50-80 each)	Central New Jersey	-growth ration index	-Distance from road to the house (house setback) -Presence or absence of competition -amount of open space b/w sidewalk and curb surrounding the tree -%permeable surface beneath crown	(Vrecenak et al., 1989)
340 (total # 165,000 trees)	Canberra, Australia	-growth -canopy dimensions - goal: to determine future arboriculture work	-Species -crown health -diameter at crown break -height of max. crown width -diameter at max crown width -age	(Banks et al., 1999)
Various, model by species	General “small forests”	Diameter increment	DBH growth curves	(Mawson, 1982)
8 open-grown deciduous trees	Northern California,	Foliar- and above-ground	Methods comparison with actual biomass: • Nowak 1996	(Peper and McPherson, 1998)

Table continuing

TREE SPECIES (# PER SPECIES)	LOCATION	RESPONSES	PREDICTORS	CITATION
12 species (incl. zelkova) -stratified random samples by age group 341 trees	Modesto, CA	dbh → Height, crown → diameter, crown height, and leaf area	from tree age from dbh	(Peper et al., 2001a)
16 species Stratified random samples by planting dates Ideally, 6-8 trees per species and age class	Santa Monica, CA	dbh → Height, crown → diameter, crown height, and leaf area	from tree age from dbh	(Peper et al., 2001b)
Tilia cordata *T. europaea* *T. euclora* *T. platyplyllos* (251 urban trees plus 80 nursery trees)	Copenhagen, Denmark	Tree height, trunk height, crown base height, dbh, crown radii,	age	(Larsen and Kristoffersen, 2002)
	UFORE (Used world wide)	-Leaf area -tree and leaf biomass etc -air pollution removal, C sequestration etc	-species composition -# of trees -diameter distribution etc -local env. data	(Nowak and Crane, 1998; Nowak et al., 2008)
many	Virginia	Canopy spread	after 10 and 20 years	(VNLA, no date)

Table continuing

TREE SPECIES (# PER SPECIES)	LOCATION	RESPONSES	PREDICTORS	CITATION
Pinus taeda L.		- Net photosynthetic rate by SI class from a process-based model (MAESTRO) to modify growth and yield predictions from PTAEDA2		(Baldwin et al., 2001)
Parameters were estimated to represent Pinus *contorta* Dougl. Ex. Loud. (lodgepole pine)		Productivity Height growth	Basis "C allocation is regulated to maximize C gain"	(Buckley and Roberts, 2005)
Ulmus americana (10) *Fraxinus pennsylvanica* Marsh. (10) *Gleditsia triacanthos* L. (10) *Celcis occidentalis* L. (10) *Acer platanoides* L. (14)		Leaf area Leaf biomass	-Dbh, tree height, height to base of live crown, crown width - crown volume was calculated from geometric measurements - subsample of leaves 0.4m^3, leaves were counted - 30-40 leaves were analyzed for leaf area and extrapolated to the individual sample	(Nowak, 1996)
Fraxinus pennsylvanica *Gleditisa triacanthos* 9 other species	Fort Collins, CO	Volume and biomass Carbon storage capacity	Dbh LIDAR for crown volume	(McHale et al., 2009)

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Chapter 3: A Critical Evaluation of Soil Measurement Techniques for Assessing Urban Tree Planting Sites

Introduction

Large, long-lived trees are important for a sustainable urban environment, yet trees living in harsh urban settings often do not achieve this large stature and thus fall short of providing anticipated ecosystem services. Many trees die prematurely due to unsuitable below- and above-ground conditions (Bassuk et al. 1998), while others outgrow their space and must be removed due to infrastructure damage and land use conflicts (McPherson 2000). Trees provide a long list of ecosystem services such as improved air quality (Akbari et al. 2001), increased property values (Martin et al. 1989), reduced crime (Kuo and Sullivan 2001), reduced noise (Fang and Ling 2003), improved water quality (Nowak 2005), faster recovery time of hospital patients (Ulrich 1984), and other valuable benefits. Many municipalities therefore set tree canopy cover goals (the % land surface area covered by tree canopy, often within a specific period of time, e.g. 15 or 30 years), to ensure provision of these benefits. However, most benefits, such as improving air quality, are proportional to leaf area and thus the size of the tree (McPherson et al. 1998). To maximize urban tree utility, it is thus essential to provide them with a growing environment that optimizes survival, canopy development, and longevity.

Tree growth, and thus canopy development, depends upon the availability and doses of four factors: air, light, water and soil. An imbalance in any of these factors can limit tree growth. While some may not be easily optimized, soil quality can be improved substantially prior to tree planting and therefore have profound impacts on tree growth and development. However, despite its crucial role in tree growth and ecosystem function, soil quality has received limited attention – and thus monetary resources – in the management of urban forests and related environments.

One possible impediment to broad-based urban soil management is the lack of standardized procedures for assessing soil characteristics that influence urban tree growth. To efficiently evaluate planting site soils for projecting tree growth and development, three things are essential. First, soil characteristics most predictive of urban tree growth must be identified to ensure the correct variables are measured. Second, the variability of these soil characteristics within a city and across cities must be quantified to guide sampling intensity decisions. Third, an efficient and practical measurement technique must be selected to ensure it is financially and technically accessible to practitioners. If conventional techniques are not practicable in urban settings, then alternative methods must be developed.

Much work has been done to identify environmental factors that influence forest tree growth. However, natural and urban forest environments differ substantially, which can limit the utility of traditional site assessment techniques. At a broad scale, temperature and precipitation varies across (metropolitan) regions influencing tree growth in various ways. Within cities, building and road construction, foot and vehicular traffic, and other factors such as air pollution and the urban heat island influence the microclimate and thus tree growth at a particular site. These same issues will play a role in tree response to soil factors. However, unlike natural soils, urban soils consist of a wide range of endogenous and exogenous materials (Alberty et al. 1984). Furthermore, urban soils often comprise a succession of layers that are not parallel to the soil surface and differ dramatically depending on their origin and composition (De Kimpe and Morel 2000; Jim 1998a). Tree species differ in their tolerance of environmental conditions and response to growth-influencing factors. Thus it may be necessary to differentiate the known tree growth-influencing factors by both species and geographic location to confidently evaluate tree plantings. However, variability of urban soils can be high even across short distances. Although their variability may be high, soil factors of possible interest in a site assessment due to their influence on tree growth can be identified from previous research.

Soil volume and exposed soil surface area (area of exposed soil surface in a planting site surrounded by pavement, such as sidewalk "tree pit") strongly influence urban tree growth, although these effects can vary by species and region (Grabosky and Gilman 2004; Day and Amateis in review). Kent et al. (2006) evaluated the conditions of various tree species, including *Acer rubrum*, *Magnolia grandiflora*, and *Quercus virginiana*, growing in varying soil volumes in a major parking lot in Orlando, FL. They found a significant effect of soil volume on tree conditions. Trees growing in less than 2.8 m^3 of soil were more likely to be in poor conditions or have died prematurely. On the other hand, the majority of trees growing in at least 28 m^3 of soil and all trees growing in a minimum of 42 m^3 of soil were in good condition. The influence of available soil volume on tree growth and health has resulted in soil volume recommendations ranging from 0.3 m^3/m^2 crown projection (CP) (Lindsey and Bassuk 1992), over 0.6 m^3/m^2 CP (Vrecenak and Herrington 1984) and 0.76 m^3/m^2 CP up to 1.71 m^3/m^2 CP (Helliwell 1986), the latter two recommendations being adapted from interpretations of the model presented by Lindsey and Bassuk. Although these recommendations are impractically high for many urban landscapes and are based on tree water demand rather than tree growth, it becomes clear that most conventional tree planting sites, such as sidewalk tree pits or parking lot islands, offer insufficient soil volume to support long-term tree growth. In addition these sidewalk tree pits are surrounded by compacted soil to meet engineering standards for road and sidewalk construction.

Compaction is a common problem for urban trees surrounded by hardscape because the underlying soil must be compacted to provide high load-bearing capacities to prevent pavement failure (Grabosky and Bassuk 1995; Alberty et al. 1984; Pan and Bassuk 1985). As a result, root growth, hydration, and aeration are hindered. Soil strength influences plant growth similarly to bulk density (Thompson et al. 1987; Sands et al. 1979). High soil strength has been found to decrease primary and lateral root length (Misra and Gibbons 1996), root elongation (Ehlers et al. 1983), and leaf area (Masle and Passioura 1987). Soil strength as well as bulk density are buffered by soil organic matter (Soane 1990). Soil organic matter not only improves soil physical properties such as soil strength, soil structure, porosity, and water holding capacity, it also nourishes soil microorganisms and thus plants (Brady and Weil 2002d). However, urban soils often lack organic matter resulting in low or no organic-matter decomposition and thus insufficient plant nutrients (Jim 1998a).

Macronutrients such as nitrogen, phosphorus, potassium, calcium, and magnesium are essential to plant growth as they are constituents of many organic compounds and integral to metabolic processes such as photosynthesis and respiration (Finck 1991; Mengel and Kirkby 2001; Pallardy 2008). Nitrogen has been found to positively correlate with urban site quality within regions, but little variation has been demonstrated between urban landscapes regionally (Scharenbroch and Lloyd 2006). Availability of soil nutrients oftentimes depend on soil pH. Soil alkalinity can cause deficiencies of micronutrients such as boron, copper, iron, manganese, and zinc in many tree species (Mengel and Kirkby 2001). Although most trees are adapted to low pH (<7), urban soils are often alkaline (Scharenbroch et al. 2005) due to the use of concrete and other calcareous materials in buildings and sidewalks (Jim 1998b). As a result, tree species and cultivars tolerant of alkaline soils are often recommended for urban plantings (Appleton and Chaplin 2001; Bassuk et al. 2003).

A range of soil variables likely influences tree growth in cities including a variety of physical and chemical factors. Some of these are straightforward to measure, such as cutout area, while others, such as soil compaction, are more difficult to measure. In addition, the potentially high variability across a city is not easily discernible. Sampling intensity within a municipality should ideally be based on observed variability in soil characteristics. Although it is impractical to evaluate every tree planting site within a municipality, it is equally unwise to make broad generalizations about soil quality based on an insufficient sample size. Developing site assessment techniques that are practical and efficient yet provide accurate, comparable, replicable, and meaningful data is critical to understanding soil properties that may influence the growth and survival of urban trees.

The objective of this study was to evaluated urban street tree plantings in two cities of differing climates and native soils– Washington DC and Jacksonville, FL – based on the following hypotheses:

- Soil physical and chemical properties vary across cities
- Sampling and analysis of these variables is very resource intensive
- Reliability, practicality, and relevance of soil physical and chemical variables can be are evaluated to make recommendations for or against their inclusion in urban tree planting site assessments

Materials and Methods

Pilot Study

To develop and refine the measurement protocol, a pilot project was conducted in the City of Roanoke, VA (lat. 37° 21' 11" N, long. 79° 58' 41" W) in April 2008. Twenty-five urban tree planting sites were selected within the city and sampled for 22 soil chemical and physical properties using conventional measurement techniques, which were simultaneously evaluated for their practicability in the urban environment. Methods that proved practicable were refined as necessary prior to the full-scale study. It was predetermined that soil measurement methods that rendered inaccurate data (not replicable upon repeated measure, or physically impossible to carry out at typical tree planting sites) during the pilot study were to be discarded from our protocol and not further evaluated. Methods employed in the pilot study are described in the following section (Washington, DC and Jacksonville, Florida studies: Soil Measurements) with the exception of soil bulk density, which was evaluated in the pilot study only. To measure bulk density, a soil core sampler (AMS, Inc., American Falls, ID) was used to extract 5-cm diameter cores from the soil in 10 cm intervals until the bottom of the tree pit was reached. Core samples were then oven-dried at 65° until mass stabilization and weighed.

Regional Studies

Site Description

In summer 2008, soils of 184 urban tree planting sites were evaluated in two cities—Washington, DC (lat. 38° 54′ 10″ N, long. 77° 01′ 45″ W) and Jacksonville, FL (lat. 30° 20′ 02 N, long. 81° 39′ 46 W). These study sites were selected because they provided two different climatic conditions as well as regionally distinct soils. Washington, DC is located in USDA hardiness zone 7 (mean annual low temperatures of -12 to -18°C) whereas Jacksonville, Florida is located in USDA hardiness zone 9 (mean annual low temperature of -1 to -7°C) (Cathey 1990). The soil in Jacksonville is predominantly sandy according to urban soil surveys (NRCS 2010a) while in Washington DC loamy soil predominates (NRCS 2010b).

Planting sites of three tree species were evaluated throughout the respective cities: 42 *Quercus phellos* (willow oak) and 42 *Zelkova serrata* (Japanese zelkova) in Washington, DC and 100 *Quercus virginiana* Mill. (live oak) in Jacksonville, FL. Only soils of trees growing in confined spaces surrounded by hardscape (e.g. buildings, sidewalks, roads) were assessed. *Q. phellos* had a mean diameter at breast height (DBH, measured at 1.3 m above the ground) of 36.6 cm. Their mean age was 24.6 years. The mean age of *Z. serrata* was 22.7 years and their DBH averaged to 27.7 cm. *Q. virginiana* which were growing in Jacksonville, FL, had a mean DBH of 28.4 cm and a mean age of 16.8 years, ranging from 8 to 30 years.

Soil Measurements

Soil physical properties Soil strength was measured with a cone penetrometer (SC 900 Soil Compaction Meter, Spectrum™ Technologies, Inc.). Penetrometer measurements were taken at three locations within each tree planting site. To evaluate different soil layers, measurements were recorded at 2.5 cm intervals until the bottom of the tree pit was reached. For analysis of gravimetric moisture content and soil texture, a composite soil sample (10-cm depth increments) from a minimum of 3 locations within each tree planting site was collected with a 22-mm diameter soil probe. In addition, volumetric soil water content was measured at two to three locations per site *in situ* at 0-20 cm using a time domain reflectometer (FieldScout TDR 100, Spectrum Technologies, Inc., Plainfield, IL). Soil texture was determined via particle size analysis using the hydrometer method including organic matter removal with hydrogen peroxide (Day 1965).

Soil volume and exposed soil surface area Tree planting soil depth was measured with a graduated metal rod pushed into the ground until very high resistance was met (i.e. it was impossible to push it further manually), which was assumed to be the bottom of the tree pit. Measurements were taken on 3-5 locations within each planting, depending on tree pit size. Exposed soil surface area of the tree planting was assumed to represent the horizontal dimension of the soil volume and was measured with a measuring tape in two directions when the tree planting shape was rectangular. More complex shapes were broken down into easy-to-calculate geometric shapes for area calculations.

Soil chemical constituents Plant available soil nutrients, cation exchange capacity (CEC), organic matter content, pH, and soluble salts were analyzed by the Virginia Tech Soil Testing Laboratory, Blacksburg, VA. Plant available nutrients (excluding N) were analyzed by elemental analysis on Mehlich-1 extracts by using inductively coupled plasma (ICP) spectroscopy. Organic matter was analyzed via loss on ignition. Analyses were done on composite surface soil samples (0-20 cm). Surface soil was chosen as the majority of nutrient-absorbing tree roots are commonly found here in urban settings (Day et al. 2010). Total nitrogen and total carbon were measured by dry combustion with an automated gas combustion analyzer (Elementar VarioMax CNS, Hanau, Germany). Inorganic nitrogen was analyzed via KCL extraction (Bremner 1965) and an auto analyzer (TRAACS 2000 Analytical Console, Bran-Luebbe, Nordersted, Germany).

Statistical analysis

To permit comparisons of variability in soil properties, the coefficient of variation (CV=sample standard deviation · sample mean^{-1}) was calculated for each property. Variability was considered high when CV ≥1 (i.e., the standard deviation equaled or exceeded the mean).

Results and Discussion

Pilot Study

During our pilot project, we determined that accurate bulk density sampling to evaluate soil compaction is impractical and unreliable in street tree planting sites. This is due to obstruction by tree roots and other objects such as gravel, rocks, asphalt, and trash mixed in with the soil. Root systems of mature trees were often densely packed in the tree planting site such that soil cores could not be extracted, but even younger tree root systems were sufficiently dense so as to make extraction of bulk density samples difficult. We therefore discarded this approach for characterizing soil compaction and opted to instead measure soil strength via penetrometer. All other soil measurements were deemed practical during our pilot study and were evaluated in the regional study.

Regional Studies

Soil texture

Soil texture variability across sites

Soil texture measurements of all depths generally agreed with soil survey data, which categorize soils in Washington, DC as loamy and those in Jacksonville, FL as sandy (Table 3.1). The vast majority of soil samples in Washington (99%) were categorized as loamy (sandy loam, loam, silt loam, and sandy clay loam). Soils in Jacksonville, FL were mainly (90%) sand and loamy sand. The remaining 10% were categorized as sandy clay loam, sandy loam, and loam. This agrees with findings of Park et al. (in press) who evaluated urban soils classified as silt loams by the NRCS and found different soil texture classes, such as silt loam, loam, and sandy loam.

Soil texture has a major influence on root growth-limiting soil compaction (Daddow and Warrington 1983) as well as nutrient and water holding properties (Brady and Weil 2002a, b). Sandy soils generally have a low cation exchange capacity (Brady and Weil 2002a), low water-holding capacity, high infiltration rate (Brady and Weil 2002b), and high growth-limiting bulk density (Daddow and Warrington 1983) compared to loams. It is therefore important to know the soil texture of a given planting site in order to evaluate its tree growth limitations. With that said, we found that surface soil texture in our two cities was dominated by two to three closely related textural classes, which suggests that soil texture for a given locality could be reliably predicted from NRCS surveys or limited field sampling.

Practicability of soil texture analyses

Soil texture is a highly static soil property and can therefore be properly measured under all ambient conditions. However, depending on the method used, it can be very resource intensive and the usefulness of the data may not justify the cost. Some methods not only require specialized tools and lab consumables (e.g. pipette method (Burt 2004b) and hydrometer method (Day 1965), but the laboratory processes are also very time consuming. Both the pipette and hydrometer methods require removal of soil organic matter if its fraction exceeds 5%, which in itself is difficult to determine because the type of soil, its origin, and composition dictate the appropriate organic matter removal method. Soil texture analysis of urban tree plantings would therefore we very difficult and thus not practical. We therefore chose to remove organic matter regardless of its fraction. Hydrogen peroxide (H_2O_2) with a 30% concentration is generally recommended for this procedure (Mikutta et al. 2005). It is however difficult to determine in advance how much H_2O_2 is needed per sample because it depends on the organic matter content and composition, although the range is typically between 25 and 75 ml per sample. In addition, each sample needs to process between 1 hr and 3 days, depending on organic matter content and composition. Laboratory sequencing can therefore make this an extremely time-consuming, and therefore costly, procedure.

Other procedures for texture analysis may only estimate particle size distribution, but do not necessarily require special equipment. Texture-by-feel (NRCS no date), for example, is a widely used field method to estimate soil texture in the field. It does not require special equipment, the removal of organic matter, or a lot of time. The "Mason Jar Method" (Sammis 1996) relies on the differential settling rate of soil particles suspended in water to provide an estimate of silt, clay, and sand content. It requires more time than texture-by-feel, but may be a suitable compromise for soil texture analysis.

In summary, soil texture is important to tree growth as nutrient and water availability as well as physical limitation to root growth is influences by soil texture. Although urban soil can vary greatly (De Kimpe and Morel 2000) even within a particular planting (Jim 1998a) our data suggest that soil texture is relatively consistent in planting pits within a city and that textural class is likely to be similar to NRCS survey data. It may therefore be appropriate to only determine it if there is reasonable doubt that soils at a particular location do not follow the NRCS surveys. It is possible that more detailed assessments of texture would be desirable if soil compaction were determined via bulk density sampling, since both factors are required for accurate interpretation of soil compaction. However, since this type of measurement was impractical for confined planting spaces, soil texture analysis is likely not necessary for each planting site. Other types of planting sites, such as parkland, open lawns, or raised beds, may have greater variability. Laboratory methods for determining soil texture are laborious. Thus when determining texture a simpler method, such as texture-by-feel, may be more practical. Although its accuracy depends on the analyst, accuracy levels are likely within the desired range for urban tree planting evaluations. There are however no data that support or dismiss this assumption.

Table 3.1 Soil texture distribution (%) of 100 street tree planting pits in Jacksonville, FL and 84 planting pits in Washington, DC.

Soil texture	Jacksonville, FL	Washington, DC
Silt loam	0.0	5.8
Sandy loam	9.6	59.7
Sandy clay loam	0.3	5.8
Sand	21.5	0.0
Loamy sand	68.3	0.7
Loam	0.3	28

Soil strength and soil moisture

Soil strength and soil moisture variability within and between cities

Soil strength and soil moisture are inextricably linked; moisture reduces soil strength, especially in soils with a significant clay content. Soil strength (Table 3.2) measured via penetration resistance in Jacksonville, FL ranged between 400 kPa (surface soil) and 2202 kPa (45 cm depth) whereas soils in Washington, DC ranged between 450 kPa (surface soil) and 2110 kPa (45 cm depth). This is within the range of the findings of Thompson et al. (1987) who, depending on location and depth, measured penetration resistances of 650 and 3200 kPa with gravimetric moisture contents between 14 and 20% on mine soils in Illinois. Penetration resistance in Jacksonville, FL showed relatively low variation across all soil depths (CV range: 0.3 to 0.6), whereas soils in Washington, DC showed higher variation in surface soil layers (CV range: 0.7 to 1) than in deeper soils (CV range: 0.4 to 0.6). One aspect potentially playing a role in the variability of soil moisture content is the high precipitation just days prior to data collection (ca. 10 cm/24 hrs). Soil moisture contents in Washington, DC were 33 to 54% where soils in Jacksonville, FL showed 10 to 16% moisture (Table 3.3). Soil moisture was significantly higher in Washington, DC for all soil layers measured, 0 to 40 cm.

Table 3.2 Mean, standard error (SE), and coefficient of variation (CV) for soil strength (kPa) measured in street tree planting pits in Jacksonville, FL (100 pits) and Washington, DC (84 pits). Three subsamples measured per pit

	Jacksonville, FL			**Washington, DC**		
Depth (cm)	**Mean (kPa)**	**SE**	**CV**	**Mean (kPa)**	**SE**	**CV**
0	399	24.5	0.6	450	48.1	1.0
2.5	687	39.8	0.6	915	81.2	0.8
5	939	45.0	0.5	1438	106.5	0.7
7.5	1091	49.2	0.5	1666	113.2	0.6
10	1264	60.4	0.5	1797	119.5	0.6
12.5	1375	60.3	0.4	1799	119.0	0.6
15	1568	62.5	0.4	1793	109.4	0.5
17.5	1649	67.8	0.4	1929	110.4	0.5
20	1721	71.7	0.4	1991	112.2	0.5
22.5	1774	64.4	0.4	1991	119.4	0.5
25	1903	66.1	0.3	1962	127.0	0.5
27.5	2067	87.8	0.4	2004	105.3	0.4
30	2157	93.7	0.4	2053	119.2	0.4
32.5	2190	85.1	0.4	2121	130.4	0.4
35	2421	98.5	0.4	2209	140.8	0.4
37.5	2523	122.4	0.4	2234	149.0	0.4
40	2583	146.0	0.5	2377	157.8	0.4
42.5	2514	131.4	0.4	2394	168.4	0.4
45	2202	217.2	0.5	2110	244.0	0.4

Table 3.3 Mean, standard error (SE) and coefficient of variation (CV) for soil moisture (%) measured in street tree planting pits in Jacksonville, FL (100pits) and Washington, DC (84 pits).

	Jacksonville, FL			Washington, DC		
Depth (cm)	**Mean (%)**	**SE**	**CV***	**Mean (%)**	**SE**	**CV***
0-10	16.4	1	0.6	53.7	5.3	0.8
10-20	10.5	0.6	0.5	38.3	4.6	0.9
20-30	9.8	0.5	0.5	33.6	6.8	1.1
30-40	11.1	1.1	0.6	37.4	10.4	0.7

* CV >1 is considered high variation

Penetration resistance of soils in both cities was lowest in the surface soils and gradually increased through deeper layers, which agrees with findings of Sands et al. (1979). Tree pits in Jacksonville, FL showed significantly lower penetration resistance in the top 25 cm compared to soils in Washington, DC whereas lower soil layers (25 to 45 cm) showed no significant differences (Table 3.2). This may be due to the fact that soils in Jacksonville, FL were sandy and therefore had higher macroporosity and lower penetration resistance.

Soils in Washington, DC had a much higher soil moisture content than soils in Jacksonville, FL (Table 3.3), yet penetration resistance was similar in lower soil layers. Soil strength in these loamy soils in Washington, DC could be much higher and possibly root growth limiting at equal soil moisture content. Sandy soils, such as those in Jacksonville, FL generally have a higher infiltration rate. Longer dry periods may therefore be needed for soils in Washington, DC to reach the low soil moisture contents found in Jacksonville soils. It is likely due to the same reasons (high infiltration rate of sandy soils and high amounts of precipitation in Washington, DC prior to measurements) that soils in both locations showed a medium to high variability. However, tree roots can penetrate strong soils if soil moisture is adequate (Bartens et al. 2008) thus the question arises as to whether the soils in Washington, DC are strong enough at representative weather conditions to limit root growth.

In Summary, soils in Washington, DC classified as loamy soils showed higher soil strength than sandy soils in Jacksonville, FL for the top 0 to 25 cm layer despite the significantly higher soil moisture content. There was no significant different in deeper soil layers. The high within-city variability for Washington, DC (surface soils) may have been due to varying soil moisture contents resulting from high rains prior to measurements. The generally low variability leads to the conclusion that soil strength measurements may not be necessary for each tree planting. However, this depends on soil moisture which may not have been representable for the entire growing season. Low soil moisture contents the majority of the growing season would result in strong soils and likely limit tree root growth.

Practicability of soil strength and soil moisture measurements

Penetration resistance as well as soil moisture can be measured quickly and easily in the field. It requires less than a minute for each measurement, which allows for adequate subsampling. The price of a TDR to measure volumetric water content is soils starts at about $700 whereas a penetrometer starts at about $200. It can be assumed that accuracy and longevity increase with price. Soil moisture can also be determined very inexpensively by transferring soil samples to the laboratory or office, determining its moist weight, drying the sample at above 100°C in an oven to remove all moisture, and calculating its moisture content.

Both penetration resistance as well as soil moisture are easy to measure. It is however important to take these measurements at times of representative weather conditions, specifically precipitation, as soil water content influences soil strength.

Combining soil moisture and penetration resistance data to make a statement on soil strength and possibly estimating bulk density could be a suitable tool to evaluate soil physical impediments to root and tree growth.

Soil depth and exposed soil surface area

Variability in exposed soil surface area and soil depth

Tree plantings were identified based on species and tree size as well as exposed soil surface area. Soil surface areas in Washington, DC were significantly larger than those in Jacksonville, FL and averaged 40 m^2 and 17 m^2, respectively with about half of the tree planting sites were smaller than 10 m^2. This also included tree plantings with multiple trees (about 10% of the sampled locations), which were larger in size than conventional street tree pits. Average soil depth in Washington, DC was 37 cm (range: 12.5 to >100 cm) and 54 cm (range: 6 to >100 cm) in Jacksonville, FL. However, we observed that the variability *within* a tree planting site (i.e., between subsamples) can be rather high (data not shown). For a number of sites, soil depth varied between 10 cm and over 100 cm within one tree planting site. This could be due to large objects in the soil that significantly reduce the available soil volume, in which case measuring soil depth by this approach could be a useful. However, variability could also be due to small obstructions in the soil that are undistinguishable from large objects. These small obstructions may not reduce the available soil volume significantly and thus our measurement technique may be inadequate. Unfortunately, besides destructively sampling and ground-penetrating radar instruments, which may be expensive or unsuitable for urban settings, we do not know of any technique or tool that measures soil depth or volume more confidently than our relatively simple technique.

Practicability of exposed soil surface areas and soil depth measurements

Using a rod for depth measurements is quick and inexpensive. Exposed soil surface area measurements were also very quick and inexpensive. However, complex tree planting shapes can make the calculations difficult and may introduce measurement errors. It would be valuable to know the accuracy level required for these calculations to determine whether a rudimentary estimate of the surface area would be sufficient for evaluating site quality.

Exposed soil surface area (Grabosky and Gilman 2004; Day and Harris 2007) as well as plant available soil volume (Kent et al. 2006; Lindsey and Bassuk 1992) have been found to significantly influence tree growth. In general, these parameters are quick and easy to measure with minimal equipment and are therefore recommended to be included in soil evaluations on a site-by-site basis. However, the utility of soil depth measurements is questionable as relatively small obstructions may result in inaccurate measurements.

Soil chemical constituents

Variability of soil chemical constituents

Our data show a significant difference for most soil chemical characteristics (incl. plant available nutrients) in Jacksonville, FL from those in Washington, DC. Soil depth, cation exchange capacity, calcium, pH, and carbon: nitrogen ratio were significantly higher in Jacksonville, FL whereas iron, boron, potassium, magnesium, manganese, organic matter, phosphorus, total nitrogen, total carbon, zinc, and exposed surface area were significantly higher in Washington, DC.

Within one municipality, the variability of certain soil parameters can be quite high, but many parameters are relatively consistent (Tables 3.4 and 3.5). This is explained by the coefficient of variation which when above 1 (standard deviation >

mean) corresponds to high variability. Available soil nutrient content ranged from very little variability to higher variability. Manganese (CV=0.3) and boron (CV=0.4) in Washington, DC (Table 3.4) and nitrate (CV=0.3) and magnesium (CV=0.4) in Jacksonville, FL (Table 3.5) showed little variability whereas ammonium (CV=2.9) and nitrate (CV=3.2) in Washington, DC (Table 3.4) and iron (CV=1.1), zinc (CV=1.2), and copper (CV=5.5) in Jacksonville, FL showed higher variability (Table 3.5). Our data show low within-city variability (CV<1) for most soil nutrients and chemical characteristics but higher variability between cities. This disagrees with findings of Park et al. (in press) who compared soils from older, middle-aged, and younger sites as well as along roads and farther from pavement. They found high variability between sites for total carbon, total nitrogen, organic matter, phosphorus, calcium, and pH. Since data are pooled in our analysis and not separated by age group (distance to pavement is similar for all sites) one would expect higher variability of soil chemical properties. This was however not the case.

Table 3.4 Mean, maximum, minimum, standard error (SE), and coefficient of variation (CV) for soil volumes and chemical properties for street tree planting pits in Washington DC (84 pits).

Measurements	Min.	Mean	Max.	SE	Coefficient of Variation[1]
B (ppm)	0.3	1.0	1.9	0.0	0.4
C/N	15.0	22.7	49.2	0.7	0.3
Ca (ppm)	455.0	2420.1	4717.0	125.1	0.4
Cation Exchange Capacity	4.4	14.2	25.7	0.6	0.4
Cu (ppm)	0.2	1.9	10.0	0.2	0.9
Depth (cm)	12.5	36.6	100.0	2.1	0.5
Exposed soil area (m^2)	2.9	33.2	422.4	7.4	1.8
Fe (ppm)	5.4	23.0	56.8	1.2	0.5
K (ppm)	51.0	155.3	1207.0	17.0	0.9
Mg (ppm)	72.0	170.0	331.0	7.7	0.4
Mn (ppm)	11.3	31.5	61.2	1.2	0.3
NH_4-N (mg kg^{-1})	2.2	16.5	281.9	5.2	2.9
NO_3-N (mg kg^{-1})	0.1	22.1	420.4	7.6	3.2
Organic matter (%)	2.2	9.9	39.0	1.0	0.8
P (ppm)	9.0	65.3	350.0	7.0	0.9
pH	5.3	7.1	8.5	0.1	0.1
Soluble Salts (ppm)	64.0	198.8	1216.0	19.9	0.9
Total C (%)	1.4	7.3	31.4	0.7	0.8
Total N (%)	0.1	0.3	0.8	0.0	0.6
Zn (ppm)	2.1	32.5	86.2	2.1	0.6

[a] CV >1 is considered high variation

Table 3.5 Mean, maximum, minimum, standard error (SE), and coefficient of variation (CV) for soil volumes and chemical properties for street tree planting pits in Jacksonville, FL (100 pits).

Measurements	Min.	Mean	Max.	SE	Coefficient of Variation[a]
B (ppm)	0.1	0.4	1.1	0.0	0.6
C/N	18.2	32.0	72.6	1.3	0.4
Ca (ppm)	573.0	3507.8	5364.0	155.0	0.4
Cation Exchange Capacity	3.4	18.7	27.8	0.8	0.4
Cu (ppm)	0.1	1.3	69.4	0.8	5.5
Depth (cm)	6.0	54.1	100.0	2.3	0.4
Exposed soil area (m^2)	1.7	15.5	97.6	1.9	1.1
Fe (ppm)	0.6	13.1	86.0	1.5	1.1
K (ppm)	5.0	35.5	161.0	2.6	0.7
Mg (ppm)	36.0	127.8	255.0	5.6	0.4
Mn (ppm)	0.3	6.0	27.0	0.6	0.9
NH_4-N (mg kg^{-1})	1.2	3.2	18.2	0.3	0.9
NO_3-N (mg kg^{-1})	0.6	11.8	65.9	1.2	0.9
Organic matter (%)	0.7	3.0	9.8	0.2	0.5
P (ppm)	2.0	21.3	74.0	1.9	0.8
pH	5.4	7.6	8.4	0.1	0.1
Soluble Salts (ppm)	51.0	173.2	550.0	10.2	0.6
Total C (%)	0.5	2.5	7.8	0.1	0.5
Total N (%)	0.0	0.1	0.3	0.0	0.7
Zn (ppm)	0.2	16.0	99.9	1.9	1.2

[a] CV >1 is considered high variation

In both cities, pH averages were above 7 (7.1 and 7.6) with a wide range (5.3-8.5) but a low variability (0.1). This disagreed with findings by Park et al. (in press) who found a significant difference in pH values between sites of varying ages and distances to pavement but agrees with findings by Scharenbroch et al. (2005) who found little pH differences between urban landscapes. Soil acidity can influence nutrient availability greatly. For example a high pH can lead to iron deficiencies in plants (Finck 1991). Thus the identifying sites with lower pHs has considerable value because it may allow planting of species less tolerant of high pH, thus providing an opportunity for increasing biodiversity within the urban forest. Grey infrastructure, such as pavement and buildings, made of limestone can increase the pH of a surrounding soil and thus influence the sufficiency or even toxicity of soil chemicals. Therefore, time of planting, age of the tree, surrounding infrastructure or industry and other factors may influence soil chemical constitution and would lead to greater variability between tree plantings sites. In addition, plants growing in different geographic regions may demand different levels of nutrients due to e.g. high solar radiation (Finck, 1991). Analyzing soil samples for nutrients would be important and only measuring cation exchange capacity would not give sufficient information to evaluate a tree planting suite for its nutritious adequacy. However, taking location and tree species (tolerances and needs) into account is important when determining soil chemical analysis of urban tree plantings.

Practicability of measurements of soil chemical constituents

We collected composite surface soil samples from each site, which is not resource intensive. The analysis for most soil chemicals (excluding N), including pH, soluble salts, and organic matter was done at the Virginia Tech Soil Testing Laboratory, Blacksburg, VA for \$0.67 per sample, but could cost \$10 or more per sample for resource professionals.

Nitrogen, on the other hand (NO_3 and NH_4 showed high variability for soils in Jacksonville, FL), is a rather complex nutrient. Measuring total nitrogen in the soil does not give information about the available fraction or the fraction of nitrogen that will become available. In order to interpret N availability, measurements of total nitrogen, inorganic nitrogen, and available nitrate and ammonium are necessary. The laboratory consumables cost approximately $ 5 per sample plus about 2-3 hours of labor per sample (multiple samples can be analyzed simultaneously). In addition, the required laboratory equipment is expensive. However, since nitrogen is important to tree growth it may be very important to be measured when evaluating soil conditions for tree development. Soil laboratories may offer soil nutrient analysis including nitrogen.

Although chemical properties can vary, analyzing all tree growth-influencing soil chemical constituents is not practicable. Knowing the surroundings of the tree planting, e.g. concrete sidewalks/roads, present soil texture, as well as understanding the general climate is very important when determining which soil chemical properties should be assessed to evaluate urban tree plantings.

Conclusions

We evaluated 184 tree plantings for 22 soil variables and found little variability between tree plantings for many, but not all, soil measurements. This suggests that only a few representative sites may need to be evaluated to result in sufficient data when evaluating tree planting spaces for their suitability. Some soil variables, however, either because of their high relevance to ultimate tree growth, their high variability between sites, their ease of measurement, or all three, may be critical to evaluate at every planting site (Table 3.6). Both of our study sites were coastal plain cities in the Eastern United States and may not be representative for every municipality.

Table 3.6 Summary of cost, practicability, relevance and within-city variability of soil properties likely influencing tree growth; CV<0.5 equals low variability, CV=0.5 to 1 equals medium variability, CV>1 equals high variability.

Soil property	Cost	Practicability	Relevance of data	Variability potential
Plant available nutrients[b]	medium	high	high	low to high
Nitrogen[b]	high	low	high	medium to high
Organic matter	low	high	high	medium
pH	low	high	high	low
Soluble salts[b]	low	high	unclear	medium
CEC	low	high	low	low
Soil texture[cd]	high	low	high	low
Soil depth	low	high	unclear	low
Soil moisture	low	high	high	medium to high
Soil strength	low	high	high	low to medium
Bulk density[a]	low	low	medium	n/a

[a] data not included
[b] depending on the access and costs of soil testing laboratories
[c] other potentially more practicable and inexpensive methods may be suitable
[d] variability potential estimated for categorical variables thus not based on CV.

Tree requirements for nutrients likely vary depending on, species, climatic conditions as well as soil conditions. For example, trees growing on sandy soils may lack mobile nutrients as those may be leached out, such as potassium, whereas trees on clayey soils may lack nutrients that are tightly bound on soil exchange sites, such as phosphorus (Mengel and Kirkby 2001). It is therefore important to understand the general site conditions at a location to determine which soil variables should be evaluated to improve tree growth.

In addition, most soil measurements we have conducted, besides nitrogen and soil texture, are relatively easy and inexpensive. In combination with the low variability between samples one can evaluate urban soil conditions with relatively low resource intensity.

The data collection team consisted of 4-5 people to take soil samples, measure soil moisture, penetration resistance, tree planting surface area, and depth, as well as tree response variables (tree height, trunk diameter, canopy dimensions, and crown health). It can be estimated that it required 10 minutes at each site for these measurements, a little less than 1 person-hour. In addition to the time needed to take data and collect samples, an additional estimated 4 hours (including waiting time within procedures but excluding time needed to acquire dry weights) were needed to analyze the samples in the laboratory for nutrient content, gravimetric moisture content, and soil texture. Thus analyzing all variables to give well-rounded information about a site may not be practicable for many purposes. More data need to be analyzed, especially asking the question as to which soil factors influence urban tree growth significantly to determine the soil variables to be measured to evaluate urban tree plantings.

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Chapter 4: Assessing the Potential for Estimating Soil Bulk Density from Other Soil Physical Properties

Introduction

Soil compaction can limit root growth and thus influences tree survival and longevity (Kozlowski 1985). Limited root growth can affect afforestation success of, for example, disturbed urban soils as well as single urban tree planting sites. Although bulk density (ϱ_b) is the generally accepted measure of soil compaction, soil obstructions – particularly in confined urban sites such as tree pits– can make ϱ_b sampling impractical and unreliable. A suitable alternative that estimates soil ϱ_b reliably would be desirable for site evaluations of urban tree planting sites.

Bulk density is the dry weight per unit volume of soil, generally expressed in equivalent units of g cm^{-3} or Mg m^{-3} (Blake and Hartge 1986). Thus any factor that influences the dry weight of a sample, such as soil texture (sand, silt, and clay fractions), soil organic matter, particle density, and the structure of the soil automatically influences the resulting ϱ_b. Generally, loose, porous soils and those rich in organic matter have low ϱ_b. Finer textured soils have a higher total porosity and lower ϱ_b than coarse textured soils, such as sands. Highly compacted soils can have a ϱ_b of 2 g cm^{-3} or even higher (Brady and Weil 2002c). However, root growth-limiting ϱ_b varies with soil texture (Daddow and Warrington 1983) due to differences in mineral particle characteristics as well as particle and aggregate sizes. Soil texture must therefore be identified in conjunction with ϱ_b measurements to allow for meaningful interpretation in the context of tree growth. Soil texture estimations can be done very quickly in the field, for example via texture-by-feel method (NRCS no date), an advantage for the urban environment where samples may be needed at every planting site.

Soils in the urban environment are generally highly compacted to meet engineering standards for road construction. Thus a typical tree planting site is surrounded by pavement underneath which is soil compacted to such degree that roots may not be able to penetrate. In addition, tree planting sites, where the soil has the potential to be less compacted, can be very small. Urban trees are often planted in soil volumes as small as 1.5 m^3. The majority, if not the entirety, of the root system is therefore being contained within this small soil volume, resulting in increased tree root density within the soil. Such high root density can make ϱ_b sampling nearly impossible. In addition, successful ϱ_b sampling is hampered by the fact that diameters of conventional core samples are too large (5 or 10 cm) to avoid interference with roots and foreign objects, such as gravel, pieces of asphalt or concrete, and trash commonly found in urban soils (see Chapter 3). Although it is possible to correct for these obstructions by subtracting the volume and weight of the non-soil material from the sample, this results in even more time-consuming measurements and creates opportunities for introducing errors. In addition, even if a suitable soil core sample can be extracted from a tree planting pit, the sample may not represent the soil conditions the tree is exposed to. Urban soil quality can vary greatly (Craul 1985b; De Kimpe and Morel 2000; Craul 1985a) sometimes in unexpected ways, even within a soil profile (Patterson 1977). Thus chemically or physically unsuitable conditions for root growth may have prevented roots from penetrating this particular soil region, explaining its feasibility for sample extraction. Its ϱ_b may therefore not be representative of the prevailing soil. In addition, ϱ_b typically increases with soil depth due to the weight of above soil layers as well as reduced organic matter, biological activity, and aggregation and thus reduced pore space compared to surface layers (Sands et al. 1979). High soil variability in conjunction with generally increasing ϱ_b in deeper soil layers show that spatially distributed measures of physical barriers to root growth are likely more informative than an isolated ϱ_b sample. Especially in urban soils, it would therefore be desirable to determine soil compaction, or another measure of soil physical resistance to root growth, easily, reliably and in a way that is representative of the prevailing conditions. A small-diameter sampling tool would be favorable to avoid interference with foreign objects to assure confident sampling especially within confined urban cutouts where reliable ϱ_b sampling would be difficult. However, small diameter bulk density hammers would not be accurate due to friction from the sides of the tool.

Soil penetration resistance, a measure of soil strength, can be measured quickly and easily with a cone penetrometer. Common penetrometers are significantly smaller than core samplers, often about 12 mm in diameter or smaller and therefore are less likely to encounter soil obstructions that can perturb core sampling. Like bulk density, penetration resistance has been demonstrated to be well correlated with plant and root growth (Masle and Passioura 1987; Misra and Gibbons 1996; Sands et al. 1979; Thompson et al. 1987; Young et al. 1997; Ehlers et al. 1983; Lowery and Schuler 1994). However, penetration resistance measures soil strength at a particular point in time. It is not a static measure because it is influenced by soil moisture, which varies considerably across seasons and soil types. Thus soil penetration resistance is not particularly informative about soil strength or tree root growth potential at a particular site unless it is measured multiple times over a range of water contents. A model that would allow ready conversion of easily-measurable soil properties (soil moisture and soil strength) to a static measure (ϱ_b) would have important advantages for easy and reliable assessments of urban soils for their potential to support vegetation. Use of ρ_b allows soils to be characterized by a single number that also allows comparisons among sites.

Previous studies have looked at the relationship between ρ_b and penetration resistance, as well as penetration resistance and plant growth. These include studies by Sands et al. (1979) for a sandy soil, Clayton et al. (1987) for loam to silt loam, Day et al. (2000) for loam, and Allbrook (1986) for a sandy loam. However, there appear to be no studies in the literature that:

- estimate ρ_b from penetration resistance and soil texture
- are applicable across a range of soil textural classes and
- across a range of soil water contents from permanent wilting point (PWP) to field water capacity (FWC)

Bulk density is related to soil strength and soil moisture, yet the specific relationship likely differs by soil type. Thus we expect that: a) ρ_b increases with increasing soil strength, b) ρ_b decreases with increasing soil moisture content, and c) both relationships vary with soil texture. It would be extremely useful for urban tree planting site assessment if these relationships could be captured in a set of models that could be employed to estimate bulk density from practical field tests of soil moisture content and soil strength.

The objective of the current study was to develop empirical models to describe the relationship between ρ_b and penetration resistance, moisture content, and soil texture. The goal was to determine whether a soil penetrometer in conjunction with a soil moisture meter could be used to reliably estimate soil bulk density from a single set of measurements and thereby facilitate evaluation of urban soils for physical limitations to tree root growth.

Materials and Methods

Experimental Setup

Thirty-one different combinations of soil texture, ϱ_b, and soil volumetric moisture content (VWC) with three replications each were created in cylindrical containers as described below. Three to four subsample measurements of water content and soil strength (at four depths) were taken per replicate, resulting in approximately 12 soil strength measurements per container.

Soil description

Soils of four different soil textures representative of a broad range of soil types were selected for evaluation (Table 4.1). Soils included a loam collected in Washington, DC (lat. 38° 5' N, long. 77° 02' W), a sand collected in Jacksonville, FL (lat. 30° 2′ N, long. 81° 3′ W), a silt loam collected from a floodplain in Ellett Valley, VA (lat. 37° 1′ N, long. 80° 2′ W, and a clay from the urban horticulture center in Blacksburg, VA (lat. 37 13′ 02″ N, long. 80° 27′ 52″ W). To characterize the collected soil, two composite soil samples were taken of the soil for organic matter and soil texture analysis. Organic matter was determined by loss on ignition. Soil particle size analysis was conducted using the pipette method (Burt 2004a).

Table 4.1 Sand, silt, clay, and organic matter contents of soils used for developing bulk density (ρ_b) estimation models based on soil moisture and texture.

	Particle Size (%)				
Soil texture	**Fine sand**	**Coarse & medium sand**	**Silt**	**Clay**	**Organic matter (%)**
Sand	82.0	9.6	5.8	2.6	0.7
Loam	29.2	10.7	41.2	18.9	6.2
Silt loam	19.5	11.5	52.8	16	2.3
Clay	11.2	7.5	29.2	52.2	3.7

Soil preparation

All soils were passed through a 2-mm sieve to remove any coarse material, such as roots and rocks. Field water capacity (FWC) and permanent wilting point (PWP) were determined by placing two loose soil samples of each texture class on a pressure plate and determining the water content at 0.033 and 1.5 MPa (Klute 1986). In addition, water contents at two additional intermediate tensions of 0.3 and 0.5 MPa were determined on the pressure plate to develop a moisture release curve (Figure 4.1). Since moisture contents at 0.3 and 0.5 MPa were very similar for the individual soil types, one representative value was chosen resulting in three moisture levels for each treatment combination (Table 4.2).

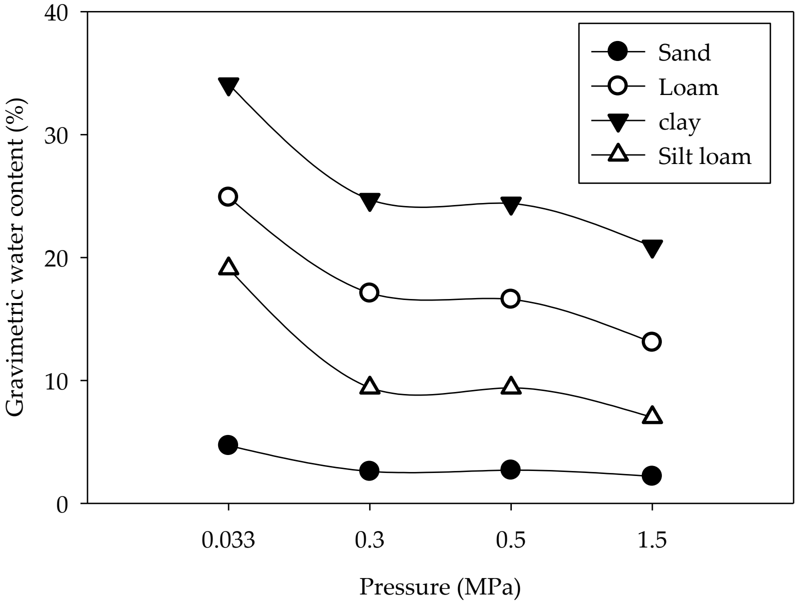

Figure 4.1 Moisture release curve for four uncompacted soil textures used in this study; *n*=2. Gravimetric moisture contents were measured at field capacity (0.033 MPa), permanent wilting point (1.5 MPa), as well as 0.3 and 0.5 MPa.

Table 4.2 Anticipated soil moisture levels for each soil textural class before compaction in containers.

	Gravimetric water content (%)		
Soil textural class	**Low**	**Medium**	**High**
Sand	2	3	5
Loam	13	17	25
Clay	21	25	34
Silt loam	7	9	19

Four ϱ_b levels were chosen as treatment factor levels based on the root growth limiting bulk density (RGLBD) thresholds established by Daddow and Warrington (1983) where root growth is halted or nearly halted (Table 4.3): At RLGBD (”growth limiting”); two ϱ_b values below RGLBD (“low” and “medium”); and one ϱ_b value above RGLBD (“high”).

Table 4.3 Soil bulk densities (ϱb) selected for measurement to characterize penetration resistance across a range of compaction levels. Bulk densities were characterized as low, medium, high, and root growth limiting compaction.

	ϱ_b (cm/g^3)			
Soil textural class	**Low**	**Medium**	**Root growth limiting***	**High**
Sand	1.4	1.6	1.8	2.0
Loam	1.2	1.4	1.6	1.8
Clay	1.0	1.2	1.4	1.6
Silt loam	1.1	1.3	1.5	1.7

* *based on* Daddow and Warrington, 1983

Measurement procedure

Air-dried soil was mixed with the amount of water needed to reach the desired moisture content (Table 4.2). This moist soil was compacted to the desired ϱ_b (Table 4.3) in a 26.5 cm wide by 20 cm high cylindrical container. Soil was compacted in three equivalent layers, each with a volume of 2,000 ml, by placing a circular wooden board of same diameter as the container on top of the soil surface and striking it with a 4.54-kg Proctor hammer. The board was struck a predetermined number of times (see Appendix tables A4.1-4 for details) either from 25 cm (½ stroke) or 50 cm (full stroke) height to reach the desired ϱ_b. Each treatment combination was replicated three times.

Once the bulk density × moisture content treatment was prepared, soil strength was measured with a penetrometer (SC 900 Soil Compaction Meter, Spectrum™ Technologies, Inc.) in 2.5-cm depth increments by manually pushing the probe into the soil at a constant rate of about 2.5 cm s^{-1}. Penetrometer readings from the top and bottom depth increments were discarded from the analysis to minimize edge effects on measurement error. Next, volumetric water content (VWC) was measured for the entire profile in 4 to 5 locations- avoiding areas of soil-structure disturbance by the penetrometer- across the container using time domain reflectrometry (HydroSense™, Campbell Scientific Australia Pty. Ltd.). Soil strength and soil VWC were averaged for each subsample. In addition, a composite soil sample of approximately 50 g was taken from multiple locations for each moisture × soil texture replicate and dried at 105°C for 24 h and gravimetric water content determined to verify the moisture-treatment levels.

Statistical analysis

Separate regression models were developed for each soil textural class using the regression procedure in SAS 9.2 (SAS Institute Inc., Cary, NC, USA); $\alpha=0.05$. Soil strength was subjected to an inverse natural log transformation to meet the distribution requirements for the statistical method.

Results and Discussion

Measured VWC (Figures 4.2-4.5) ranged from 2% (low moisture treatment) in sand to 34% (high moisture treatment) in loam. For each soil texture, three different VWC were reached representing low, medium, and high water contents. Final gravimetric soil moisture values varied from targeted values by between 0 and 10%. All moisture levels for silt loam and the medium moisture level for loam were significantly different from the target initial moisture level at the 0.05 confidence level whereas sand and clay moisture levels were not significantly different (see Appendix, table A4.5). Since soil was wetted with a predetermined volume of water, these deviations suggest there may have been either an uneven distribution of moisture within the prepared soil or unexpectedly high water content in the air-dried soil prior to wetting. However, the achieved gravimetric moisture levels were within the range of commonly observed levels for these soil textures (see Chapter 3 as well as Voorhees et al., 1975) and provided the range of soil moisture levels and soil strengths desired for this study.

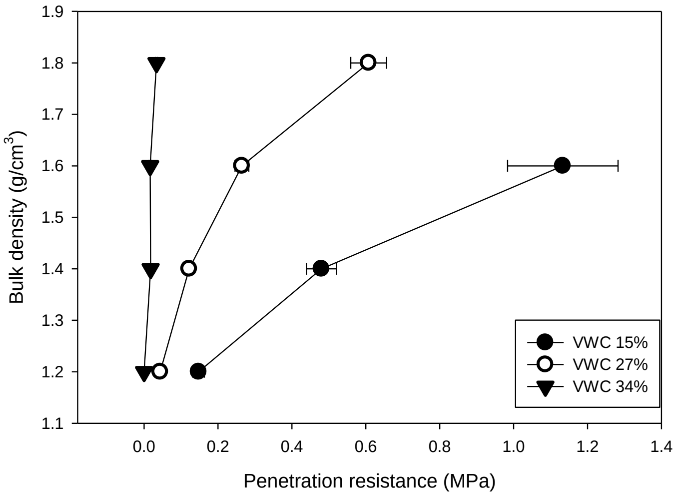

Figure 4.2 Mean penetration resistance (MPa) of a loam soil for three to four bulk density levels (ρ_b) and three volumetric water contents (VWC); *n*=3 with 9 subsamples (27 total measurements total per point). Bars indicate standard errors of the mean.

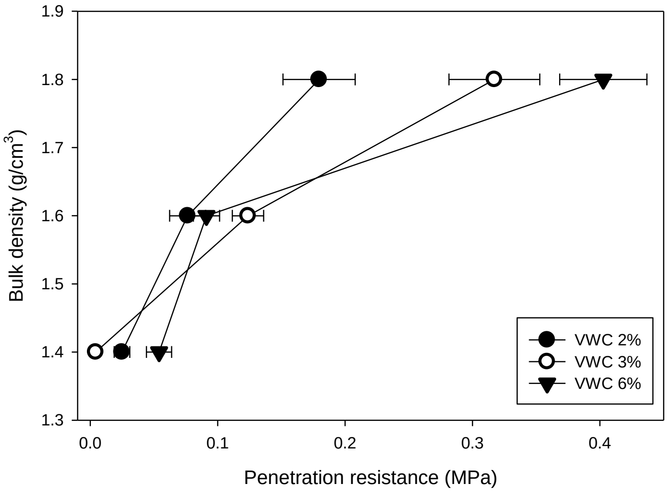

Figure 4.3 Mean penetration resistance (MPa) of a sand soil for three bulk density levels (ϱ_b) and three volumetric water contents (VWC); *n*=3 with 27 to 36 total measurements per point. Bars indicate standard errors of the mean.

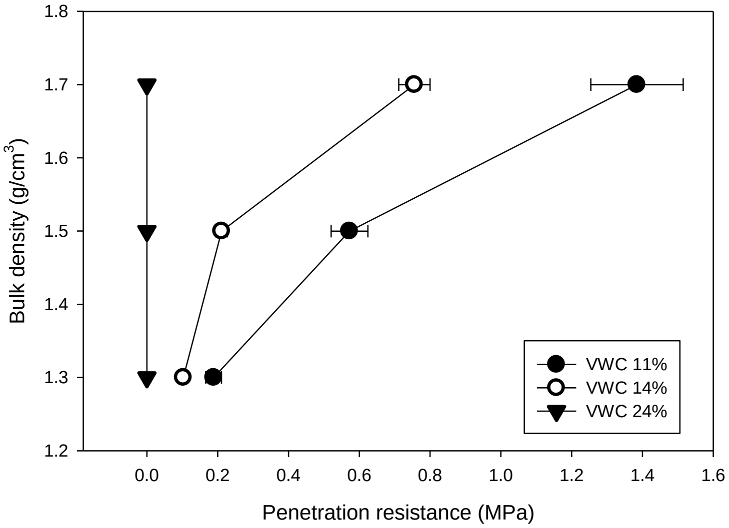

Figure 4.4 Mean penetration resistance (MPa) of a silt loam soil for three bulk density levels (ϱ_b) and three volumetric water contents (VWC); *n*=3 with 27 to 36 total measurements per point. Bars indicate standard errors of the mean.

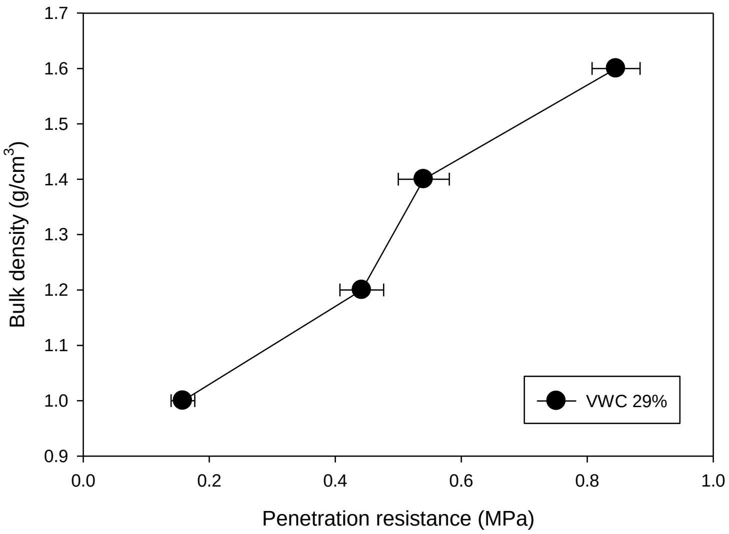

Figure 4.5 Mean penetration resistance (MPa) of a clay soil for four bulk density levels (ϱ_b) and one volumetric water contents (VWC); *n*=3 with 27 to 36 total measurements per point. Bars indicate standard errors of the mean.

Loam and silt loam had the highest soil strength at any of the measured soil moisture and ϱ_b levels (Figures 4.2 and 4.4) with up to 1.2 and 1.4 MPa. Clay had low soil strength, up to about 0.9 MPa (Figure 4.5). The clay soil formed large clumps when wetted resulting in uneven and incomplete compaction. Because of the creation of clumps when wetted heavily and resulting difficulty in applying the desired treatment, only the lowest soil moisture level was subsequently included in the evaluation of clay soil strength. Sand had the lowest soil strength, reaching only a maximum of 0.4 MPa (Figure 4.3). This disagrees with findings by Sands et al. (1979) who measured soil strength of up to 7 MPa in sand soils at bulk densities of only 1.5 g cm^{-3}. In addition, the highest bulk density we measured, 1.8g cm^{-3}, is categorized as limiting for tree root growth for sandy soils (Daddow and Warrington 1983), yet the corresponding soil strength in our study (0.2-0.4 MPa) cannot be considered root growth limiting (Busscher et al. 1986). This indicates however that the soil we used, despite having a high fraction of fine sands (82%; Table 4.1), lacked structure and particles were therefore easily displaced to allow penetration.

Overall, all soil texture classes showed an exponential increase in penetration resistance with increasing ϱ_b. The lowest moisture content resulted in a steeper increase in soil strength with increasing ϱ_b. This nonlinear relationship suggests that soils, as they dry or become compacted, provide an exponentially stronger barrier to tree root growth.

Bulk density estimation models

Regression models were developed to predict bulk density based on VWC and soil strength. A log transformation of VWC was performed to meet the distribution requirements for the statistical method. Separate models were developed for each soil texture and VWC and soil strength explained from 42% to 85% of the variability of ϱ_b (Table 4.4). Combining all soil texture measurements into a single model based on VWC and soil strength only explained 7% of variability in bulk density, demonstrating the influence of soil texture on this relationship and thus the importance of developing separate models for each soil textural class. The model developed for bulk density of sandy soils had a coefficient of determination of 0.42, which may reflect the lack of structure and the ease of soil displacement regardless of moisture content.

Table 4.4 Regression analysis for estimating bulk density (ρb) from soil strength (MPa) and volumetric water content (VWC, %) for five individual soil types and a combined data set; α=0.05; variance inflation factor (VIF) < 2 for all models.

Texture	Regression model	R^2	p-value
Loam	$\rho_b = 1.6 - 0.56*(1/e^{\text{soil strength}}) + 0.01*\text{ VWC}$	0.56	<0.0001
Sand	$\rho_b = 1.98 - 0.58*(1/e^{\text{soil strength}}) + 0.03*\text{ VWC}$	0.42	<0.0001
Silt loam	$\rho_b = 1.39 - 0.3*(1/e^{\text{soil strength}}) + 0.03*\text{VWC}$	0.85	<0.0001
combined	$\rho_b = 1.7 - 0.24*(1/e^{\text{soil strength}}) - 0.001*\text{ VWC}$	0.07	<0.0001

Testing the models with soil moisture and soil strength data combinations in ranges up to root growth-limiting soil strength values suggested by Day and Bassuk (1994) and Young et al. (1997) resulted in ρ_b estimates (Figure 4.6) comparable to those reported in other studies (Lampurlanes and Cantero-Martínez 2003; Patterson 1977). With the developed models, a loam with 5% VWC and a penetration resistance of 3 MPa would indicate a ρ_b of 1.6 g cm^{-3}. However, the same soil at a higher moisture content, say 15%, would result in a soil strength of less than 1.25 MPa and therefore less than half the soil strength of the same soil at a drier stage (Figure 4.8). A loam with a ρ_b of 1.6 g cm^{-3} can be considered root-growth limiting (Daddow and Warrington 1983), and a penetration resistance of 3 MPa severely restricts root growth as well, but a penetration resistance of 1.25 likely does not (Day and Bassuk 1994). This illustrates that soil strength is a better indicator of root growth limiting soil physical properties at any given time than ρ_b, as past research has demonstrated (Lampurlanes and Cantero-Matrinez (2003); Day et al. (2000). However, interpreting soil strength measurements for the purposes of assessing soil quality or specifying soil improvement practice is difficult, precisely because an individual soil does change with water content. Thus ϱb is a more useful measurement for comparison purposes as long as soil texture is known.

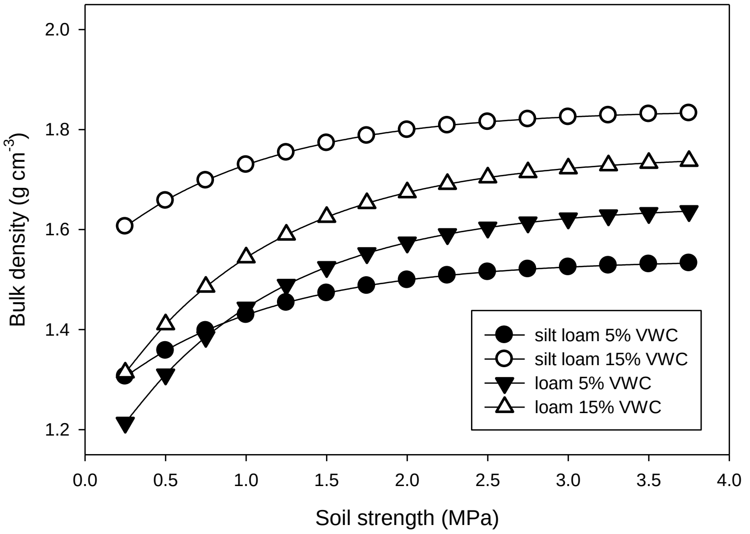

Figure 4.6 Bulk density (ϱb) estimations for 15 soil strength levels between 0.25 and 2.0MPa and 2 moisture levels (5 and 15% volumetric water content) for 2 soil textural classes (silt loam and clay) based on the developed models (Table 4.5).

Conclusions

Bulk density estimation models were developed for three soil textural classes based on VWC and soil strength. Models were highly significant ($p<0.0001$) and resulted in medium (0.42) to high (0.85) coefficients of determination when VWC was log transformed.

This suggests that the development of models for estimating ϱb can be achieved based on easy and fast soil strength and soil moisture measurements. Separate models are necessary for different soil textural classes, but that these models could provide a useful tool to help assess urban tree plantings, and other applications, reliably and practically. In addition, the sensitivity of these models to small changes in soil texture is unknown, but additional models for intermediate textures could potentially be constructed. However, it is reasonable to suggest that a tool could be developed that converts soil strength measurements and soil moisture data to the commonly accepted static measure ρ_b.

Homogenized soils were used that were prewetted and then compacted and measured with a penetrometer. However, this prewetting process, especially at high water contents, led to clumping of some soils. This clumping led to the exclusion of these treatment combinations from the experiment. An experiment that prevents clumping of soil prior to compaction would be desirable. In addition, the evaluation of non-homogenized soils would be desirable because soils, especially urban soils, consist of varying soil quality, textures, and foreign objects. A penetrometer was used with an accuracy level higher than the minimum soil strength measurements. A more accurate penetrometer should be used for further analysis to decrease uncertainties of the data. The penetrometer used had an accuracy of 0.13 MPa which indicate low confidence in measurements below this level such as reading for wet soils or less compacted sands. The bulk density-soil strength relationship for the sand soil in our study varied considerably from results of previous studies, suggesting that soil structure, rather than simply bulk density, may play an important role in the penetration resistance of sand soils. Further investigation is needed to determine if models described here will be applicable to other sand soils. However, the method used is similar to those found in the literature (Henderson et al. 1988) and the shape of the curves of average soil strength measurements (Figures 4.2-4.5) is reasonable and comparable to the literature (Sands et al. 1979).

Further research is needed to confidently evaluate more soil textures as well as clayey soils confidently. In addition, field data should be included to develop more confident ϱ_b models.

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Appendix

Table A4.1 Compaction procedure for sand: moist soil weight per layer, moisture, and blows with a proctor hammer are given for each treatment combination. Soils were compacted in three equal soil layers.

Bulk density	Moisture content		
	Low	Medium	High
Low			
Soil mass (g)	2856	2884	2940
Hammer strokes (#)	1 x ½	1 x ½	4 x ½
Medium			
Soil mass (g)	3264	3296	3360
Hammer strokes (#)	4 x ½	8 x ½	6 x ½
High			
Soil mass (g)	3672	3708	3780
Hammer strokes (#)	30	15 x ½ plus 5 full	15 x ½ plus 5 full
Growth limiting	--------------impossible---------------		

Table A4.2 Compaction procedure for loam: moist soil weight per layer, moisture, and blows with a proctor hammer are given for each treatment combination. Soils were compacted in three equal soil layers.

Bulk density	Moisture content		
	Low	Medium	High
Low			
Soil mass (g)	2712	2808	impossible
Hammer strokes (#)	6 x ½	4 x ½	
Medium			
Soil mass (g)	3165	3276	3500
Hammer strokes (#)	20 x ½	6 x ½	5 x ½
High			
Soil mass (g)	3616	3744	4000
Hammer strokes (#)	30 x ½ plus 30 full	1 x ½	8 x ½
Root limiting			
Soil mass (g)	n.a.	4212[a]	4500[a]
Hammer strokes (#)		8 x ½ plus 20 full	12 full

[a] only 2 soil layers were used

Table A4.3 Compaction procedure for clay: moist soil weight per layer, moisture, and blows with a proctor hammer are given for each treatment combination. Soils were compacted in three equal soil layers.

Bulk density	Moisture content		
	Low	Medium	High
Low			
Soil mass (g)	2420	--------impossible--------	
Hammer strokes (#)	4 x ½		
Medium			
Soil mass (g)	2904	--------impossible--------	
Hammer strokes (#)	8 x ½		
High			
Soil mass (g)	3388	--------impossible--------	
Hammer strokes (#)	15 x ½		
Root limiting			
Soil mass (g)	3872	--------impossible--------	
Hammer strokes (#)	18 full		

Table A4.4 Compaction procedure for silt loam: moist soil weight per layer, moisture, and blows with a proctor hammer are given for each treatment combination. Soils were compacted in three equal soil layers.

Bulk density	Moisture content		
	Low	Medium	High
Low			
Soil mass (g)	--------impossible-----------		
Hammer strokes (#)			
Medium			
Soil mass (g)	2782	impossible	3094
Hammer strokes (#)	2 x ½		missing data
High			
Soil mass (g)	3210	3270	3570
Hammer strokes (#)	4 x ½	missing data	missing data
Root limiting			
Soil mass (g)	3638	3706	4046
Hammer strokes (#)	12 x ½ plus 4 full	missing data	missing data

Table A4.5 Comparison of targeted and actual gravimetric moisture content via ttest procedure in SAS 9.2

texture	targeted moisture (% g/g)	actual moisture (% g/g)	p-value
loam	13.0	15.0	0.0003
loam	17.0	26.9	0.0001
loam	25.0	33.7	0.0196
sand	2.0	1.5	0.0863
sand	3.0	3.2	0.2640
sand	5.0	5.6	0.3004
silt loam	7.0	11.0	0.1148
silt loam	9.0	13.7	<0.0001
silt loam	19.0	23.7	0.2003
clay	21.0	29.2	0.0650

Chapter 5: Evaluating the Potential of Dendrochronological Analyses of Live Oak (*Quercus virginiana* Mill.) Cores and Cross Sections

Introduction

Quercus virginiana Mill. (live oak) is a broadleaf evergreen hardwood species native to the southeastern United States. Its range reaches from the Coastal Plain in southeastern Virginia down to Florida, and west to southern and central Texas (Harms, 1990). It is a large-stature, long-lived tree, reaching heights of 24 m and crown widths of 36 m at maturity (Dirr, 1998; Samuelson and Hogan, 2006). The species purportedly lives 500 or more years (Harms, 1990), but no precise ring counts or dendrochronological dating has been performed on this species to our knowledge. Because it transplants easily and grows rapidly in its youth (Harms, 1990), live oak is commonly planted in urban forests of the southeastern United States. For example, live oak is the most common urban species in Savannah, Georgia, accounting for nearly one-fifth of the city's 65,000 park and street trees (M. Pavlis, Urban Forester for Savannah, GA, *personal communication*).

Live oak predominantly occurs in areas with a frost-free period between 240 and 300 days and winter minimum temperatures between 2 and 16 °C (Harms, 1990) such as Jacksonville, Florida (Figure 5.1) where average monthly winter temperatures have not been below 10 °C in the past two decades. Such conditions can preclude a definite dormancy period in trees, which may lead to indistinct ring boundaries and poorly-defined growth rings (Sass et al., 1995). Tree-ring analysis could help determine whether growth rings can be reliably discerned and accurately dated to their exact calendar years of formation, and whether environmental information can be retrieved from its growth ring record. The potential of dating growth rings from live oak has important implications for interpreting urban ecosystem dynamics as well as dating historical events, examining the impacts of land use on trees, and analyzing climate (their coastal location would make them ideal for analyzing ocean-atmosphere oscillations, such as the Atlantic Multidecadal Oscillation).

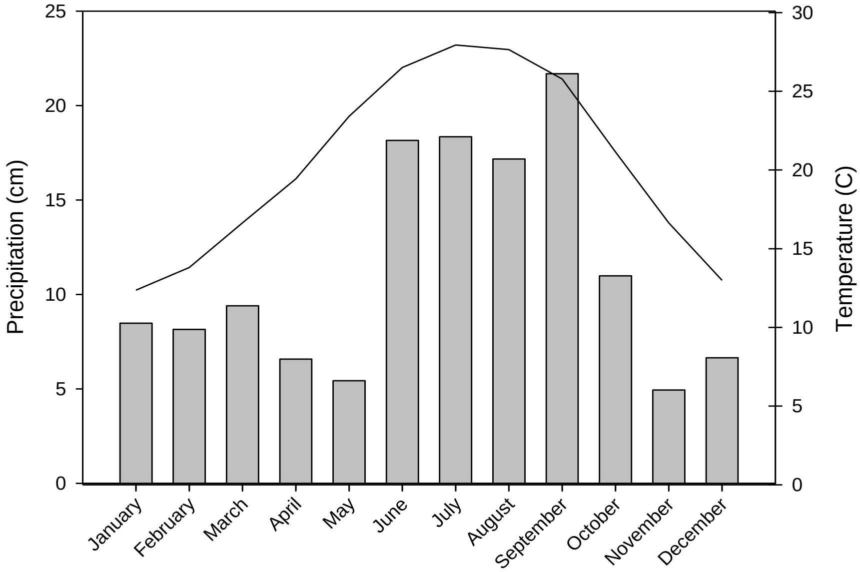

Figure 5.1 Monthly average (1987–2007) of precipitation (bars) and temperature (line) for Jacksonville, FL.

Numerous tree species found in the southeastern U.S. have been assessed for their suitability in dendrochronological studies, including coastal plain longleaf pine (*Pinus palustris* Mill.) (Henderson and Grissino-Mayer, 2009), central Appalachian Table Mountain pine (*Pinus pungens* Lamb.) (DeWeese et al., 2010), and eastern hemlock (*Tsuga canadensis* (L.) Carrière) in Alabama (Hart et al., 2010). Moreover, numerous published studies have demonstrated the potential of urban trees for tree-ring analysis (Aslanboga et al., 1978; Eckstein et al., 1981; Luken et al., 1994; Riek, 1998; Watmough et al., 1998; He et al., 2007). Despite its longevity and abundance, live oak has received limited attention concerning identification of its annual growth rings and the information that its rings may provide.

Considering the significant role of live oak in many urban forests, assessing its potential for dendrochronological analysis in urban settings as well as more traditional applications is of particular interest. Urban trees are often stressed from exposure to adverse growing conditions, such as insect infestation, water stress, and air pollution (Lillesand et al., 1979). In addition, many urban trees are subjected to site-specific above- and below-ground conditions that can impair growth, such as acute stress from disturbance during building construction as well as chronic stress from poor soils and excessive heat (Grabosky and Bassuk, 1995; Jim, 1998b). Tree growth patterns may reflect these conditions and thus have the potential to date historical land use changes around the tree as well as provide information on climatic or ecological events in the region. Banks (1994), for example, attributed growth decline of a narrow-leafed ash (*Fraxinus angustifolia* Vahl) to increased pedestrian traffic adjacent to the tree that accompanied changes in surrounding building use. Similarly, Catton et al. (2007) found that decline of a large, indigenous bur oak (*Quercus macrocarpa* Michx.) population in Winnipeg, Canada coincided with a period of intense urban development and suggested that changes in natural drainage patterns had exposed the trees to unfavorable, water-logged soils. Stravinskiene and Simatonyte (2008) evaluated growth rings of Scots pine (*Pinus sylvestris* L.) growing in two city parks in Lithuania and attributed a period of growth decline to adverse conditions, such as air pollution, following an exceptionally cold winter in 1979–1980, which likely weakened the trees.

Dendrochronological data can also be used to evaluate urban tree planting specifications (the detailed plans of how a planting site will be constructed and the tree planted). Neal and Whitlow (1997) analyzed 96 increment cores of *Quercus phellos* L. (willow oak) in Washington D.C. and found that trees planted in irrigated, fertilized lawns grew significantly more for the first seven years than trees in non-irrigated lawns, parkland, tree lawns, shared beds, linear pits, or vault systems (uncompacted soil/gravel mix below supported pavement). Because interest in the role of trees in urban ecosystems is increasing (Pickett and Cadenasso 2008), dendrochronology may be a useful tool, not only for interpreting the interactions of these trees with their immediate environment, but also for creating tree biomass growth models for urban ecosystems, which has implications for emerging issues such as air quality, carbon sequestration, and stormwater abatement.

Despite its potential use for studying ecology of urban forests in the southeastern U.S., live oak has not been examined to test the feasibility and reliability of crossdating its tree rings. Anecdotal evidence suggests live oak growth rings cannot be reliably identified because of their semi-ring porous nature and missing or inconsistent ring boundaries. The objective of this study was therefore to develop a method to consistently identify growth rings in live oak cores and cross-sections qualitatively via visual inspection and quantitatively by conducting correlation analyses on ring measurements obtained from live oak cores to ensure crossdating accuracy. Both urban and non-urban specimens were analyzed to determine whether urban trees, which are generally exposed to rather heterogeneous conditions that may be reflected in dendrochronological analyses, can still provide ring patterns suitable for drawing conclusions about historic and environmental events as well as data for other types of urban ecosystem studies.

Materials and Methods

Specimen collection

Increment cores were collected in the summer of 2008 from 100 live oaks growing in urbanized areas of Jacksonville, Florida. One or two cores were taken per tree at 1.4 m above ground level. When two cores were sampled, they were extracted from opposite sides of the tree.

All trees were growing in confined spaces such as sidewalk cutouts, road medians, and parking lot islands. Sampled trees had a mean height of 8.7 m (SE=0.2) and a mean trunk diameter of 28.4 cm (SE=0.9) measured at 1.4 m above ground level. Tree cutouts (openings within paved areas, such as sidewalks, created for tree planting) had a mean area of 16.8 m^2 (SE=1.9) with the smallest being 1.7 m^2 and the largest 97.6 m^2. Only trees appearing healthy were chosen for sampling to avoid any incomplete cores caused by internal stem decay.

To supplement the urban tree core samples, four cross-sectional specimens were obtained from trees at four additional locations in the Southeastern U.S.: Beaufort, South Carolina (an urban environment); Charles Pinckney National Historic Site, Sullivan's Island, South Carolina (a rural but managed area); Augusta, Georgia (an urban golf course); and New Smyrna Beach, Florida (a rural setting in a former sugar plantation). The samples were complete or near complete cross-sections from dead trees and the agencies or individuals providing the samples were primarily interested in obtaining an age estimate for their tree. No downsizing was possible because the samples had to be returned to their owners. Because of the immense weight of these specimens (up to 90 kg), the measurement of tree-ring widths via either a Velmex measuring stage or WinDendro was not possible. Nonetheless, these samples afforded a rare opportunity to closely evaluate the growth ring structure of live oak for its dendrochronological potential.

Specimen preparation

Once mounted, core samples were sanded using an ANSI 60-grit (250–297 μm) sanding belt with a belt sander until about half of the core diameter was removed. The samples were then sanded by hand with progressively finer paper up to ANSI 400-grit (20.6–23.6 μm) (Orvis and Grissino-Mayer, 2002). The cross-sections were also progressively sanded using a belt sander and ANSI 60- to 400-grit sanding belts until a high polish was obtained. The goal was to produce the largest possible surface for analysis of tree rings on the core samples, and produce as smooth a surface as possible by removing all scratches to avoid obscuring the faint ring features. The cross sections were evaluated qualitatively by marking each ring boundary along portions of the polished surface to obtain an age estimate from pith to bark. Because no measurements were possible, the tree rings were not crossdated statistically, nor were skeleton plots feasible because individual rings varied in width from one side of the section to the other (i.e., the rings were non-concentric).

Protocol verification

To ensure accuracy of the measurements obtained from the core samples, two independent analysts marked the annual rings of each series. The analysts independently agreed on approximately 96% of ring measurements. The remaining 4% of rings were reevaluated by both analysts until they reached consensus. Every 10th ring was labeled based on the technique described by Stokes and Smiley (1968). A Velmex measuring system with a precision of 0.001 mm coupled with the measurement software MeasureJ2X were used to measure widths of the marked rings.

COFECHA (Holmes, 1983; Grissino-Mayer, 2001) was used to evaluate the crossdating accuracy of each series against all others by calculating interseries correlations, which measures the strength of the overall dating. For each series, 20 year segments lagged successively by 5 years were examined. These short lengths were necessary because the living live oaks, typical of many street trees, were quite young when cored with a maximum of 29 years. COFECHA flagged those segments on each series having correlation coefficients below the correlation coefficient associated with the 99% confidence level (Grissino-Mayer, 2001). Segments with potential errors were carefully re-inspected and if a dating error was found they were re-dated and re-measured to ensure crossdating accuracy. The series with the highest interseries correlations ($r > 0.40$) were used to create a final chronology that demonstrates the potential of live oak for dendrochronological analyses.

The influence of climate (precipitation, temperature, Palmer Drought Severity Index (PDSI), and Palmer Hydrologic Drought Index (PHDI)) was analyzed via Spearman's rank correlation tests using the RESIDUAL chronology produced by ARSTAN. The Spearman's correlation analysis was appropriate here because of the short length of the RESIDUAL chronologies developed due to the young ages of these urban trees, and the difficulty in proving normality on so few observations (Chen and Popovich, 2002). The calculation of the residual chronology removes effects of autocorrelation arising from biological inertia from year to year that can potentially mask any climate information (Fritts, 1976; Cook, 1985; Henderson and Grissino-Mayer, 2009).

In addition, possible influences of site conditions, soil conditions (available soil volume, nutrients), and tree attributes on tree growth were evaluated. Composite surface soil samples (0–20 cm), which generally contain the majority of nutrient-absorbing roots (Day et al. 2010), were taken from each urban tree planting and analyzed for plant available nutrients, cation exchange capacity (CEC), organic matter content, pH, and soluble salts (analyzed at the Virginia Tech Soil Testing Laboratory, in Blacksburg, Virginia). Plant available nutrients (excluding N) were analyzed by elemental analysis on Mehlich-1 extracts by using inductively coupled plasma (ICP) spectroscopy and organic matter was analyzed by loss on ignition. Total nitrogen and total carbon were measured by dry combustion with an automated gas combustion analyzer and inorganic nitrogen was analyzed via KCL extraction (Bremner 1965) and an auto analyzer. Tree attributes included diameter at breast height (DBH), total height, canopy projection (ground surface area covered by canopy calculated from canopy-width measurements in two perpendicular directions), and sidewalk clearance (distance to lowest branch). Soil and site conditions of live oaks with higher interseries correlations were compared to those with lower interseries correlations by performing the TTEST procedure in SAS 9.2.

Results and Discussion

Tree rings are typically identified by the abrupt transition from small latewood cells to large earlywood cells. For many deciduous, ring-porous tree species (such as those in the elm and ash family), a clear boundary can be seen between these cell types, making growth rings easily identifiable. However, live oak is an evergreen, semi-ring porous species and ring boundaries are generally less clear and can vary in clarity (Figure 5.2). Therefore, identification characteristics of live oak growth rings must be pre-defined to assure replicability and consistency. The point between small and large vessels was selected as the criterion for live oak ring identification because boundaries demarcated by terminal parenchyma were not always visible. In addition, it was found to be important to measure the cores along the same line outward from the pith because live oak growth rings are less parallel than, for example, those of Japanese zelkova (Figure 5.2). Depending on measurement location, the lack of ring parallelism may lead to variations in ring width measurements and thus decreased accuracy of overall results. It was also found essential to analyze live oak cores by two independent analysts to optimize ring identification.

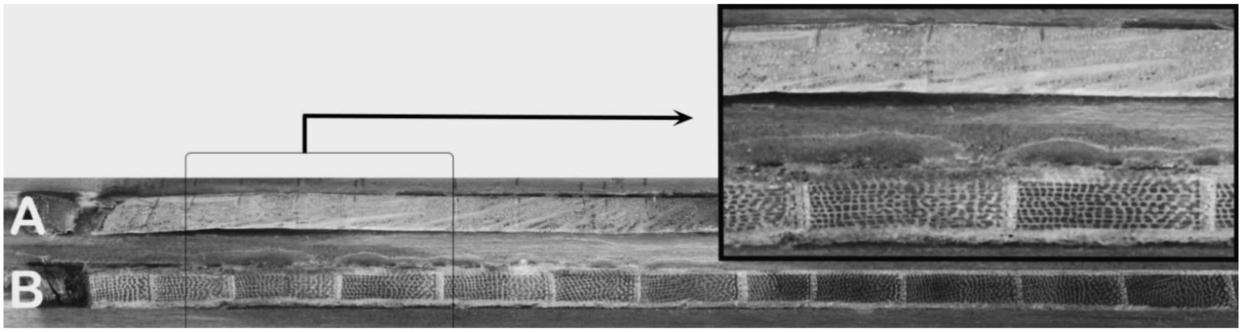

Figure 5.2 One *Quercus virginiana* (A) and one *Zelkova serrata* (B) core; magnified section in top right box. The live oak cores show markings from two analysts prior to measuring ring widths. The *Z. serrata* cores were collected from street trees in Roanoke, Virginia and are displayed here to show the considerable difference in clarity of *Q. virginiana* ring boundaries compared to *Z. serrata*.

Core analysis

The trees for which the cores were evaluated had a mean age of 16.8 years (SE=0.5) and mean ring width of 6.441 mm (SE=0.1796). Each core sample contained both pith and bark, thus our data did not include incomplete series. A total of 1,860 total rings were measured in 111 series with an overall average interseries correlation of 0.213 and an average mean sensitivity of 0.338 (Table 5.1). Although the average interseries correlation was below the generally accepted benchmark of 0.4 (Grissino-Mayer, 2001), the fact that the coefficient was positive suggests that a potentially discernable signal exists in live oak.

A low average interseries correlation was not surprising given that the core samples were collected from trees growing in very heterogeneous conditions, which are typical of urban ecosystems and likely contribute to considerable variation in tree growth rates. For example, solar radiation in urban settings can vary greatly with aspect (Tuller, 1975) due to shading by buildings and other structures. This likely influences the development of urban trees as light is one of the four factors (air, light, water and soil) essential to tree growth. Similarly, urban soils, in contrast to natural soil, often comprise of a series of layers that may not be parallel to the soil surface and these layers may have very different characteristics depending on their origin and nature (Jim, 1998a; De Kimpe and Morel, 2000). This may lead to varying soil quality. In addition, soil volume can vary greatly in urban settings, resulting in profound differences in tree growth (Grabosky and Gilman, 2004; Day and Amateis, in review). This suggests that the observed interseries correlation coefficient of 0.231 may represent a minimum expected value for this species and that the coefficient would likely increase under more uniform tree growing conditions.

Table 5.1. Summary of tree-ring data for the overall *Quercus virginiana* chronology (LO all) as well as the 27 series with >0.4 interseries correlation (LO high).

Live oak chronologies	Master series	Number of samples	AIC [a]	AMS [b]
LO all	1979–2008	111	0.21	0.338
LO high	1987–2008	27	0.65	0.398

[a] Average interseries correlation

[b] Average mean sensitivity

Development of a live oak chronology

To develop a chronology for live oak, the series with the highest correlation coefficients (>0.4) were chosen and reanalyzed with COFECHA. These 27 series had a mean growth ring count of 16.4 (range: 9 to 22). COFECHA analysis of these 27 series revealed an average interseries correlation of 0.654 and an average mean sensitivity of 0.398 (Table 5.1), indicating that a reliable analysis of live oak rings is possible.

Climate and environment analysis

The correlation of ring width indices with climate (Figures 5.3 and 5.4) showed some statistically significant correlations between all live oak and climate as well as for those 27 cores with high interseries correlation. The maximum correlations for all live oak series with climate were 0.31 for precipitation, -0.38 for temperature, 0.32 for PDSI and 0.35 for PHDI. The maximum correlations of climate with tree ring indices of trees with high interseries correlation were -0.42 for precipitation, 0.47 for temperature, and 0.38 for PDSI. However, the statistical significance of climate across all 12 months was relatively low. Only temperature in January was significantly correlated ($p < 0.05$) with ring-width index for all live oaks whereas only November temperature was significantly correlated ($p < 0.05$) with live oaks with high interseries. Similarly, Henderson and Grissino-Mayer (2009), also, correlated *Pinus palustris* Mill. tree-ring indices with the same four climate variables (temperature, precipitation, PDSI and PHDI). They found comparably high correlation with between 1 and 10 months per climate variable to be significantly correlated with correlation coefficients of up to 0.55 ($p < 0.001$).

The low correlation between live oak ring width and climate suggests that site-specific conditions (microclimate and soil properties) strongly influence tree growth. Trees growing in more similar growing conditions would be expected to show higher correlations. Comparisons of trees with high interseries correlation to those with lower interseries correlation (Table 5.2) showed that better correlated trees grew slightly faster (not significant). They attained greater size in terms of trunk diameter (mean 28.7 cm vs. 28.3 m, p=0.8105), height (mean 9.1 m vs. 8.6 m, p=0.3813), and canopy projection (56.4 vs. 55.2 m^2, p=0.8557) at a younger age (mean 16.4 vs. 16.8, p=0.7411) and had slightly lower sidewalk clearance (mean 2.3 versus 2.5 m, p=0.3213). Trees with high correlations had significantly higher available soil ammonium (Table 5.2). However, there was limited statistical evidence to allow clear conclusions to be drawn concerning why certain trees were better correlated. It seems plausible that specific site conditions that are not shared across all street trees in Jacksonville, Florida may have a stronger influence on trees at some sites than at others. These differences could in turn reduce interseries correlation statistics. More analyses need to be conducted to evaluate the ability to crossdate live oak across a range of environmental conditions. Because the trees in this study had a mean age of only about 16 years, further research is needed with trees of greater age.

Table 5.2. Mean values (SE) comparisons of tree and soil properties of 27 Quercus virginiana with high interseries correlations, >0.4 (LO high), compared to 84 series with low interseries correlation (LO low).

Properties	LO high	LO low	*p*-value*
Canopy projection (m^2)	56.4 (5.0)	55.2 (4.1)	0.8557
Sidewalk clearance (m)	2.3 (0.1)	2.5 (0.1)	0.3213
Tree height (m)	9.1 (0.4)	8.6 (0.3)	0.3813
Age	16.4 (0.8)	16.8 (0.7)	0.7411
DBH (cm)	28.7 (1.4)	28.3 (1.1)	0.8105
NH_4 (mg/kg)	2.4 (0.4)	3.4 (0.2)	0.0192
Soluble salts (ppm)	145.7 (17.8)	181.1 (12.0)	0.1442
Mn (ppm)	6.8 (1.2)	5.5 (0.6)	0.3377
Mg (ppm)	117.8 (11.9)	129.0 (6.3)	0.4006
Cu (ppm)	0.7 (0.1)	1.4 (0.9)	0.4216
P (ppm)	22.7 (3.5)	20.0 (2.0)	0.5180
K (ppm)	33.4 (4.3)	36.6 (2.8)	0.5803
Depth (cm)	55.8 (5.6)	52.9 (2.6)	0.6069
Cutout area (m^2)	18.0 (3.7)	20.2 (2.1)	0.6172
K Saturation (%)	0.6 (0.1)	0.7 (0.1)	0.6341
Mg Saturation (%)	6.2 (0.7)	6.5 (0.4)	0.7053
Ca (ppm)	3398.9 (306.0)	3517.3 (175.7)	0.7445
pH	7.6 (0.1)	7.6 (0.08)	0.7489
CEC	18.1 (1.5)	18.8 (0.9)	0.7570
Organic matter (%)	2.9 (0.4)	3.0 (0.2)	0.7994
B (ppm)	0.4 (0.1)	0.4 (0.0)	0.8226
Fe (ppm)	13.2 (2.7)	12.6 (1.6)	0.8511
NO_3 (mg/kg)	11.0 (1.6)	10.8 (1.5)	0.9103
Ca Saturation (%)	91.6 (1.8)	91.4 (0.8)	0.9334
Zn (ppm)	15.2 (2.8)	14.9 (2.2)	0.9483

*Two-sample t-test of H_0: $\mu_1 = \mu_2$

Cross-section analysis

Qualitative assessment of ring patterns from the cross sections was illustrative of the difficulties in aging and crossdating tree rings in live oaks. First and foremost, the rings were not distinct (Figure 5.5), although rings formed early in the life of the tree (< 30 years) were more clear and discernible than rings formed later (Figure 5.6). Ring boundaries were successfully delineated, however, only because specimens were large cross sections, which allowed inspection of a greater surface area to identify the rings. The analysis of cores from such large trees may have resulted in considerable error in obtaining accurate ring counts may have occurred. Second, the widths of the rings were not consistent from one area of the cross section to another area (Figure 5.5). One of the requirements for crossdating in dendrochronology (and especially for dendroclimatic analyses) is that tree rings display consistent widths around the circumference of the tree. Crossdating older live oaks would be challenging because narrow rings (on which crossdating largely emphasizes) on one side of the tree could potentially be wide rings on the opposite side of the tree. This finding suggests that obtaining meaningful paleoclimatic information from long live oak tree-ring chronologies could be difficult, although future research should consider measuring ring widths along several radii along the cross sectional areas of live oaks and average together these data to compare with climatic data.

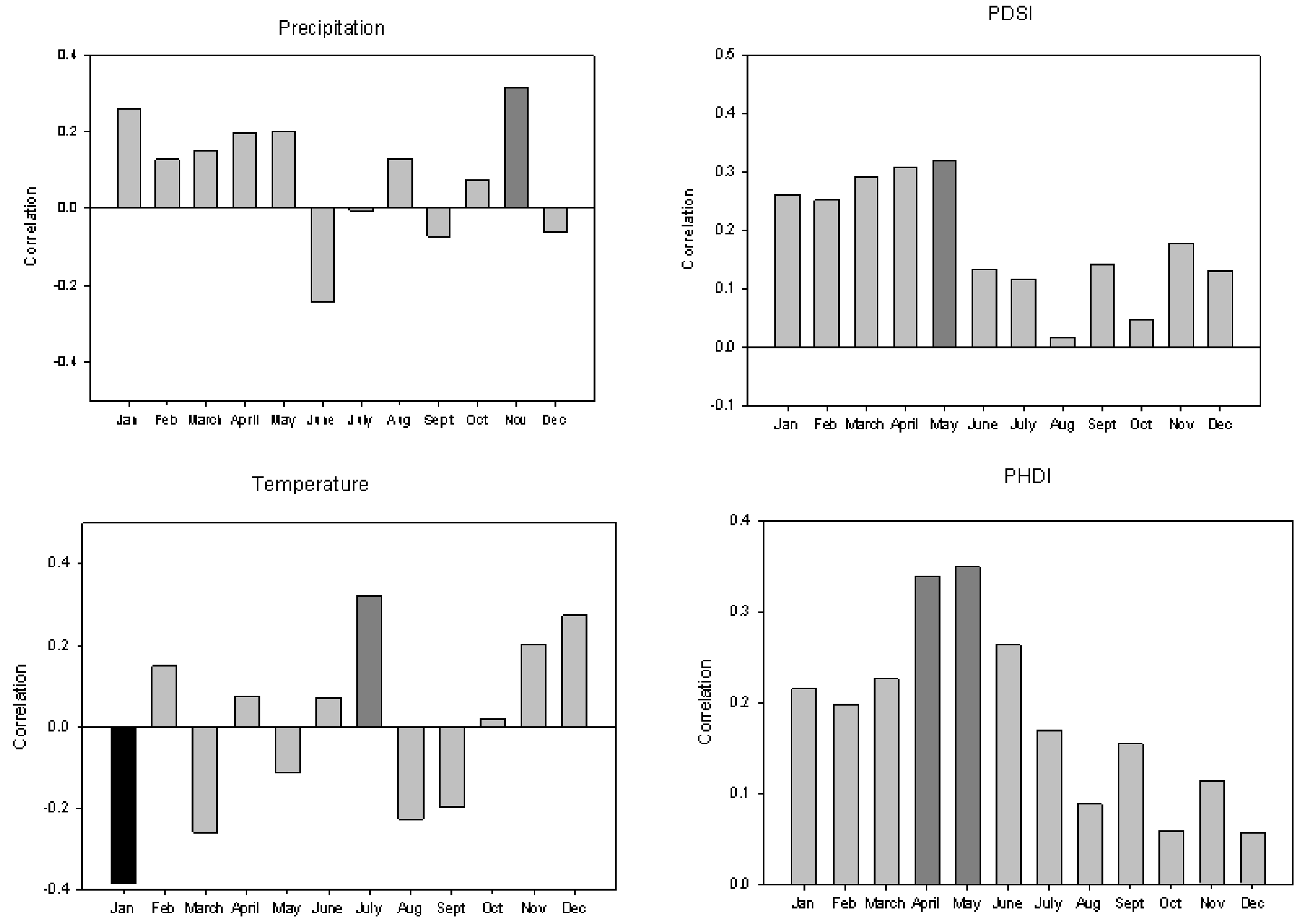

Figure 5.3 Correlations between tree-ring indices (1979-2008) of *Quercus virginiana* cores and precipitation, temperature, Palmer Drought severity Index (PDSI), and Palmer Hydrologic Drought Index (PHDI). Black and grey bars indicate a significant correlation at the a=0.05 and a=0.1 level, respectively.

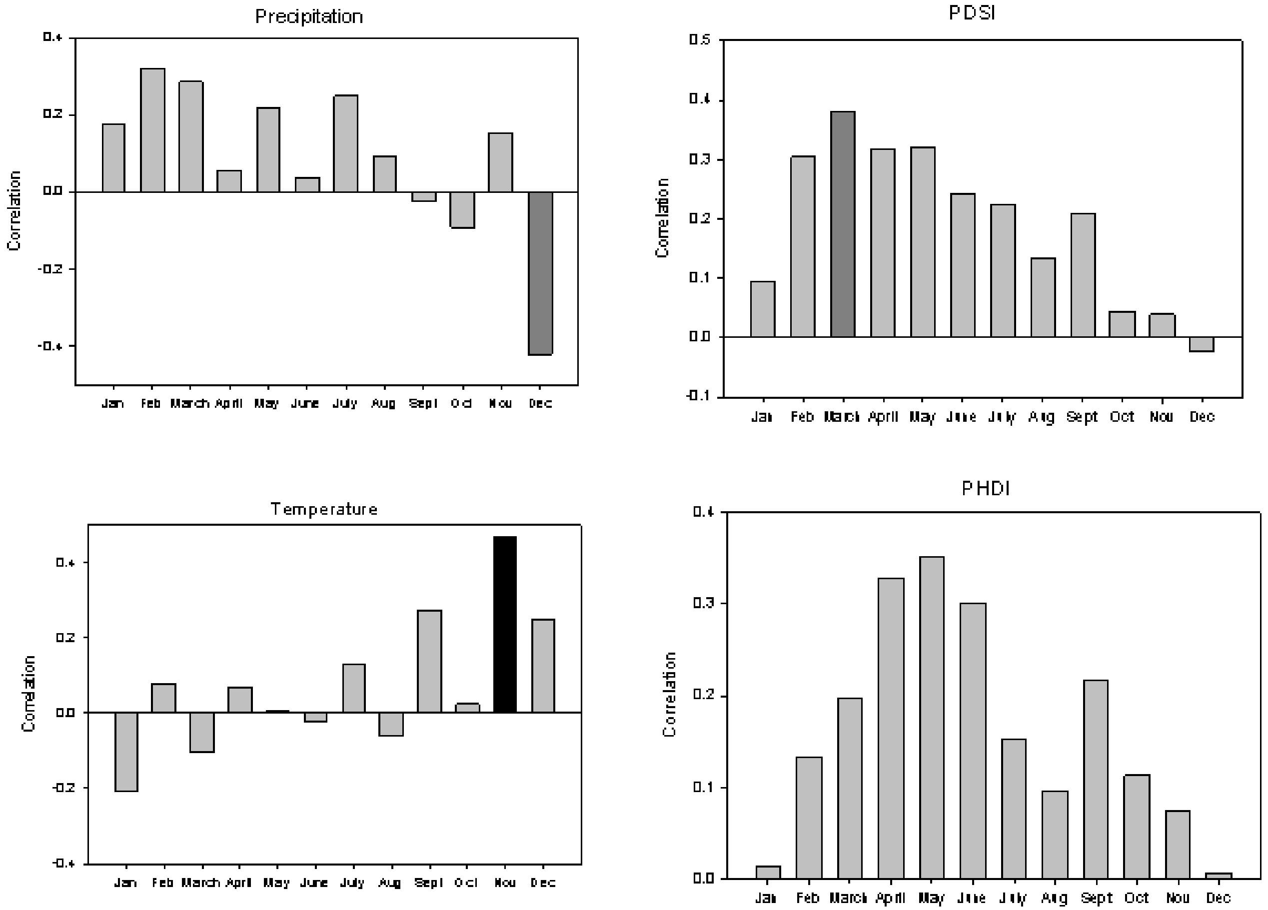

Figure 5.4 Correlations between tree-ring indices (1987-2008) of *Quercus virginiana* cores with high interseries correlation (27 series) and precipitation, temperature, Palmer Drought severity Index (PDSI), and Palmer Hydrologic Drought Index (PHDI). Black and grey bars indicate a significant correlation at the a=0.05 and a=0.1 level, respectively.

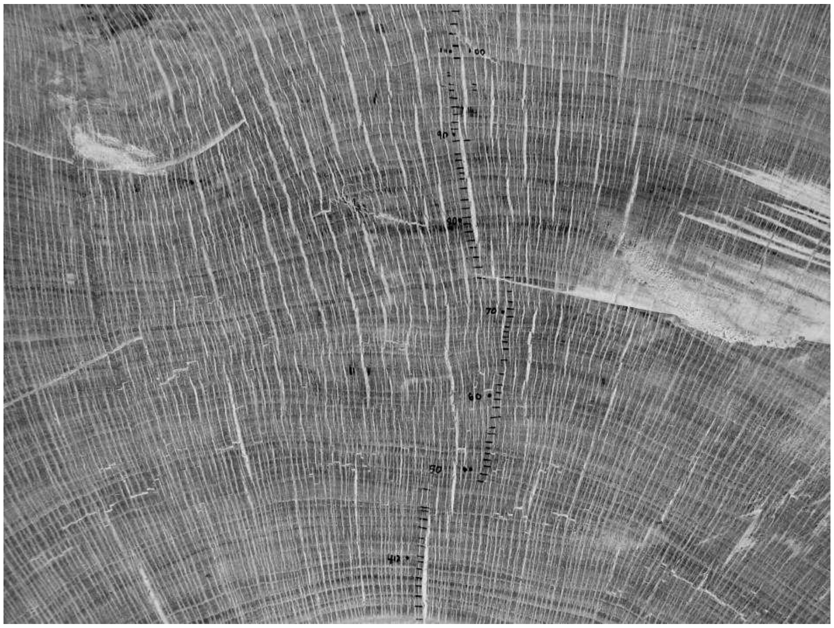

Figure 5.5 Tree-ring patterns on a *Quercus virginiana* from a former sugar mill plantation in Florida, showing indistinct and non-concentric ring patterns, making aging and crossdating difficult on this species.

Figure 5.6 Tree-ring patterns on a *Quercus virginiana* from the Charles Pinckney National Historic Site in South Carolina, showing more distinct but still non-concentric tree rings during early growth of the tree.

Conclusions

Growth patterns of 100 live oaks growing in urban settings as well as four live oak trunk cross-sections were assessed to evaluate the potential for dendrochronological analyses. Live oak rings are often faint, presumably because live oak is an evergreen, broadleaf species found in regions where winter temperature and precipitation patterns may deter a distinct dormancy period. Thus live oak growth rings can be easily missed if samples are not prepared and evaluated carefully. Careful sanding, establishing one measurement line extending out from the pith, and using two independent analysts were found to give reliable results and decreased the potential of missing rings.

Tree core analysis resulted in an overall interseries correlation of 0.213, showing a discernable signal in live oak. Samples with a high correlation coefficient ($r > 0.4$) were used to develop a chronology for live oak. This analysis revealed an interseries correlation of 0.654, suggesting that a more robust analysis of live oak tree growth is possible with the methodology used in this study. Because regional climate indicators did not strongly correlate with tree growth, site-specific conditions (such as plant-available soil quality and quantity) may play a significant role in urban tree development. The concept of a strong influence of site variables on tree growth may explain the lower overall interseries correlation; however, comparisons of single soil variable of trees with high interseries correlation to those with low interseries correlation did not provide conclusive statistical evidence for this assertion. Nonetheless, the data show that tree-ring analysis of live oak is possible and can result in high interseries correlation. However, urban trees are exposed to varying above and below ground conditions and these varying soil conditions likely influence tree growth significantly to the extent that interseries correlations are adversely influenced. To take these highly variable urban soil and site conditions into account, it may be prudent to lower the generally accepted correlation threshold of 0.4 when conducting dendrochronological analysis in an urban environment.

Only cores from relatively young urban street trees growing in confined spaces were used in this study, yet the average interseries correlation was positive, and the live oak chronology showed a high interseries correlation. If trees had been older and/or growing in natural conditions, one would expect these signals to be stronger. However, the difficulty in delineating ring boundaries on older sections of live oaks, coupled with the high variation in individual rings along the circumference of the tree bole, could preclude identifying a strong climate signal from older live oaks. Further research on older trees as well as trees growing in natural environments is needed to further develop information on the accuracy of dendrochronological analyses of live oak.

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Chapter 6: New models for predicting growth and expected size attainment for urban street trees

Introduction

Urban trees provide a wide range of ecological, socioeconomic, and aesthetic benefits, yet many trees do not reach their genetic potential for height and canopy size resulting in suppressed benefit provision. This inhibited tree growth results from harsh above- and below-ground growing conditions. Many benefits provided by trees are well known and appreciated by the public, especially in the urban environment where environmental quality can be vastly impaired by many anthropogenic activities (Callender and Rice 2000; Koerner and Klopatek 2002). Ecological and environmental benefits provided by urban vegetation (including trees) include the reduction of atmospheric carbon through carbon sequestration (Nowak 1993); improvement of water quality (Nowak 2005) as well as air quality (Scott and Simpson 1998); reduction in stormwater runoff through rainfall interception (Xiao and McPherson 2003), improvement of soil infiltration (Bartens et al. 2008), and water use by trees (Calder et al. 2008; Cermák et al. 2000; Hinckley et al. 1994; Simpson 2000); and provision of wildlife habitat (Calder et al. 2008; Dwyer et al. 1992). Vegetation can also help decrease crime (Kuo and Sullivan 2001), shorten the time hospital patients need to recover (Ulrich 1984), reduce noise pollution (Fang and Ling 2003), lower energy costs (Dwyer et al. 1992), increase property values (Martin et al. 1989), and generally provide aesthetic benefits valuable to peoples' everyday life (Wolf 2004). However, benefits provided by trees are greatly affected by tree size and species.

The majority of beneficial tree functions are related to the leaf area of the tree (McPherson et al. 1998; Peper et al. 2001a, b; Scott and Simpson 1998). In addition, to assure a minimum level of benefits provided by trees, many municipalities develop canopy goals (percent of land area covered by tree canopy), sometimes to be reached within a certain time period, such as within 15 or 20 years. One guideline to determine canopy goals for a municipality are recommendations by American Forests which include 40% canopy cover on average for humid climates as well as 25% for drier regions (American Forests, 2006). In addition, canopy conservation as well as tree preservation ordinances have been developed (and are enforced) by many municipalities to conserve existing canopy cover in areas of new development as well as preserve trees during and after construction. However, to assure a certain canopy cover for a municipality and benefits from urban trees, it is essential to predict the eventual size and canopy of individual trees confidently.

Various models that describe tree growth have been developed over time, however, most of these are targeted to estimating and maximizing timber production in the rural environment. It has been found that growth-prediction models are not easily, if at all, transferable to the urban environment (Peper and McPherson 1998) with a majority of models varying in prediction ranges by ca. 100 to 200% (McHale et al. 2009). Tree growth models are therefore needed that focus on the urban environment.

A number of models have been developed that estimate canopy information from current inventory measurements. The primary purpose of these models has been to provide a basis for calculating ecosystem service provision for the existing urban forest stand. These include models to:

1) estimate above-ground biomass (Nowak 1996; Nowak and Crane 1998; Nowak et al. 2008; Peper et al. 2001a, b; Valentine and Mäkelä 2005; Banks et al. 1999; Buckley

and Roberts 2005; Larsen and Kristoffersen 2002; Peper and McPherson 1998; Stoffberg et al. 2008), and

2) estimate canopy/biomass-based ecological benefits such as carbon storage (McHale et al. 2009; Nowak and Crane 1998; Nowak et al. 2008) of urban trees (Summary Table 2.1 in Chapter 2).

However, there has been insufficient information available to develop models to predict urban tree growth, and thus ecosystem service provision, into the future. Leaf area and thus the level of benefits provided by urban trees have been found to depend on a number of factors. Although certain shade trees have a high leaf mass, conifers tend to be evergreen and may have a higher leaf mass per unit canopy projection (Karlik and Winer 2001). However, this may indicate greater level of benefits in regards to e.g. stormwater runoff reduction through transpiration, but may imply lower levels of shade provision. Larger trees generally provide a higher level of benefits than smaller trees (McPherson 1992; Nowak 1994b). In turn, the size of the tree depends on species (Neal 2002; Peper et al. 2001a), and growing conditions (Harris and Bassuk 1993; Kjelgren and Clark 1992a, b), including soil conditions and water availability (Paludan-Müller et al. 2002; Lindsey and Bassuk 1991). Urban soils can be very heterogeneous (De Kimpe and Morel 2000; Jim 1998a), making the determination of their influence on tree growth an important component of any model. Although many environmental factors significantly influence some trees, it can be said that soil conditions, including water and nutrient provision, influence all trees.

A significant component of the urban forest is made up of trees bordered by pavement, such as street trees and trees in parking lots, plazas, or medians. In these situations, soil volume as well as planting pit size are among the most critical site factors when it comes to tree growth, although these effects can vary by species and region (Grabosky and Gilman 2004; Day and Amateis in review). Recommended soil resources are typically described in terms of volume, although studies typically measure exposed soil surface area only and estimate volume based on assumptions about soil depth available for rooting (e.g. Kent, 2006). Kent et al. (2006) evaluated the conditions of various tree species, including *Acer rubrum* (red maple), *Magnolia grandiflora* (Southern magnolia), and *Quercus virginiana* (live oak), growing in varying planting pit sizes (depth was assumed the same for all plantings) in a major parking lot in Orlando, FL. They found a significant effect of planting pit size on tree conditions. Trees growing in less than 2.8 m^2 of soil were more likely to be in poor condition or have died prematurely. On the other hand, the majority of trees growing in at least 28 m^2 of soil and all trees growing in a minimum of 42 m^2 of soil were in good condition. Observations of the influence of available soil volume on tree growth and health has resulted in minimum soil volume recommendations ranging from 0.3 m^3/m^2 crown projection (CP) (Lindsey and Bassuk 1992), over 0.6 m^3/m^2 CP (Vrecenak and Herrington 1984) and 0.76 m^3/m^2 CP up to 1.71 m^3/m^2 CP (Helliwell 1986), the latter two recommendations being adapted from interpretations of the model presented by Lindsey and Bassuk. Although these recommendations are impractically high for many urban landscapes and are based on tree water demand rather than tree growth, it becomes clear that most conventional tree planting sites, such as sidewalk tree pits or parking lot islands, offer insufficient soil volume to support long-term tree growth. In addition, soil surrounding these sidewalk tree pits is typically soil compacted to meet engineering standards for road and sidewalk construction making soil compaction another critical factor to tree growth.

Compaction is a common problem for urban trees surrounded by hardscape because the underlying soil must be compacted to provide high load-bearing capacities to prevent pavement failure (Grabosky and Bassuk 1995; Alberty et al.

1984; Pan and Bassuk 1985). As a result, root growth, hydration, and aeration are hindered. Soil strength influences plant growth similarly to bulk density (Thompson et al. 1987; Sands et al. 1979). High soil strength has been found to decrease primary and lateral root length (Misra and Gibbons 1996), root elongation (Ehlers et al. 1983), and leaf area (Masle and Passioura 1987). Soil strength as well as bulk density is buffered by soil organic matter (Soane 1990). Soil organic matter not only improves soil physical properties such as soil strength, soil structure, porosity, and water holding capacity, it also nourishes soil microorganisms and thus plants (Brady and Weil 2002d). However, urban soils may lack organic matter resulting in low or no organic-matter decomposition and thus insufficient plant nutrients (Jim 1998a).

Besides soil physical characteristics, soil chemical properties, such as available soil nutrients and soil acidity, can highly influence tree development. Macronutrients such as nitrogen, phosphorus, potassium, calcium, and magnesium are essential to plant growth as they are constituents of many organic compounds and integral to metabolic processes such as photosynthesis and respiration (Finck 1991; Mengel and Kirkby 2001; Pallardy 2008). Available soil nutrients oftentimes depend on soil pH. Soil alkalinity can cause deficiencies of micronutrients such as boron, copper, iron, manganese, and zinc in many tree species (Mengel and Kirkby 2001). Although most eastern hardwood species are adapted to low pH (<7), urban soils are often alkaline (Scharenbroch et al. 2005) due to the use of concrete and other calcareous materials in buildings and sidewalks (Jim 1998b). As a result, tree species and cultivars tolerant of alkaline soils are often recommended for urban plantings (Appleton and Chaplin 2001; Bassuk et al. 2003).

To estimate future canopy and ecosystem services of urban forests, models must be developed to predict tree growth and ultimate tree size for the types of settings prevalent in urban areas. The ability to predict growth can provide a more realistic foundation for developing sound urban forest policy and management. The site restrictions for urban trees are very different than those of rural trees. This project aims to develop a protocol and initial models for estimating future tree growth and canopy development of trees growing in confined urban planting spaces.

The fact that a) all trees are influenced by the soil conditions they are growing in, b) in confined urban spaces surrounded by pavement soil conditions may be the most limiting factor for growth, c) soil conditions can be readily measured, and d) soils can be modified in advance, led us to focus on developing urban tree growth models based on soil chemical and physical properties.

The objectives of this project were therefore to 1) evaluate relationships of soil properties to tree growth and 2) develop growth prediction models for three common urban tree species, *Quercus phellos*, *Quercus virginiana*, and *Zelkova serrata* growing in two generally different climatic conditions; Washington DC and Jacksonville, FL. Tree growth models were developed based on the following hypothesis:

- Regression analysis with a wide range of soil and site attributes results in significant prediction models (α=0.05) for *Q. phellos*, *Z. serrata*, and *Q. virginiana*
- Tree growth influencing variables vary by climatic condition (e.g. USDA hardiness zone)
- Tree growth influencing variables vary by soil texture class (loam vs sand).

Materials and Methods

Site Description

In summer 2008, 184 urban tree planting sites were evaluated in Washington, DC (lat. 38° 54′ 10″ N, long. 77° 01′ 45″ W) and 100 in Jacksonville, FL (lat. 30° 20′ 02 N, long. 81° 39′ 46 W). These study sites were selected because they provided two different climatic conditions as well as regionally distinct soils. Washington, DC is located in USDA hardiness zone 7 (mean annual low temperatures of -12 to -18°C) whereas Jacksonville, Florida is located in USDA hardiness zone 9 (mean annual low temperature of -1 to -7°C) (Cathey 1990). The soil in Jacksonville is predominantly sandy according to urban soil surveys (NRCS 2010a) while in Washington DC loamy soil predominates (NRCS 2010b).

Tree species

Common urban tree species were chosen with ring to semi-ring porous annual growth patterns to assure confident tree ring analysis. Tree species sampled in Washington, DC were *Quercus phellos* L. (willow oak) and *Zelkova serrata* (Thunb.) Mikano (Japanese zelkova) whereas *Quercus virginiana* Mill. (live oak) was chosen in Jacksonville, FL. *Q. phellos* is a medium to large, fast growing, bottom land species. Its range reaches from New Jersey and southeastern Pennsylvania to Georgia and northern Florida and west to eastern Texas and southeastern Oklahoma and Arkansas. It grows in humid and temperate climates with 180-190 frost-free days in the north and 300 in the south-southwestern range. *Q. phellos* grows best on deep, relatively undisturbed soils that are medium textured, silty or loamy, with no compaction in the top 30 cm and optimally pH values of 4.5-5.5 (Schlaegel 1990). *Zelkova serrata* is native to Japan and widely planted within the US in USDA hardiness zones 5-8. It can potentially reach a height of about 40 m (120 ft) with a spread generally less than its height. *Z. serrata* prefers moist and deep soils but it is said to be pH adaptable (Dirr 1998), meaning that a wide range of soil pHs are tolerated. *Quercus virginiana* is an evergreen, broadleaf species growing from the Coastal Plain of the southeastern states, west to southern and central Texas. The climate in its native range is humid with frost-free periods of 240-300 days. *Q.*

virginiana most often grows on sandy soils and tolerates high levels of soil salinity (Harms 1990).

In the urban environment, most street trees are planted in single-tree street tree cutouts, medians, or planting strips between sidewalks and streets, more often than not in very confined spaces. Thus only trees in confined spaces were included in the study to minimize trees with “escaped” roots into open space and thus obtained access to unquantifiable resources. Dead trees and trees in poor conditions were excluded from this study because concealed decay would have limited growth-ring analysis and may have resulted in damage to increment borers. Planting space served as another criterion to determine which trees were sampled. The goal was to include a wide range of planting designs to incorporate a variety of cutout sizes and tree-available soil volumes.

Measurements

Soil Measurements

Soil physical properties. Soil strength was measured with a cone penetrometer (SC 900 Soil Compaction Meter, Spectrum™ Technologies, Inc.). Penetrometer measurements were taken at three locations within each tree planting site. To evaluate different soil layers, measurements were recorded at 2.5 cm intervals until the bottom of the tree pit was reached. For analysis of gravimetric moisture content and soil texture, a composite soil sample for each 10-cm depth increment from a minimum of 3 locations within each tree planting site was collected with a 22-mm diameter soil probe. In addition, volumetric soil water content was measured at two to three locations per site *in situ* at 0-20 cm using a time domain reflectometer (FieldScout TDR 100, Spectrum Technologies, Inc., Plainfield, IL). Soil texture was determined via particle size analysis using the hydrometer method including organic matter removal with hydrogen peroxide (Day 1965).

Soil volume and exposed soil surface area. Tree planting soil depth was measured with a graduated metal rod pushed into the ground until very high resistance was met (i.e. it was impossible to push it further manually), which was assumed to be the bottom of the tree pit. Measurements were taken at 3-5 locations within each planting, depending on tree pit size. Exposed soil surface area of the tree planting was assumed to represent the horizontal dimension of the soil volume and was measured with a measuring tape in two directions when the tree planting shape was rectangular. More complex shapes were broken down into easy-to-calculate geometric shapes for area calculations.

Soil chemical constituents. Plant available soil nutrients, cation exchange capacity (CEC), organic matter content, pH, and soluble salts were analyzed by the Virginia Tech Soil Testing Laboratory, Blacksburg, VA. Plant available nutrients (excluding N) were analyzed by elemental analysis on Mehlich-1 extracts by using inductively coupled plasma (ICP) spectroscopy. Soil organic matter was analyzed via loss on ignition. Analyses of plant available nutrients and soil organic matter were performed on composite surface soil samples (0-20 cm). Surface soil was chosen as the majority of nutrient-absorbing tree roots are commonly found here in urban settings (Day et al. 2010). Total nitrogen and total carbon were measured by dry combustion with an automated gas combustion analyzer (Elementar VarioMax CNS, Hanau, Germany). Inorganic nitrogen was analyzed via KCL extraction (Bremner 1965) and an auto analyzer (TRAACS 2000 Analytical Console, Bran-Luebbe, Nordersted, Germany).

Tree parameters

Trunk diameter at breast height was measured with a sliding caliper at 1.37 m above the ground in two perpendicular directions. **Tree height, trunk height/road clearance** was measured with a Vertex hypsometer (Haglof Inc., Långsele, Sweden). **Canopy dimensions** were measured with a measuring tape in two perpendicular directions and canopy projection was calculated from these measurements by assuming an ellipse (Canopy projection = π * Canopy radius I * canopy radius II). Because trees were growing in highly urbanized areas surrounded by frequent vehicular traffic oftentimes within two feet of the tree trunk, we were not able to persistently measure canopy dimensions with the same orientation (aspect) while maintaining personnel safety. **Crown volume** and **crown transparency** were analyzed from digital pictures with the software "Urban Crowns" developed by Sang-Mook Lee, Matt Winn, Philip Araman, and others (USDA Forest Service Southern Research Station, Blacksburg, VA; software not commercially available at this point).

Increment cores for analysis of tree growth patterns and rates. One to two cores were taken from each tree at approximately 1.37 m above ground level using an increment borer (Haglof Inc., Långsele, Sweden). When two cores were sampled, they were extracted from opposite sides of the tree at a 5 to 10 cm vertical offset. Samples were mounted on slotted wooden holders on the same day that they were collected to ensure they would remain straight after drying. Core samples were first sanded using an ANSI 60-grit (250–297 µm) sanding belt with a Makita belt sander (Makita USA, Inc. La Mirada, CA, USA) until about half of the core diameter was removed to produce the largest surface area for the analysis. The samples were then sanded by hand with progressively finer paper up to ANSI 400-grit (20.6–23.6 µm) (Orvis and Grissino-Mayer 2002) to produce as smooth a surface as possible by removing all scratches to avoid obscuring any faint ring features. A TA Unislide Tree-Ring Measurement System (Velmex Inc., Bloomfield, NY) with a precision of 0.001 mm coupled with the measurement software MeasureJ2X (VoorTech Consulting, Holderness, NH) were used to measure widths of the marked rings. COFECHA (Grissino-Mayer 2001; Holmes 1983) was used to evaluate the crossdating accuracy of each series against all others by calculating interseries correlations, which measures the strength of the overall dating. For each series, 20-year segments lagged successively by 5 years were examined. These short lengths were necessary because the sampled trees, typical of many street trees, were quite young when cored. COFECHA flagged those segments on each series having correlation coefficients below the correlation coefficient associated with the 99% confidence level (Grissino-Mayer 2001). Segments with potential errors were carefully re-inspected and if a dating error was found they were re-dated and re-measured to ensure crossdating accuracy.

Statistical Analysis

Data exploration techniques were used to identify appropriate parameters for use in developing regression models to predict tree growth patterns. Growth-prediction models were developed using the REG procedure in SAS 9.2 (SAS Institute Inc., Cary, NC, USA). Stepwise regression as well as Mallows' CP statistic were used to identify the predictor variables appropriate for each response variable. Multiple linear regression was used to develop the models because it can be assumed that, in the range of data collected, a linear relationship is present. The variables were evaluated based on the p-value (α=0.05), the variance inflation coefficient (to determine multicollinearity), and the magnitude and sign of the parameter for each variable. The fit of the models was then evaluated based on the distribution of the residual compared to the predicted data (Appendix II and III). If the residual graphs showed a discerning pattern, the response variable was transformed (logarithmic transformation) and the process was started again. If the residual did not show a discerning pattern, the model was determined appropriate.

Data Analysis: Response Variables

Growth rates: Identification of the growth period of interest

Transplant shock typically greatly slows tree growth for several years after transplanting. We therefore excluded the post-transplant period from our analysis of growth rate and identified a "period of interest" for growth analysis that began after recovery from transplant shock and extended to the measurement year The growth period of interested was determined by identifying and excluding the transplanting period, the period of poor growth following transplanting of the tree from the nursery into the urban environment. Annual ring width first graphed and the first 10 years of growth visually analyzed for growth patterns. The first precipitous drop followed by depressed growth followed by sustained increase was determined to be the transplanting year. DBH at transplanting was noted. The first sustained increase in growth was determined to be the start of the 'growth period of interest'. We compared this information with the digital pictures and information obtained from city foresters concerning planting practices to evaluate the reasonableness of the result. If it was reasonable, the next tree was analyzed. If it was not reasonable, for example, the DBH at transplanting was 1.5 cm based on our data although trees in DC were commonly planted at 5 cm, then the second precipitous depression was considered. If no clear depression could be identified, the first 4 years of growth (at breast height) were excluded to result in the 'growth period of interest'. The growth period of interest was used for further analysis of growth rates.

Growth rates: point of maximum growth

By collecting tree ring data, we were able to analyze growth patterns over the life history of the tree. Although urban trees are widely spaced and do not experience the same type of competition from other trees that trees in rural forests experience, tree growth appears to slow once site capacity is reached. Thus, determining the age and size when growth is suppressed is of interest for predicting urban tree growth rates and patterns. Therefore, once the growth period of interest (growth excluding transplanting period) was determined, an 'age of apparent suppression' was calculated by two methods. First, a graphical analysis of cumulative ring width of individual trees was used to calculate this point. We predetermined that a decline in slope of cumulative ring width (slope=0.85) followed by two years of low growth (slope<1) identifies the 'age of apparent suppression'. A slope of 0.85 was determined based on cumulative growth patterns of trees that showed a clear decline and thus 'age of apparent suppression'. Two years of low growth had to follow the 0.85-slope year for each tree to be identified as the 'age of apparent suppression' because trees show slow growth on a yearly basis due to unsuitable weather conditions thus only a persistent decline could indicate the age of apparent suppression.

Stepwise approach one to calculate 'age of apparent suppression'*; the "ratio < 0.85" method:*

1. Cumulative growth was calculated for each increment core for the 'growth period of interest'
2. The sum per year per tree was calculated to determine the diameter increase per year
3. The slope for each year segment was calculated
4. The average slope for each 3-year segment was calculated

5. The ratio between the slope of each 1-year segment and the previous 3-year segment was calculated
6. The year at which the ratio falls below 0.85 followed by two years of < 1was determined to be the age of apparent suppression (Fig 6.1).
7. The age and DBH at age of apparent suppression was noted.

Another method of calculating the age at which growth rates of trees potentially slows down is the "peak-increment-area" method. This method estimates the age of the tree at which the tree produced its maximum area increment in the tree-ring record available. Calculating the annual growth rate on a cross-sectional area basis prior to the peak-area age and comparing it with the subsequent growth, by year, revealed a decline in growth rate post peak-area age. This analysis resulted in a significant regression model, (see example for *Q. phellos* Figure 6.X), to calculate % basal area growth post 'peak increment area' age (PIA) of average growth rate pre-PIA:

Basal area growth=0.6106*exp*(-0.1138*years after PIA); R^2=0.26; p<0.0001.

Stepwise approach two to calculate 'age of apparent suppression'; *the "peak-increment-area" method:*

1. Cumulative tree growth was calculated
2. The basal area for each year was calculated by assuming a circular shape (area = πr^2)
3. The previous year's basal area was subtracted from the current year to calculate the increase in basal area for each year
4. The year showing the greatest increase in basal area was determined to be the age of apparent suppression (Fig 6.1).

The "peak-increment-area" method resulted in one year at which the tree produced the largest increment area whereas the "ratio < 0.85" method may identify several years as "tipping point" for tree growth. However, both methods resulted in comparable results (see example Fig A.IV 6.1-3) but since the "peak-increment-area" method seems ecologically more reasonable because it identifies one year of maximum growth, this method was used for further analyses. To verify that the "peak-increment-area" method identifies the point where growth permanently slows, annual growth subsequent to the peak increment age (PIA) was compared the average growth rate up to PIA (Figure 6.1). The general declining trend in annual growth shows that the peak-increment-area method is a reasonable approach to determine the age of maximum growth, or the age after which growth rates will be slowed.

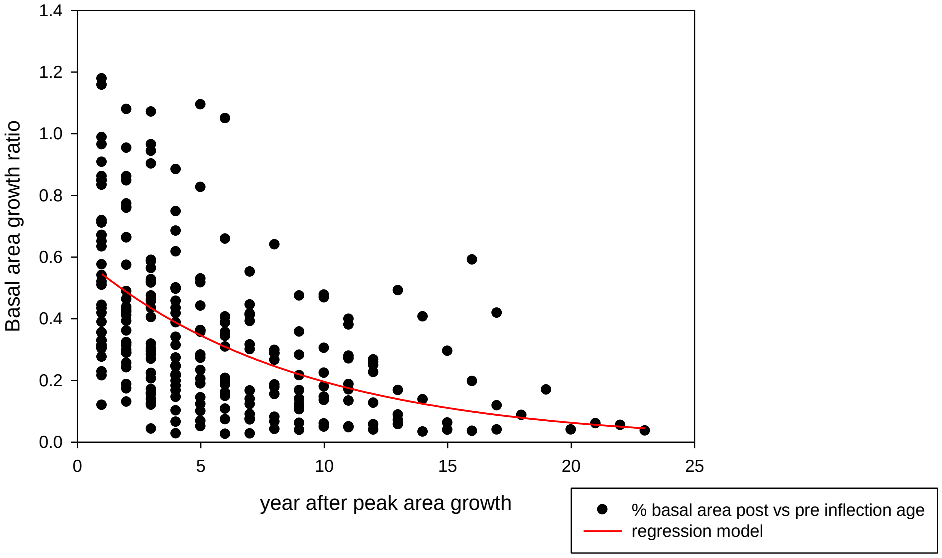

Figure 6.1 Basal area growth ratio (basal area for each year post peak increment area age (PIA)* mean annual increment area growth prior to PIA^{-1}) for 34 *Quercus phellos* growing in confined street tree cutouts in Washington, DC showing the decline in growth rate subsequent the year of maximum increment area growth.

Response-variable determination to be used for tree growth models

Six potential variables to be used as responses- variables to be estimated- were identified. Diameter at breast height, tree height, canopy projection, and crown volume as indicators for size. In addition, indicators for tree growth were developed, peak-increment age (PIA) and DBH at peak-increment age.

Response variables were determined based on 1) correlation with one another (Tables A.V 6.1–3) and 2) importance to urban forest management and policy. Correlation coefficients were calculated with the CORR procedure in SAS 9.2 (SAS Institute Inc., Cary, NC, USA).

Three tree-response variables were selected to be further used as response variables for model development for all three tree species. Canopy projection and canopy volume because both show high correlation with other response variables. These variables are also of great importance to urban forest managers as most tree benefits depend on the leaf area and therefore size of the canopy (McPherson et al. 1998; Peper et al. 2001a, b; Scott and Simpson 1998) and canopy projection is therefore often used by municipalities as a measure of tree size to be reached to assure ecosystem services. Age at peak-increment area growth (PIA) was chosen because it did not correlate well with other response variables, especially for *Z. serrata* and *Q. virginiana* yet it would be of great importance for practitioners to know at what age a tree may reach its growth maximum and thus perhaps approach the maximum level of benefits that can be expected from that tree.

Description of response variables in sampled trees

Q. phellos growing in Washington, DC showed the highest PIA (table 6.1) as well as significantly higher DBH at PIA (data not presented) indicating that these trees were growing in more suitable growing conditions than *Z. serrata* and *Q. virginiana*. In addition, *Q. phellos* had a higher average canopy volume as well as canopy projection indicating that a) trees were, again, growing in more suitable conditions for this species and b) trees were older. *Q. phellos* had an average age of 25 years, followed by *Z. serrata* with 23 years and *Q. virginiana* with 17.

Table 6.1 Means and standard errors of the three response variables chosen to be modeled for three species, 100 *Quercus virginiana* sampled in Jacksonville, FL, and 42 *Quercus phellos* and 40 *Zelkova serrata* sampled in Washington, DC.

Response variable	*Q. virginiana*	*Q. phellos*	*Z. serrata*
PIA	12.7 (0.5)	18.4 (1.4)	15.3 (6.9)
Canopy projection (m^2)	55.0 (3.3)	73.2 (6.9)	58.6 (4.2)
Canopy volume (m^3)	300.5 (29.0)	339.6 (52.9)	151.0 (17.0)

Data Analysis: Predictor variables

A total of 30 variables (Table A.V 6.4) were analyzed as potential predictor variables for tree growth. The majority of these variables, such as soil nutrients, were straight forward and needed no further conditioning. The shape of the tree planting pit, on the other hand, varied greatly from square shaped to a high length-to-width ratio. Since it can be assumed that a square-shaped planting pit would offer different soil conditions from a narrow but long planting pit of the same area, tree pit dimensions needed further definition. In addition, some tree planting strips were as long as a city block or longer, much longer than tree roots can extend. Therefore it was necessary to standardize tree pit area measurements by determining the maximum tree pit length that might still restrict tree growth.

Two tree parameters were chosen to determine to what extent increasing tree pit length influences tree growth. Diameter at breast height (DBH) and PIA were used to determine the maximum influence of tree pit length. Regression models were developed in Sigma Plot 11.0 (Systat Software Inc., San Jose, CA) for both tree parameters based on the longer tree pit side (Figure A.IV. 6.5-6; plotted in green dots for tree pit length up to 100 m)). The point at which an increase in tree pit length ceased to result in an increase in DBH or age of apparent suppression was determined.

<u>Examples of regression models:</u>

Z. serrata:

PIA=17.5938*(1-exp*(-0.4744*tree pit length))

R^2=0.08, p=0.0585

DBH= 30.8854 * (1-exp*(-0.5584*tree pit length))
R^2=0.15, p=0091

Q. phellos:

PIA= 21.554 * (1-exp*(-0.4581*tree pit length))
R^2=0.07, p=0.0725

DBH was only marginally influenced but tree planting pits longer than 5 meters whereas PIA was influenced by up to 10 m tree pit length. Although tree pit length explained only very small proportions of the variation in our response variables and the models can be used as an estimate of maximum tree pit length influencing tree growth for the purpose of our project. Thus tree pit lengths greater than 10 m were set at 10 m for further analysis.

Data Analysis: Model development

For each species, an overall growth-prediction model for each of the three response variables- crown projection, crown volume, and PIA- was developed based on all measured variables (Table Appendix V 6.4, left). In addition, 'simplified' growth-prediction models were developed based on measurements that can be easily and inexpensively done in the field (Table Appendix V 6.4, right).

Sensitivity analysis was then performed to determine what influence the statistically significant predictor variables had on the response. For each predictor variable of each developed model, the minimum, mean, and maximum influence on the response variable was determined. This was done by multiplying the particular parameter with the mean, minimum, and maximum value of each predictor distribution. The resulting values then indicate the magnitude of influence by the particular variable on the response variable within the range of data collected.

Results and Discussion

Full growth prediction models were developed based on approximately 30 soil and site variables (Table A.V 6.4, left). In addition, simplified models were developed based on easy-to-measure soil and site attributes (Table A.V 6.4, right). The following sections discuss the results starting with full models followed by the simplified models. Within each section, response variable models are discussed by species.

Full growth-prediction models

Zelkova serrata

The results for *Z. serrata* (Table 6.2) show that all three response variables can be explained by significant models with a maximum of six predictor variables, including interactions. Maximum variation of 83% can be explained for PIA, followed by 53% for canopy volume, and 49% for canopy projection.

Canopy projection was explained by Mn, P, the shorter cutout side (SCS), the interactions of pH and Cu (pH*Cu), organic matter and cation exchange capacity (OM*CEC), and soil strength and soil moisture (S*M). Manganese (mean=34.2 ppm) and P (mean=60.3 ppm) were likely deficient compared to commonly found concentrations in the soil (Mengel and Kirkby 2001) which would explain their positive influence on canopy growth. Organic matter as well as CEC would be expected to positively influence tree growth because they are associated with water and nutrient holding capacity of the soil (Brady and Weil 2002d). However, the soil in Washington, DC can be expected to descend from an old and well-weathered soil (Smith, 1976) with a potentially high capacity to store nutrients yet with only a small fraction of these exchange sites actually being occupied by nutrients. Thus CEC may only represent the potential of the soil to store nutrients but not the actual availability. In addition, organic matter content of soils in Washington, DC can be considered very high (mean=9.9%) which probably results from the high organic mulch applications that we observed. High levels of mulch applications have been found to result in water infiltration abatement and thus dryer soils which can lead to depressed plant growth (Arnold et al. 2005; Gilman and Grabosky 2004). The interaction of pH and Cu may indicate that soils were too alkaline to allow micronutrient availability. Plant available Cu levels were relatively low, averaging to less than 2 ppm, while 5-100 ppm may be commonly found in soils based on (Mengel and Kirkby 2001). Thus deficiency may be more likely than Cu toxicity because Cu toxicities have been found to result from higher Cu levels, such as 700 ppm for maize plants on calcareous soils (Guo et al. 2010). However, metals, such as Cu, have been found to be increased in urban soils through deposition by motor vehicles (Ward et al. 1977). Thus the negative effect of Cu and pH on plant growth could also be an indicator for decreasing canopy growth in areas of high vehicular traffic and the pollutants and physical damage associated with it rather than Cu and pH levels per se. This notion is strengthened by the fact that alkaline soils, such as those in Washington, DC, show generally low availability of elements such as Cu due to their dependency to soil acidity (Mengel and Kirkby 2001) yet high temporal variability

(Robertson and Taylor 2007). Thus the levels may have been low for our samples but may not actually be representative of long-term status. Canopy projection was also positively influenced by the soil strength * soil moisture interaction indicating that with increasing soil strength and moisture canopy projection increases as well. This is unlikely because soil strength and thus soil resistance to root growth has been found to limit root and tree growth (Masle and Passioura 1987; Misra and Gibbons 1996; Sands et al. 1979; Thompson et al. 1987; Young et al. 1997; Ehlers et al. 1983; Lowery and Schuler 1994). However, soil moisture was very high (mean=37% which is above field capacity Table 4.1) due to large amounts of precipitation just days prior to data collection. Thus soil moisture data likely do not show representative levels for Washington, DC and this interaction may therefore not show representative influences on tree growth. In addition, sensitivity analysis showed (Table A.V 6.8) that soil strength and moisture, though being statistically significant, showed virtually no biologically meaningful influence on the response variable. Both the unrepresentative data and the small influence on the response variable suggest that soil strength*soil moisture should be ignored. The shorter cutout side (SCS) also negatively influenced canopy projection. The negative effect of the shorter as well as longer cutout side was determined to mimic the potentially competing vegetation present in some planting pits. Comparing tree plantings with potentially competing vegetation- the entire tree planting pit is covered with ground covers, shrubs and other vegetation- with tree plantings without any vegetation- it can be seen that ground covers were commonly found in longer and wider tree plantings (Table 6.3). Thus longer and wider tree pit dimensions likely reflect the influence of competing groundcovers rather than tree pit dimensions. The development of tree growth models for trees with and those without competing vegetation are discussed later.

Table 6.2 Growth models for *Zelkova serrata* growing in confined spaces along streets in Washington, DC. Predictor variables# were significant from a pool of 30 variables.

Response	Model	R^2	p-value
Canopy Projection (m^2)	39.18 – 24.95SCS– 1.14(pH*Cu) – 0.15(OM*CEC) + 1.63Mn + 0.05(S*M) + 0.24P	0.49	0.0044
logPIA (yr)*	2.87 + 0.0006(S*M) – 0.11LCS + 0.04area – 0.003SS – 0.005NH_4	0.83	<0.0001
log Canopy Vol. (m^3)	3.72 + 0.09 % Clay + 0.006P – 0.03Fe	0.53	0.0001

* Identified outliers (tree # 15 and 34) excluded.

for predictor variables, their abbreviation and units, see Table A.V 6.4

S*M=soil strength * soil moisture

SCS=shorter cutout side

area=cutout area

Prediction models for **canopy volume** included percent clay, P, and Fe as predictors. Clay content may indicate a stronger adhesion to soil nutrients that may normally be leached from this weathered soil and possibly an increased water holding capacity during dry periods. Phosphorus positively influences tree growth which agreed with the literature in that P is oftentimes limiting to plant growth due to low availability and not low concentrations in the soil (Mengel and Kirkby 2001); available P averaged 60.3 ppm which can be considered limiting (Mengel and Kirkby 2001). Iron was found to negatively influence canopy volume. This negative influence disagrees with the literature in that iron is commonly deficient especially in alkaline soils (Brady and Weil 2002e) and its increase in availability would therefore be expected to positively influence tree growth. *Zelkova* is however very pH adaptable and may therefore be able to make Fe available on its own, thus, the influence of Fe may, again, indicate the influence of vehicular traffic. In addition, the soil tests used by the soil testing laboratory have been found to inaccurately predict some elements, especially metals, on soils with low acidity (*personal communication* W. Lee Daniels) thus the low influence and the inaccurate value may suggest that iron likely had no influence on tree growth. In addition, as discussed above for Cu, the negative influence of metals may be associated with degree of urbanization or vehicular traffic.

Peak-increment-area age (PIA) was found to be influenced by the interaction of soil strength and moisture and the longer cutout side (see discussion above). It is also described by the cutout area, soluble salts, and ammonium. Ammonium as well as the influence of the interaction of soil strength and moisture show very low sensitivity indices showing that both variables had next to no influence on the response despite being statistically significant. Soluble salt levels are below the toxic level of 2000 ppm (*personal communications*, W. Lee Daniels). However, deicing salts have been found to negatively influence plant growth (Izabela and Grzegorz Kusza 2004). Levels of soluble salts may have been growth impairing during spring months until being washed out from the soil through precipitation. The influence of cutout area on PIA agreed with findings from the literature. It has been documented in various studies that the planting pit area significantly influences plant growth (Day and Amateis in review; Grabosky and Gilman 2004).

Table 6.3 Mean cutout dimensions of tree plantings with competing vegetation compared to those without competing vegetation for 38 *Zelkova serrata* growing in Washington, DC.

Cutout dimension	Competing vegetation		p-value
	no	yes	
Shorter cutout side (SCS)	1.72 (0.17)	2.37 (0.21)	0.0210
Longer cutout side (LCS)	4.57 (0.63)	7.53 (0.75)	0.0046

Analysis via TTEST procedure in SAS 9.2

Growth-prediction models for developed for *Z. serrata* with and those without competing vegetation resulted in an increase in explained variation for PIA as well as canopy volume and a decrease for canopy projection. The shorter as well as the longer cutout side were no longer significant in these models indicating that the influence of competing vegetation is stronger than these cutout dimensions. **Canopy projection** of trees with potentially competing vegetation (Table 6.4) was predicted by Mn and NO_3 suggesting a possible deficiency of these nutrients in the prevailing soils. This agrees with the literature in that Mn deficiencies are common in soils with low acidity (Brady and Weil 2002e), such as those in Washington, DC. Nitrate is taken up by plants via co-transport with H^+ (Mengel and Kirkby 2001) which may have been limited due to these high pH and thus low H^+ concentrations.

PIA was explained by the cutout area* SCS interaction indicating that an increase in area, or more specifically, increase in symmetrical area increases PIA. Ammonium and clearance was found to positively influence **canopy volume**. Ammonium may be deficient due to low nutrient cycling resulting in decreased plant growth. Clearance seems to have a large influence on canopy volume which is counter-intuitive because higher clearance directly decreases canopy volume compared to untouched trees. Higher clearance does not indicate a superior tree planting or more adequate soil quality because higher clearance can be associated with vehicular traffic rather than pedestrian traffic (Jim 1987). Clearance has not been found to correlate with tree age (data not presented) which would have explained the large canopy but with a number of soil nutrients, such as K, P, Zn, N (data not presented) that may be deficient.

Table 6.4 Growth prediction models for *Zelkova serrata* growing in confined spaces along streets in Washington, DC with potentially competing groundcover. Predictor variables[#] were significant from a pool of 30 variables.

Response	Model	R^2	p-value
Canopy Projection (m^2)	$-29.13+1.90Mn+3.42\ NO_3$	0.37	0.0962
logPIA (yr)	$2.42 + 0.01(area*SCS) - 0.03(pH*Cu)$	0.91	<0.0001
Canopy Vol. (m^3)	$-661.68+21.17NH_4 + 198.16clearance + 0.19(S*M)$	0.86	<0.0001

[#] for predictor variables, their abbreviation and units, see Table A.V 6.4
SCS=shorter cutout side
S*M=soil strength * soil moisture
area=cutout area

Canopy projection of *Z. serrata* without potentially competing vegetation (Table 6.5) was positively influenced by nitrogen concentration of the soil indicating a deficiency, at the time of measurement. In addition to an influence of organic matter*CEC interaction (see discussion above) trees were also negatively influenced by a Cu*Zn interaction. Although the concentration of Cu and Zn in the soil can be considered low (Mengel and Kirkby 2001) their availability as well as uptake have been found to interact (Luo and Rimmer 1995). However, considering the high pH of the soil, both elements would be expected to be deficient rather than toxic (Brady and Weil 2002e). This may, again, indicate negative effects of a higher degree of urbanization and vehicular traffic on tree health.

Canopy volume, besides clay (see discussion above) is also influenced by Mg as well as soil depth. Magnesium, though being present in neither deficient nor excessive concentrations could have been overestimated by the soil testing method due to the high pH of the soil. Soil depth however has been found to be low in Washington, DC (mean 34 cm) thus an increase in soil depth and resulting increase in resources availability may increase tree development; especially since *Z. serrata* is said to grow better on deeper soils (Dirr 1998).

For all models developed for *Z. serrata,* canopy projection was the least well predicted tree growth variable. This may be due to other influencing factors, such as pruning or vandalism, that affect canopy projections but that were not evaluated. Canopy volume, especially when data were analyzed separately for trees with and without competing vegetation, was more completely explained by the variables in the model. PIA was the tree growth variable whose variation was explained to the largest extent, thus most reliably. This shows that the developed model confidently predicts the age of the tree at which it reaches its maximum and thus after which its growth rate declines.

Table 6.5 Growth prediction models for *Zelkova serrata* growing in confined spaces along streets in Washington, DC without potentially competing groundcover. Predictor variables# were significant from a pool of 30 variables.

Response	Model	R^2	p-value
Canopy Projection (m^2)	33.73+154.37N – 0.11(OM*CEC) – 0.08(Cu*Zn)	0.32	0.0914
logPIA (yr)	3.8+0.0017(S*M)-0.01SS-0.03Fe+0.02depth -0.003Ca-1.2moisture	0.95	<0.0001
Canopy Vol. (m^3)	-347.68+17.58 %clay+1.0Mg+1.58depth	0.83	<0.0001

for predictor variables, their abbreviation and units see, Table A.V 6.4
S*M=soil strength * soil moisture
SS=soluble salts
depth=soil depth
moisture=soil moisture

<u>Quercus phellos</u>

Tree growth models for *Q. phellos* had coefficients of determination of 0.54 for canopy projection, 0.58 for crown volume, and 0.78 for PIA (Table 6.6). **Canopy projection** was negatively influenced by Cu content and Mg saturation and positively influenced by crown clearance. Given that the sampled Cu content of the soils was relatively low and high soil alkalinity typically diminishes Cu availability (Brady and Weil 2002e), the negative influence of Cu in the model was unexpected. However, metals, such as Cu, can vary greatly temporally (Robertson and Taylor 2007) and may indicate an unmeasured influence of urbanization or vehicular traffic on tree growth. The negative influence of Mg saturation is also unclear because neither Mg nor Ca were in such moderation or excess to explain this influence. However, Mg saturation was found to correlate significantly with soil strength, the soil strength*moisture interaction, and B, which suggests that the significance of Mg saturation may be due to its correlation with another, perhaps unmeasured, variable. (Brady and Weil 2002e) Canopy projection was positively related to clearance but, as opposed to *Z. serrata*, age and clearance of *Q. phellos* had a significant (<0.0001) correlation coefficient of 66%. This indicated that trees with a higher clearance were also older and therefore had a larger canopy projection. This may be due to the rounded and full crown typical of *Q. phellos* that requires pruning to maintain clearance, whereas *Z. serrata* has a vase-shaped crown that is less likely to require clearance pruning.

The **canopy volume** model had two significant predictor variables: clearance (positive influence) and Cu content (negative influence). As mentioned above, clearance was correlated with tree age and demonstrates that, as expected, older trees have a larger canopy. Canopy volume was negatively influenced by Cu despite the fact that toxic levels were not detected in samples , suggesting an unmeasured influence of urbanization on tree growth.

For *Q. phellos*, **PIA** was negatively influenced by soil depth, pH, Cu, C, and soluble salts (SS) and positively influenced by P, Mn, and organic matter (OM). As opposed to *Z. serrata* (Table 6.5), soil depth negatively influenced PIA of *Q. phellos* despite a slight difference in mean soil depth, 37.1 cm for *Q. phellos* and 34.0 cm for *Z. serrata*. Because rootable soil volume typically increases with greater soil depth, one would expect a positive influence of increasing soil depth. In this case, soil depth may have been correlated with an unmeasured site variable that negatively influenced soil growth, thereby exerting influence on the growth model Likewise, soil carbon would be expected to positively influence tree growth similarly to organic matter, which promotes soil structure and nutrient and water holding capacity (Brady and Weil 2002d). It is unclear, why carbon and organic matter do not influence PIA in a similar way. Soil pH negatively influenced PIA in the model, which is reasonable given that high pH values commonly found in the urban soils contribute to nutrient deficiencies (Scharenbroch et al. 2005).

As with *Z. serrata*, the PIA model for *Q. phellos* had the highest coefficient of determination, strengthening the assertion that PIA is a suitable variable to estimate the year of maximum growth with subsequently declining growth rate. Canopy projection and volume were reasonably high though considering the high variability of urban soils (Alberty et al. 1984; De Kimpe and Morel 2000; Jim 1998a) and their influence tree growth.

Table 6.6 Growth models for *Quercus phellos* growing in confined spaces along streets in Washington, DC. Predictor variables[#] were significant from a pool of 30 variables.

Response	Model	R^2	p-value
Canopy Projection (m^2)	105.23-7.26Cu + 16.87clearance – 6.03Mg Saturation	0.54	<0.0001
log PIA (yr)	6.17 – 0.02depth – 0.39pH + 0.01P + 0.02Mn – 0.14Cu– 0.12C + 0.08OM– 0.002SS	0.78	<0.0001
Canopy Vol. (m^3)	-91.9 + 184.75clearance – 49.43Cu	0.57	<0.0001

[#] for predictor variables, their abbreviation and units, see Table A.V 6.4
SS=soluble salts
depth=soil depth
clearance=distance to lowest branch

Quercus virginiana

Growth models developed for *Q. virginiana* resulted in lower R^2 values than those of *Q. phellos* and *Z. serrata*, ranging from 0.25 to 0.54 *(Table 6.7)*. This may be partially explained by the fact that *Q. virginiana* were growing in sandy soils, which – due to their high macroporosity and lack of structure – have a very high growth-limiting bulk density compared to loamy soils (Daddow and Warrington 1983). Thus, even when highly compacted, sandy soils may still allow root penetration and extension beyond the perceived spatial limits of the tree pit. As such, the trees sampled for this modeling endeavor may have possessed root systems that had escaped from their confined spaces and accessed soil resources that were not quantified well by the field measurements. In the warm climate and well-drained, sandy soils of Jacksonville, tree growth may be largely influenced by water supply in the soil. In addition, studies (e.g. Kent, 2006 ; Gilman and Grabosky, 2004) have found that *Q. virginiana* growth responses are inconsistent with those of other species in urban settings, further suggesting that the species may be responding more strongly to other site variables than those quantified.

Prediction models for **canopy projection** and **canopy volume** were not particularly robust, having an R^2 of 0.28 and 0.25, respectively. Both response variables were negatively influenced by pH, suggesting that an average pH of 7.6 is too high for *Q. virginiana* growth. The Zinc-Cu interaction negatively influenced canopy growth despite the low concentrations of these micronutrients, similarly to soils in Washington, DC. Zinc alone as well as the Zn*pH interaction positively influenced canopy dimensions suggesting a deficiency of this nutrient. However, the effect of the Cu*Zn interaction is unclear.

PIA was positively influenced by clearance and although this influence is unclear it may represent the effect of variables that are correlated with clearance such as P, K, N, and organic matter. Boron was also positively related to PIA, which can be explained by its low concentration of B (0.4 ppm) in the soil and the fact that B is the most commonly deficient micronutrient, especially in alkaline soils (Brady and Weil 2002e). Soil volume was found to negatively influence PIA, suggesting a correlation with another factor that has not been included in this study; its influence on tree growth is however very low.

All models developed for *Q. virginiana* showed the lowest R^2 values compared to those for *Q. phellos* and *Z. serrata,* suggesting that prevailing soil conditions were more difficult to quantify and that *Q. virginiana* had greater chances to be a successful opportunist in regards to resource acquisition. Of the three tree response variables, PIA showed the highest R^2 for all three species, showing the highest confidence in its prediction.

Table 6.7 Growth models for *Quercus virginiana* growing in confined spaces along streets in Jacksonville, FL. Predictor variables# were significant from a pool of 30 variables.

Response	Model	R^2	p-value
log Canopy Proj. (m^2)	$5.74 – 0.28pH + 0.002(pH*Zn)– 0.0004(Cu*Zn)$	0.28	<0.0001
PIA (yr)	$5.6 + 2.21clearance – 0.07volume – 0.11Cu + 6.62*B$	0.54	<0.0001
log Canopy Vol. (m^3)	$7.967 - 0.396pH – 0.0005(Zn*Cu) + 0.0231Zn$	0.25	<0.0001

# for predictor variables, their abbreviation and units, see Table A.V 6.4
volume=soil volume
clearance=distance to lowest branch

Simplified growth-prediction models

Municipalities do not always have access or resources to collect samples and analyze soils in soil testing laboratories. Thus the question arises as to how much variation of these three tree response variables can be explained with only easily-measurable soil attributes (Table A.V 6.4, right), such as pH, soluble salts, and planting pit dimensions. To address this practical need, a series of simplified growth-prediction models were developed based on easily-measured site variables.

Zelkova serrata

Canopy projection could be explained by pH, SCS and the soil strength*moisture interaction, resulting in an R^2 of 0.40. SCS, again, is affected by competing vegetation and influence of soil strength and moisture is marginal and due to the weather conditions likely not representative. Decreases in soil pH would increase canopy projection which is reasonable due to the commonly alkaline urban soils and resulting nutrient deficiencies (Scharenbroch et al. 2005). **Canopy volume** is similarly affected by soil pH than canopy volume while PIA is not. **PIA** increased with increased (symmetrical) cutout area. PIA's R^2 was still 0.64, higher than that of models for canopy dimensions that included all variables.

Table 6.8 Models developed from 10 easy-to-measure soil variables[#] for *Zelkova serrata* growing in confined spaces along streets in Washington, DC.

Response	**Model**	**R^2**	**p-value**
log Canopy Proj. (m^2)	8.3 – 0.56pH – 0.27SCS +0.0004(S*M)	0.40	0.0017
PIA (yr)*	7.34 + 0.008(S*M) + 0.08(area*SCS)	0.64	<0.0001
log canopy Vol. (m^3)	10.14 – 0.74pH	0.18	0.0137

* excluding outlier # 15 and 34
[#] for predictor variables, their abbreviation and units, see Table A.V 6.4
SCS=shorter cutout side
S*M=soil strength*soil moisture
area=cutout area

Quercus phellos

Only one model was found significant using the limited number of soil variables. Only **PIA** was to be predicted with only soil depth as predictor variable. However, soil depth negatively influenced PIA despite the fact that soils in Washington, DC were generally shallow (mean=37 cm). The influence of soil depth is however small (0.01). Overall, easily-measurable soil attributes did not explain variation in *Q. phellos* growth satisfactorily.

Table 6.9 Models developed from easy-to-measure soil variables[#] for *Quercus phellos* growing in confined spaces along streets in Washington, DC.

Response	Model	R^2	p-value
log Canopy Proj. (m^2)	No significant model		
PIA (yr)	3.24 – 0.01depth	0.25	0.0007
log canopy Vol. (m^3)	No significant model		

[#] for predictor variables, their abbreviation and units, see Table A.V 6.4
depth=soil depth

Quercus virginiana

Growth-prediction models of *Q. virginiana* with easily-measurable soil attributes showed R^2 values of between 24 and 32%; with PIA having the lowest and canopy volume the highest value. Soluble salts as well as pH were similarly related to all three tree growth variables; decreases in pH as well as increases in SS increased tree growth. This is reasonable considering the high alkalinity and low nutrient availability of the present soils. Soluble salts include carbonates and other compounds supportive of plant growth and were found very low, mean-223 ppm. Salt toxicities can be found when soluble salt concentrations reach 2000 ppm and higher (personal communications, W. Lee Daniels). The negative influence of tree pit dimensions is unclear but, as previously mentioned, sandy soils, such as those in Jacksonville, FL, do not limit plant growth as much as e.g. loamy soils, even when compacted. Thus the influence of planting pit dimension may be correlated with other soil characteristics not included in this study.

Table 6.10 Models developed from easy-to-measure soil variables[#] for *Quercus virginiana* growing in confined spaces along streets in Washington, DC.

Response	Model	R^2	p-value
Log Canopy Proj. (m^2)	6.97 – 0.04LCS – 0.42pH + 0.002SS	0.28	<0.0001
PIA (yr)	23.18-0.14volume + 0.01SS – 1.47pH	0.24	<0.0001
log canopy Vol. (m^3)	9.09 – 0.5pH + 0.03(S*M) – 0.05moisture – 0.21SCS + 0.003SS	0.32	<0.0001

[#] for predictor variables, their abbreviation and units, see Table A.V 6.4
LCS=longer cutout side
moisture=soil moisture
SCS=shorter cutout side
S*M=soil strength * soil moisture
SS=soluble salts
volume=soil volume

Conclusions

Growth prediction models based on 30 soil and site variables were developed for *Z. serrata* and *Q. phellos* growing in Washington, DC and *Q. virginiana* growing in Jacksonville, FL. Three growth response variables, canopy projection (CP), canopy volume (CV), and peak-increment area age (PIA) were chosen, resulting in three models per tree species. In addition to the more complex models, simplified models were developed for each growth response variable and species using only easy-to-measure variables, such as tree pit dimensions, soil pH, and soil soluble salts.

Multiple linear models fit the data well, resulting in significant growth models that explained between 25 and 83% of the variability observed in tree physical dimensions and growth rate. Tree growth models for PIA resulted in the highest coefficients of determination, indicating that PIA is highly responsive to the evaluated predictor variables and that models can be used confidently to predict the age of the tree at which its growth rate declines. CV and CP were less sensitive to prevailing below-ground growing conditions presumably because, above ground, the tree is subject to cultural practices-such as pruning- and other abiotic and biotic conditions-such as diseases and vandalism- that may constrain canopy size yet may not appreciably affect the health and growth of the tree.

Certain prediction models for all three species included predictor variables with counterintuitive influences on tree growth, suggesting that either urban trees are responding to these variables in a novel manner or that variables unaccounted for in these models (perhaps related to urbanization or high vehicular traffic) are concomitantly influencing tree growth. Soil pH was found to be significant for the majority of models as well as deficiencies of some nutrients such as Fe, B, Mn, and Zn, which are also associated with soil alkalinity. The influence of many variables is however unclear, such as clearance, soil depth for *Q. phellos* and soil volume for *Q. virginiana,* which suggests a correlation to other growth-influencing conditions that were not measured in this study.

Research limitations

Soil measurements in Washington, DC were taken just days after a heavy rain event (>10 cm) which may have led to unrepresentative data for soil moisture and soil strength. In addition, soil tests commonly conducted at the soil testing laboratory are targeted to soils with lower soil pH which may have resulted in inaccurate measurements of plant available nutrients, including metals, Ca, Mg, as well as organic matter.

Recommendations to urban foresters

These results show that it is possible to predict growth of urban trees growing in confined spaces with fairly high confidence. Tree size can be estimated based on the developed models, which would be a suitable tool for urban foresters to evaluate a site prior to tree planting. PIA is a very important tree-growth indicator because it shows how long a tree will increase its growth rate before it starts declining, and it can be determined with great confidence. Based on my model, a *Z. serrata* growing in a small planting pit may reach its age of maximum growth at the age of 6 whereas one in a large planting pit may grow for 20 years before reaching its maximum. It is important to estimate the age at which the tree reaches its maximum of provided benefits to evaluate the magnitude of these benefits. CP and CV are indicators of these benefits which makes them useful tree-growth variables to be estimated.

Growth prediction models based on easy-to-measure variables resulted in models with a lower coefficient of determination. The highest was determined for PIA of *Z. serrata* with 64%. This shows that a) most influential site variables are more complex, yet b) even simple measurements can give important information that would significantly improve tree growth if taken into account. With these simplified models one would have a reasonable estimate of the eventual size of a tree at a particular site and thus an estimate of the site's capacity or potential to support tree growth.

Future research

Major influencing factor that needs incorporation in tree growth models are degree of urbanization or traffic and well as (historic) weather data. Several soil metals indicated that traffic influenced tree growth but the data collected did not fully show this. Temporally distributed analysis of soils for metals may be needed to include this aspect. Another attribute may be rooting volume or degree of root escapees. It was impossible to determine whether tree roots were fully contained in a tree pit or whether surrounding infrastructure such as sewer line supplemented the tree with nutrients that could not be measured from surface soils. Incorporating surroundings into the dataset may help to more accurately predict tree growth. Furthermore, this data analysis only investigated three tree species in two geographic locations. Because urban forests typically comprise dozens of tree species and cultivars, generalization of the developed models is tenuous. However, these modeling efforts have provided empirical evidence on the site factors influencing urban tree growth and the feasibility of modeling tree growth in the complex urban ecosystem. Further data collection of different species, in different locations is necessary to result in well-rounded tree growth models for suitable urban tree species.

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Appendix

Appendix I SAS Codes

```
libname Julia "C:\Documents and Settings\User\My Documents\PhD\Data\play with data\SAS";

proc corr data=Julia.wo;
var P OM pH Ca;
run;

data Julia.zelk;
set Julia.zelk;
interactstrengthmoist=(strength*moisture);
areaadj=(area*shorter);
interactCuZn=(Zn*Cu);
interactstrengthclay=(strength*clay);
interactOMCEC=(OM*CEC);
InteractMNOM=(MN*OM);
InteractpHZn=(pH*Zn);
interactpHCu=(ph*cu);
run;

proc reg data=julia.zelk;
model canopyproj= interactstrengthmoist areaadj interactCuZn interactstrengthclay interactOMCEC
InteractMNOM
interactpHZn interactpHCu clearance   shorter  longer   area     depth    volume pH       P        K
         Ca       Mg       Zn       Mn       Cu
Fe       B        N        C        CNratioAmmonium     Nitrate  CEC      CaSat    MgSat    KSat     OM
         SS       strength          moisture
Clay/selection=stepwise;
run;
```

Appendix II Residual plots: general models

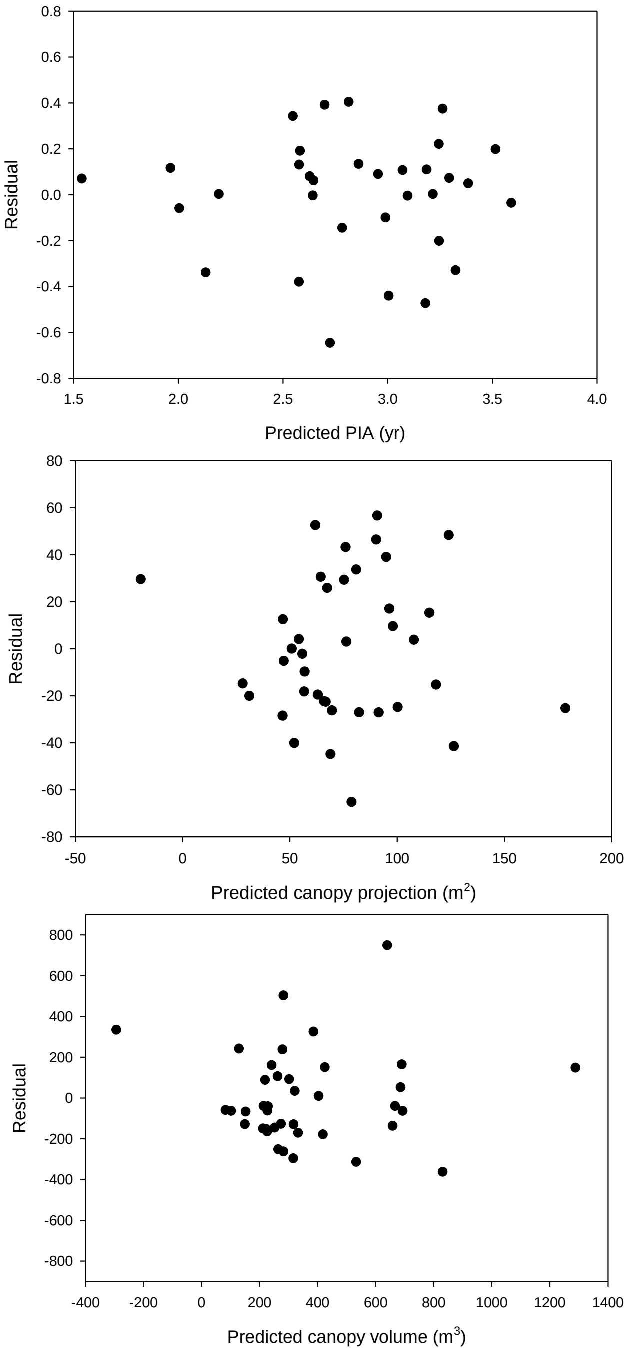

Figure A.II 6.1 Comparisons of <u>full</u> model residuals and predictions for *Quercus phellos* growing in Washington, DC, for PIA (top), canopy projection (center), and canopy volume (bottom).

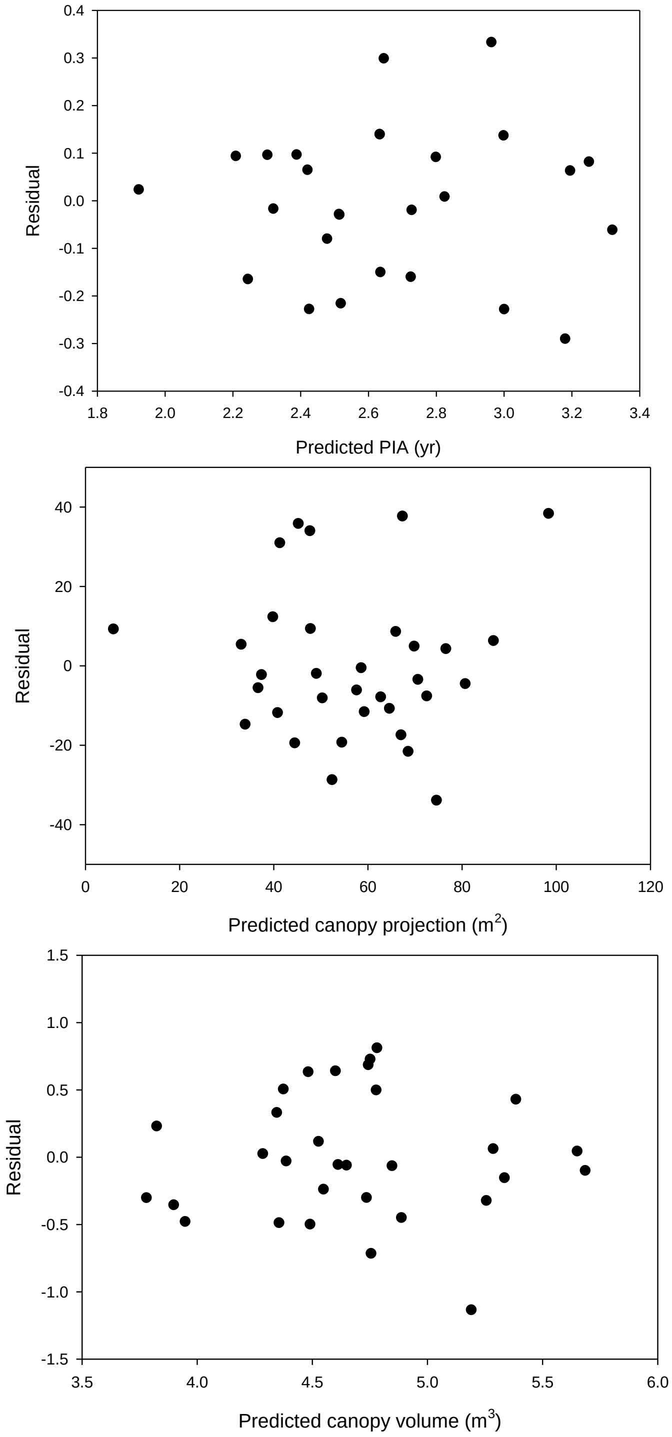

Figure A.II 6.2 Comparisons of full model residuals and predictions for *Zelkova serrata* growing in Washington, DC, for PIA (top), canopy projection (center), and canopy volume (bottom).

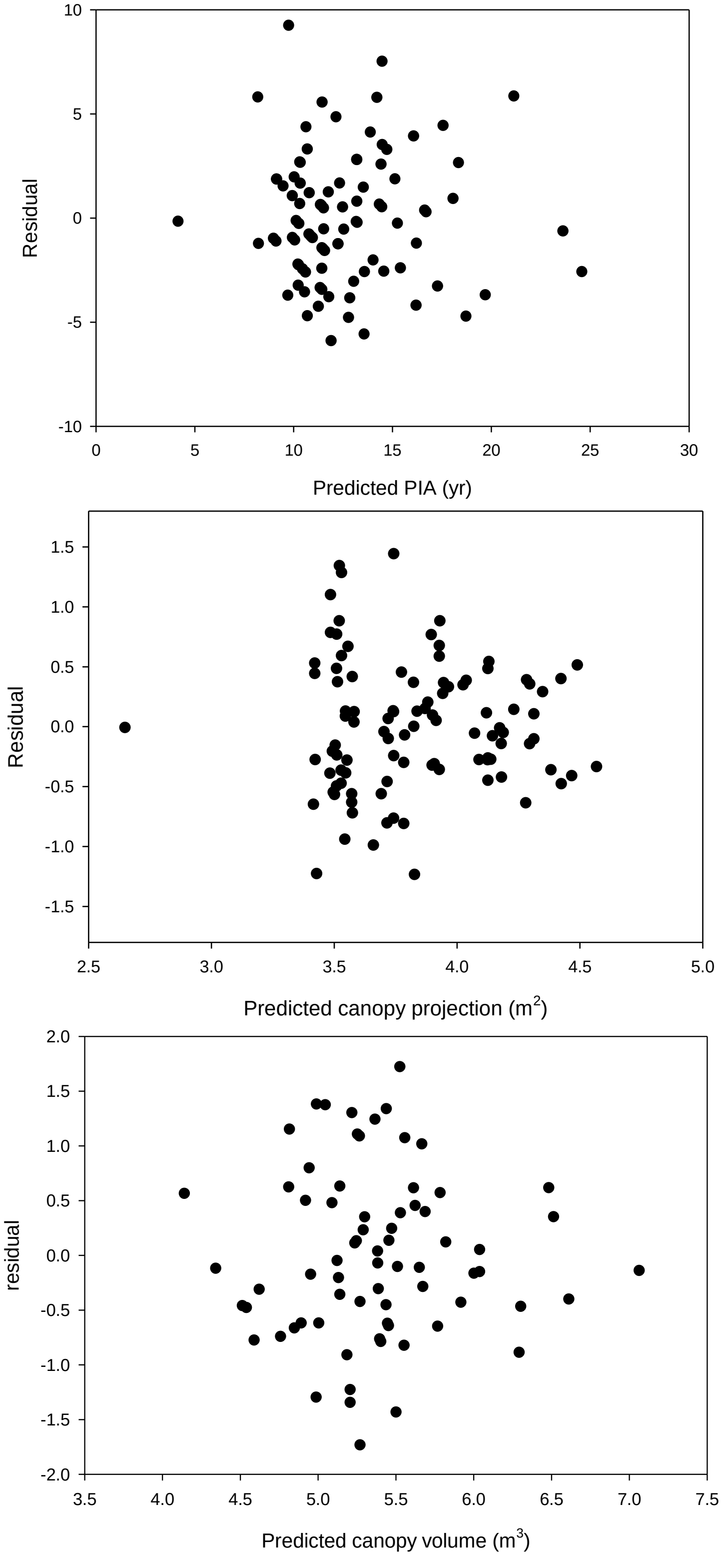

Figure A.II 6.3 Comparisons of <u>full</u> model residuals and predictions for *Quercus virginiana* growing in Jacksonville, FL, for PIA (top), canopy projection (center), and canopy volume (bottom).

Appendix III Residual plots: Simplified models

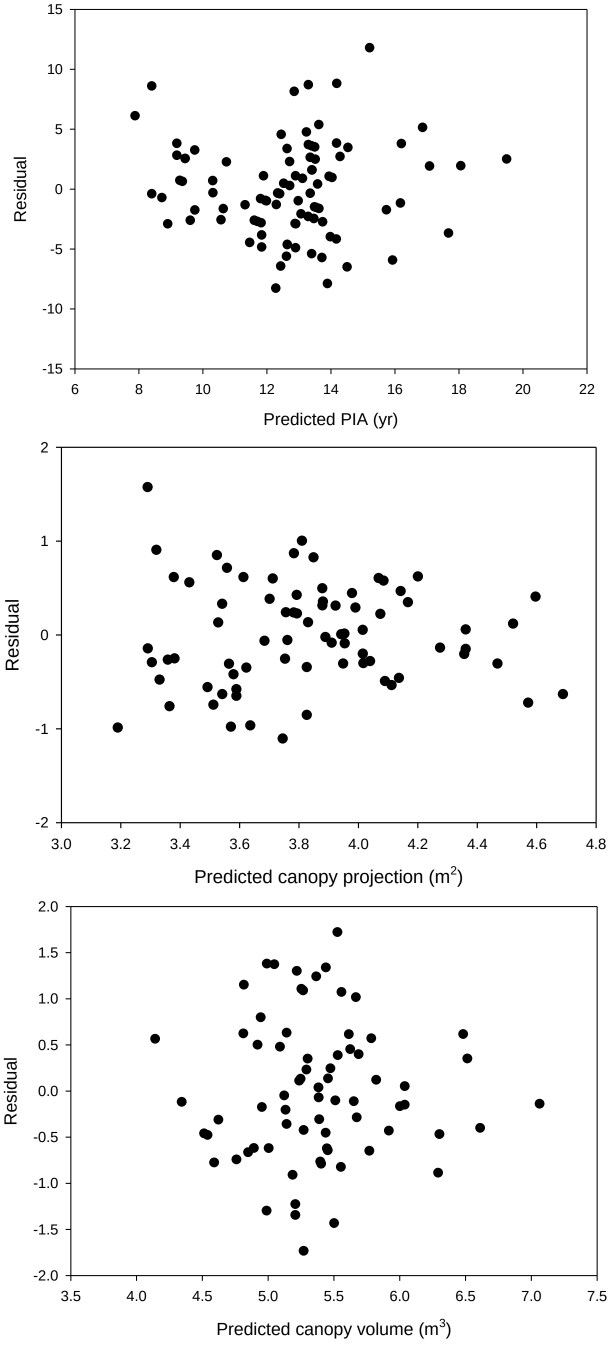

Figure A.III 6.1 Comparisons of simplified model residuals and predictions for the simplified models for *Quercus virginiana* growing in Jacksonville, FL, for PIA (top), canopy projection (center), and canopy volume (bottom).

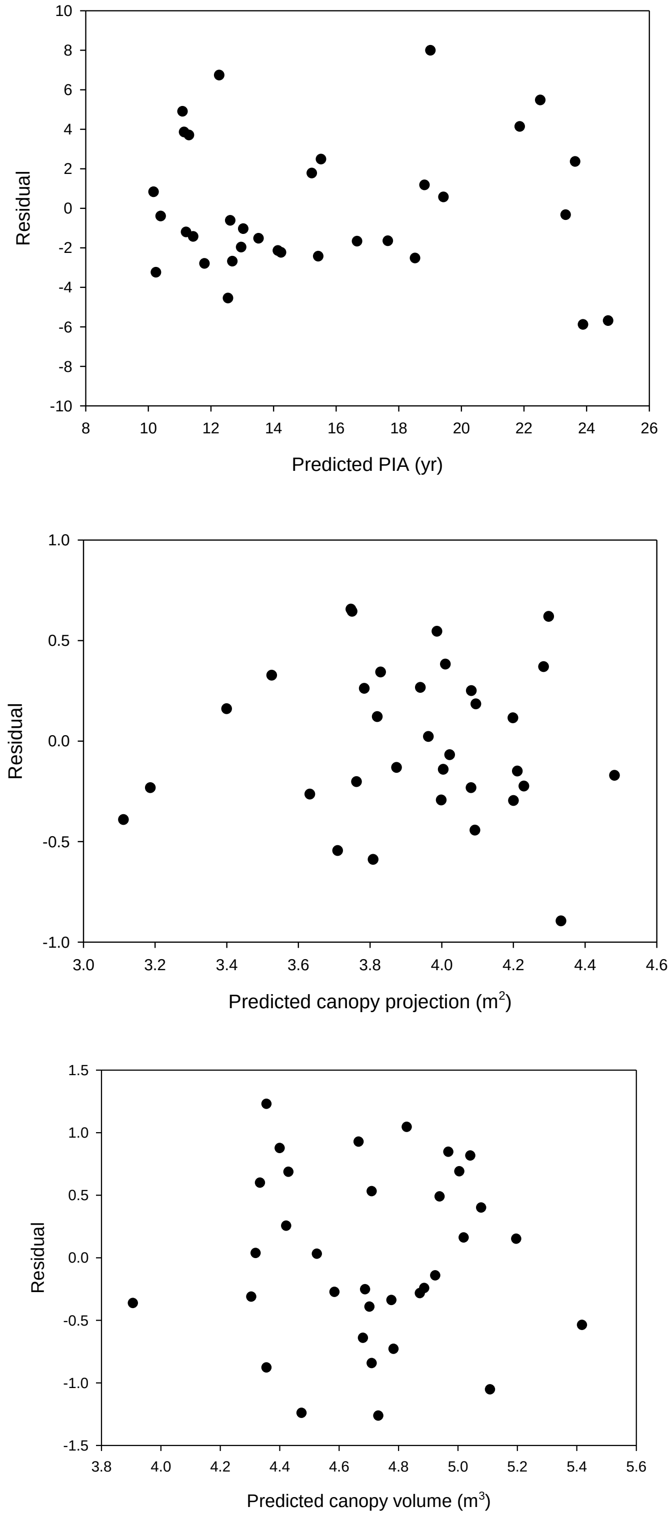

Figure A.III 6.2 Comparisons of <u>simplified</u> model residuals and predictions for the simplified models for *Zelkova serrata* growing in Washington, DC, for PIA (top), canopy projection (center), and canopy volume (bottom).

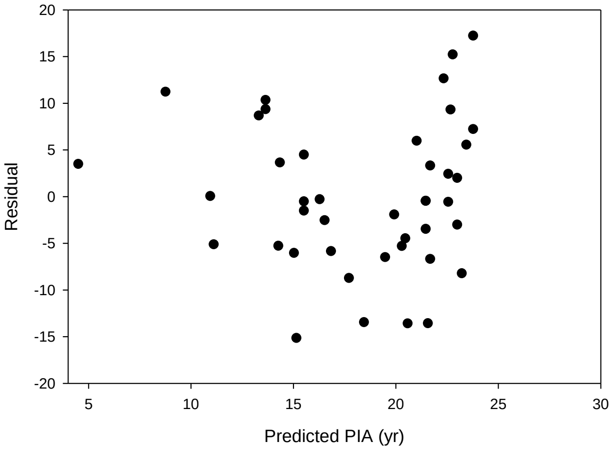

Figure A.III 6.3 Comparisons of simplified model residuals and predictions for the simplified model for PIA for *Quercus phellos* growing in Washington.

Appendix IV Additional Figures

Figure A.IV 6.1 Two *Quercus phellos* growing in large cutouts in Washington, DC. Tree #13 (left) may have a larger available soil volume than tree #14 (right) which is growing in the 'tip' of a teardrop-shaped cutout.

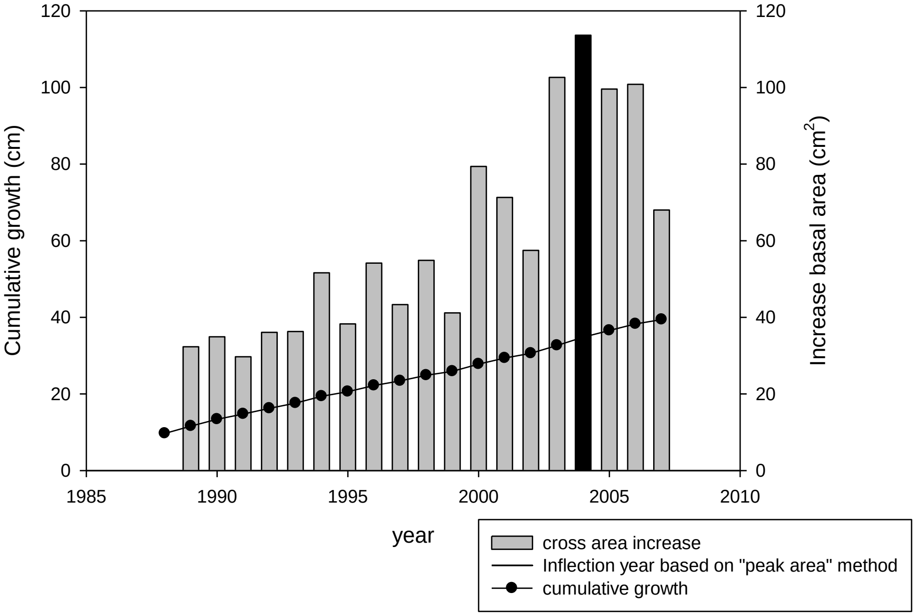

Figure A.IV 6.2 Cumulative growth (black dots) and basal area increase (vertical bars) of a *Quercus phellos* (#13) growing in Washington DC. Inflection years are shown for the "ratio < 0.85" (red dot) and "peak area" (black bar) methods.

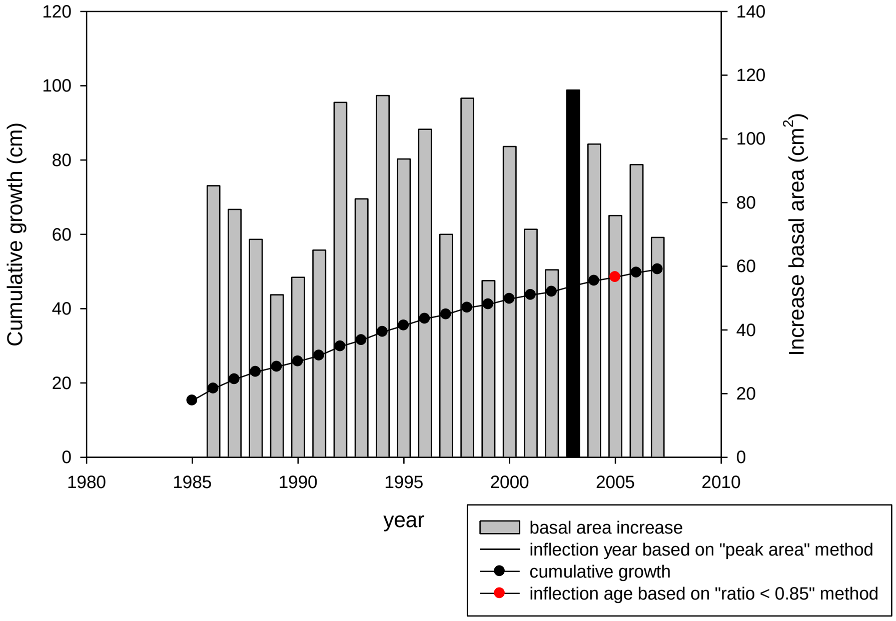

Figure A.IV 6.3 Cumulative growth (black dots) and basal area increase (vertical bars) at breast height (1.3 m) of a *Quercus phellos* (#14) growing in Washington DC. Inflection years are shown for the "ratio < 0.85" (red dot) and "peak area" (black bar) methods.

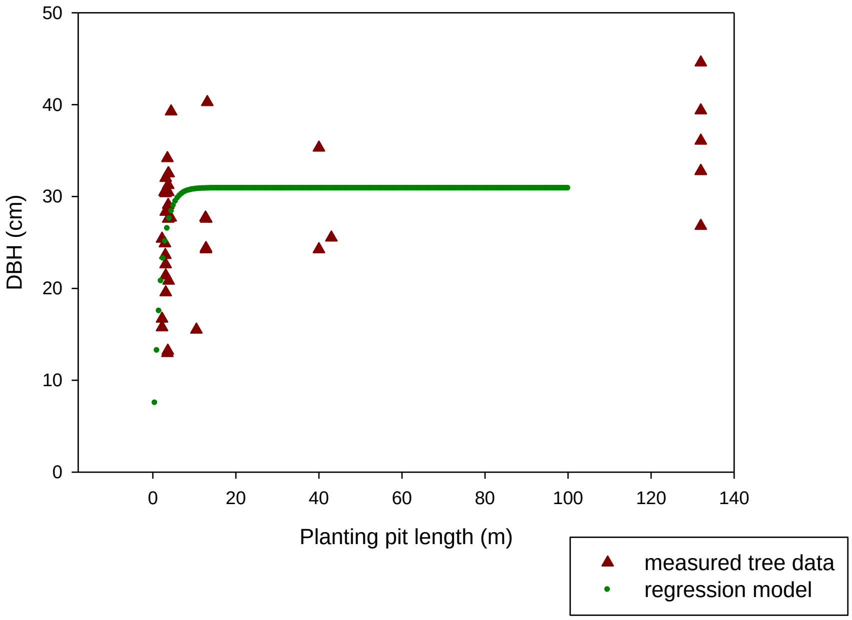

Figure A.IV. 6.4 Trunk diameter (cm) at breast height (1.4 m) plotted against tree pit length (m) for 39 *Zelkova serrata* measured in Washington, DC (regression model overlaid).

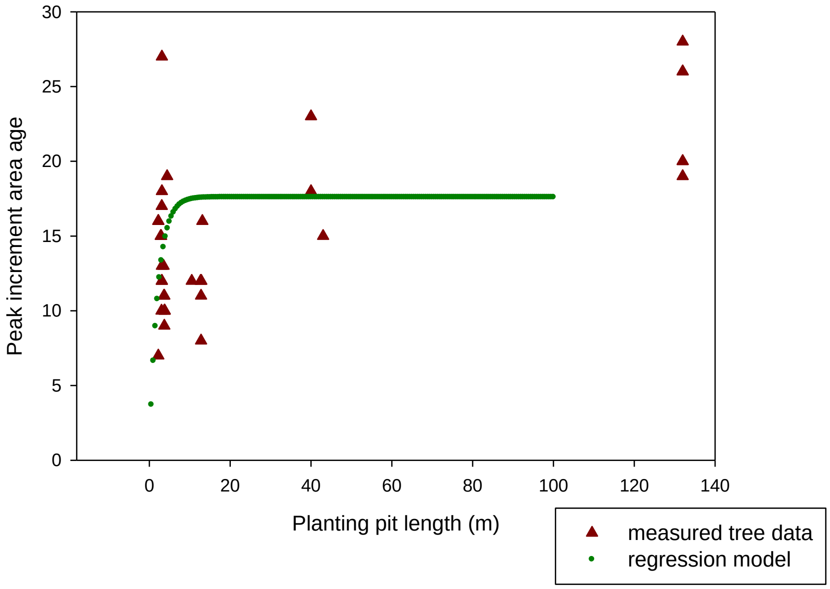

Figure A.IV. 6.5 Peak increment area age at breast height (1.3 m) plotted against tree pit length (m) for 39 *Zelkova serrata* measured in Washington, DC (regression model overlaid)

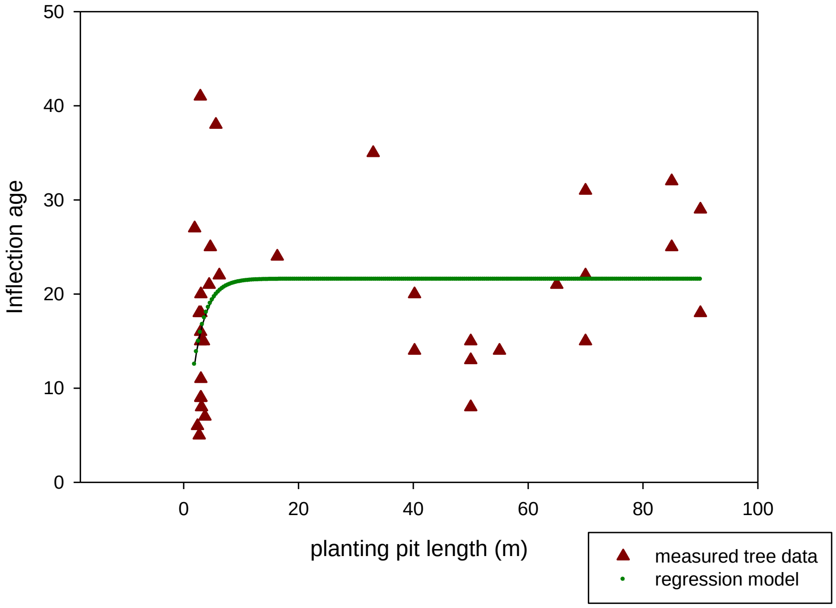

Figure A.IV. 6.6 Peak increment area age at breast height (1.3 m) plotted against tree pit length (m) for 36 *Quercus phellos* measured in Washington, DC (regression model overlaid)

Appendix V Additional Tables

Table A.V 6.1 Coefficients* and p-values for response variable for correlations of *Q. phellos*

Response variable	DBH	Height	Canopy projection	Height via UC software	Crown volume	DBH at PIA
Height	**0.887** <0.0001					
Canopy projection	**0.927** <0.0001	0.64 <0.0001				
Height via UC software	**0.89** <0.0001	**0.99** <0.0001	**0.84** <0.0001			
Crown volume	**0.85** <0.0001	**0.88** <0.0001	**0.82** <0.0001	**0.89** <0.0001		
DBH at PIA	**0.94** <0.0001	**0.87** <0.0001	**0.89** <0.0001	**0.87** <0.0001	**0.84** <0.0001	
PIA	**0.76** <0.0001	**0.72** <0.0001	0.65 <0.0001	**0.73** <0.0001	0.63 <0.0001	**0.80** <0.0001

[*] Correlation coefficients >0.7 are associated with high correlation and are shown in bold numbers.

Table A.V 6.2 Coefficients* and p-values for response variable for correlations of *Z. serrata*

Response variable	DBH	Height	Canopy projection	Height via UC software	Crown volume	DBH at PIA
Height	0.67 <0.0001					
Canopy projection	**0.71** <0.0001	0.61 <0.0001				
Height via UC software	0.68 <0.0001	**1.0** <0.0001	0.67 <0.0001			
Crown volume	**0.76** <0.0001	**0.77** <0.0001	**0.7** <0.0001	**0.78** <0.0001		
DBH at PIA	**0.82** <0.0001	0.52 0.0012	0.47 0.0042	0.54 0.0010	0.54 0.0009	
PIA	0.45 0.0054	0.08 0.6255	0.13 0.4376	0.12 0.5019	0.21 0.2381	**0.74** <0.0001

*Correlation coefficients >0.7 are associated with high correlation and are shown in bold numbers.

Table A.V. 6.3 Coefficients* and p-values for response variable for correlations of *Q. virginiana*

Response variable	**DBH**	**Height**	**Canopy projection**	**Height via UC software**	**Crown volume**	**DBH at PIA**
Height	**0.80** <0.0001					
Canopy projection	**0.90** <0.0001	**0.72** <0.0001				
Height via UC software	**0.78** <0.0001	**1.0** <0.0001	**0.71** <0.0001			
Crown volume	**0.81** <0.0001	0.66 <0.0001	**0.79** <0.0001	**0.70** <0.0001		
DBH at PIA	**0.80** <0.0001	0.64 <0.0001	**0.71** <0.0001	0.64 <0.0001	0.68 <0.0001	
Peak-area age	0.42 <0.0001	0.50 <0.0001	0.34 0.0006	0.48 <0.0001	0.29 0.0034	0.62 <0.0001

*Correlation coefficients >0.7 are associated with high correlation and shown in bold numbers.

Table A.V. 6.4 List of variables used to develop tree growth models

Variables used for overall models	Easy-to-measure variables
NH_4 (ppm)	Cutout area (m^2)
Cutout area (m^2)	area*shorter
B (ppm)	Soil depth (cm)
C (%)	Longer cutout side, LCS (m)
Ca (ppm)	Soil moisture (% volumetric water content (VWC))
Ca Saturation (%)	pH
CEC (meq/100g)	Shorter cutout side, SCS (m)
Clay (%)	Soluble salts, SS (ppm)
Clearance (m)	Soil strength (MPa)
C/N ratio	Soil volume (m^3)
Cu (ppm)	
Soil depth (cm)	
Fe (ppm)	
K (ppm)	
K Saturation (%)	
Longer cutout side, LCS (m)	
Mg (ppm)	
Mg Saturation (%)	
Mn (ppm)	
Soil moisture (% volumetric water content (VWC))	
N (ppm)	
NO_3 (ppm)	
organic matter (%)	
pH	
Shorter cutout side, SCS (m)	
Soluble salts, SS (ppm)	
Soil strength (MPa)	
Soil volume (m^3)	
Zn (ppm)	

Table A.V 6.5 Mean soil attributes (SE) for *Z. serrata* as well as common concentrations in the soil -based on Mengel and Kirkby (2001) unless otherwise noted- and their dependencies and interactions.

Soil chemical property	Common concentration in soils (ppm)	Mean availability in soils sampled (SE) (ppm)	Dependencies or interactions	Significant correlation of soil property and known dependencies?
P	500-800; 11-15[5]	60.3 (8.3)	OM, pH, Ca	No
K	2,000-30,000 51-75[5]	158.6 (31.3)	OM, clay	No
Ca	400-4000[13] 481-600[5]	2757.3 (135.9)	pH, Fe	↓Fe
Mg	20-400[13] 49-61[5]	180.8 (9.9)	pH	No
Zn	10-300	36.7 (3.0)	Clay, OM, pH, Mg, Ca	No
Mn	200-5,000	34.2 (1.4)	Fe, clay, OM, pH	↓pH, ↑OM
Cu	5-100	1.8 (0.3)	OM, pH, N	↓OM, ↑pH, ↓N
Fe	5,000-40,000[13]	19.6 (1.2)	pH, Ca	↓Ca
B	20-200[3]	1.1 (0.1)	pH	No
%N	200-5000[4]	0.3 (0.0)	OM,	
%C		6.8 (0.6)		
CEC (meq/100g)		15.7 (0.7)	OM, Clay	
NH4		10.4 (4.2)	OM,	
NO3		15.7 (6.5)	OM,	
OM	>3% = high[6]	9.9 (1.2)		
SS	Toxicity above 844[6]	166.4 (13.7)		
pH		7.4 (0.07)		
Mg Saturation %		10.0 (0.7)		
Ca Saturation %		86.6 (1.2)		
K Saturation %		3.1 (0.8)		
Cutout area (m^2)		13.2 (1.7)		
Soil depth (cm)		34.0 (2.5)		
Clay content (%)		13.8 (0.6)		
Soil strength (MPa)		2.0 (0.1)		
Soil moisture (GWC)		0.37 (0.02)		

[1] based on Finck (1991)

[2] exchangeable

[3] most unavailable

[4] based on Essington (2004)

[5] medium soil test levels based on Maguire and Heckendorn (2010)

[6] based on Maguire (2009)

Table A.V 6.6 Mean soil attributes (SE) for *Q. virginiana* as well as common concentrations in the soil -based on Mengel and Kirkby (2001) unless otherwise noted- and their dependencies and interactions.

Soil chemical property	Common concentration in soils (ppm)	Mean availability in soils sampled (SE) (ppm)	Dependencies or interactions	Significant correlation of soil property and known dependencies?
P	500-800; 11-15[5]	20.6 (1.8)	OM, pH, Ca	↑OM, ↓pH, ↓Ca
K	2,000-30,000 51-75[5]	35.8 (2.4)	OM, clay	↑OM, ↑clay
Ca	400-4000[13] 481-600[5]	3490.1 (151.8)	pH	↑pH
Mg	20-400[13] 49-61[5]	126.4 (5.5)	pH	↑pH
Zn	10-300	15.0 (1.8)	Clay, OM, pH, Mg, Ca	↓clay, ↓OM,
Mn	200-5,000	5.8 (0.6)	Fe, clay, OM, pH	↑OM, ↑Fe
Cu	5-100	1.2 (0.7)	OM, pH, N	No
Fe	5,000-40,000[13]	12.8 (1.4)	pH	↓pH
B	20-200[3]	0.4 (0.0)	pH	No
%N	200-5000[4]	0.1 (0.0)	OM,	
%C		2.4 (0.1)		
CEC		18.6 (0.8)	OM, Clay	
NH4		3.2 (0.3)	OM,	
NO3		11.0 (1.2)	OM,	
OM	>3% = high[6]	3.0 (0.2)		
SS	Toxicity above 844[6]	172.9 (10.2)		
pH		7.6 (0.1)		
Mg Saturation		6.4 (0.4)		
Ca Saturation		91.5 (0.8)		
K Saturation		0.7 (0.1)		
Cutout area (m^2)		19.7 (1.8)		
Soil depth (cm)		53.6 (2.4)		
Clay content (%)		8.5 (0.2)		
Soil strength (MPa)		1.5 (0.1)		
Soil moisture (GWC)		0.13 (0.01)		

[1] based on Finck (1991)

[2] exchangeable

[3] most unavailable

[4] based on Essington (2004)

[5] medium soil test levels based on Maguire and Heckendorn (2010)

[6] based on Maguire (2009)

Table A.V 6.7 Mean soil attributes (SE) for *Q. phellos* as well as common concentrations in the soil -based on Mengel and Kirkby (2001) unless otherwise noted- and their dependencies and interactions.

Soil chemical property	Common concentration in soils (ppm)	Mean availability in soils sampled (SE) (ppm)	Dependencies or interactions	Significant correlation of soil property and known dependencies?
P	500-800; 11-15[5]	69.9 (11.1)	OM, pH, Ca	↑OM, ↑Ca[4]
K	2,000-30,000 51-75[5]	152.3 (15.8)	OM, clay	↑OM
Ca	400-4000[13] 481-600[5]	2108.9 (194.0)	pH	↑pH
Mg	20-400[13] 49-61[5]	159.9 (11.5)	pH	↑pH
Zn	10-300	28.6 (2.9)	Clay, OM, pH, Mg, Ca	No
Mn	200-5,000	29.0 (1.9)	Fe, clay, OM, pH	↓Fe, ↑OM, ↑pH[4]
Cu	5-100	2.0 (0.3)	OM, pH, N	No
Fe	5,000-40,000[13]	26.2 (2.0)	pH	↓pH
B	20-200[3]	0.8 (0.1)	pH	↑pH
%N	200-5000[4]	0.3 (0.0)	OM,	
%C		7.9 (1.3)		
CEC		12.8 (1.0)	OM, Clay	
NH4		23.0 (9.8)	OM,	
NO3		27.9 (13.9)	OM,	
OM	>3% = high[6]	10.0 (1.5)		
SS	Toxicity above 2000	223.2 (35.7)		
pH		6.8 (0.1)		
Mg Saturation		10.9 (0.5)		
Ca Saturation		78.5 (2.3)		
K Saturation		3.5 (0.4)		
Cutout area (m^2)		18.7 (4.4)		
Soil depth (cm)		37.1 (3.2)		
Clay content (%)		11.6 (0.8)		
Soil strength (MPa)		1.8 (0.2)		
Soil moisture (GWC)		0.28 (0.02)		

[1] based on Finck (1991)

[2] exchangeable

[3] most unavailable

[4] based on Essington (2004)

[5] medium soil test levels based on Maguire and Heckendorn (2010)

[6] based on Maguire (2009)

Sensitivity analysis for growth-prediction models

Table A.V 6.8 Results of sensitivity analysis for growth-prediction models for Z. serrata

Z. serrata	Canopy Projection (m^2) [mean=58.6 SE=4.2]			PIA (yr) [mean=15.3 SE=0.9]			Canopy Volume (m^3) [mean=151.0 SE 17.0]		
predictors	**min**	**mean**	**max**	**min**	**mean**	**max**	**min**	**mean**	**max**
shorter	40.4	17.5	-39.5						
pH*Cu	31.1	17.5	-22.8						
OM*CEC	38.3	17.5	-62.3						
Mn	-4.4	17.5	61.6						
strength* moisture	17.5	17.5	17.5	9.5	9.5	9.5			
P	6.4	17.5	43.1				84.0	110.8	210.3
longer				14.3	9.5	6.1			
area				6.4	9.5	20.3			
SS				11.6	9.5	7.0			
Ammonium				9.7	9.5	9.1			
Clay							69.0	110.8	258.2
Fe							160.4	110.8	66.8

Table A.V 6.9 Results of sensitivity analysis for growth-prediction models for Q. phellos

Q. phellos	Canopy Projection (m^2) [mean=73.2 SE=6.9]			PIA (yr) [mean=18.4 SE=1.4]			Canopy Volume (m^3) [mean=339.6 SE=52.9]		
predictors	**min**	**mean**	**max**	**min**	**mean**	**max**	**min**	**mean**	**max**
Cu	86.3	73.5	15.1	30.9	24.2	7.8	425.1	338.4	-59.3
clearance	37.3	73.5	159.1				-59.0	338.4	1275.6
Mg Saturation	109.0	73.5	28.8						
depth				39.5	24.2	6.9			
pH				42.8	24.2	15.4			
P				24.2	24.2	24.2			
Mn				17.0	24.2	41.1			
C				53.0	24.2	1.4			
OM				12.9	24.2	245.7			
SS				33.2	24.2	3.3			

Table A.V 6.10 Results of sensitivity analysis for growth-prediction models for *Q. virginiana*

Q. virginiana	**Canopy Projection (m^2) [mean=55.0 SE=3.3]**			**PIA (yr) [mean=12.7 SE=0.5]**			**Canopy Volume (m^3) [mean=300.5 SE=29]**		
predictors	**min**	**mean**	**max**	**min**	**mean**	**max**	**min**	**mean**	**max**
pH	82.4	45.2	35.9				455.7	194.7	140.6
pH*Zn	36.2	45.2	165.9						
Cu*Zn	46.7	45.2	2.9				203.0	194.7	6.3
clearance				9.9	12.7	23.1			
soil volume				13.4	12.7	13.4			
Cu				12.8	12.7	5.2			
B				10.8	12.7	17.5			
Zn							138.3	194.7	1383.4

Sensitivity analysis for simplified models

Table A.V 6.11 Results of sensitivity analysis for the simplified growth-prediction models for Z. serrata

Z. serrata	**Canopy Projection (m^2) [mean=58.6 SE=4.2]**			**PIA (yr) [mean=15.3 SE=0.9]**			**Canopy Volume (m^3) [mean=151.0 SE 17.0]**		
predictors	**min**	**mean**	**max**	**min**	**mean**	**max**	**min**	**mean**	**max**
shorter	62.7	61.2	57.5						
pH	105.2	61.2	33.4				220.65	107.71	48.40
strength* moisture	61.2	61.2	61.2	10.0	10.0	10.0			
area* shorter				7.7	10.0	15.5			

Table A.V 6.12 Results of sensitivity analysis for the simplified growth-prediction model for Q. phellos

Q. phellos	**Canopy Projection (m^2) [mean=73.2 SE=6.9]**			**PIA (yr) [mean=18.4 SE=1.4]**			**Canopy Volume (m^3) [mean=339.6 SE=52.9]**		
predictors	**min**	**mean**	**max**	**min**	**mean**	**max**	**min**	**mean**	**max**
depth		n.a.		3.1	2.9	2.2		n.a.	

Table A.V 6.13 Results of sensitivity analysis for the simplified growth-prediction models for Q. virginiana

Q. virginiana	**Canopy Projection (m²) [mean=55.0 SE=3.3]**			**PIA (yr) [mean=12.7 SE=0.5]**			**Canopy Volume (m³) [mean=300.5 SE=29]**		
predictors	**min**	**mean**	**max**	**min**	**mean**	**max**	**min**	**mean**	**max**
pH	122.8	49.8	35.3	15.4	12.3	11.1	627.0	214.2	142.0
longer	59.2	49.8	23.2						
soluble salts	39.1	49.8	105.9	11.0	12.3	16.0	148.6	214.2	664.0
strength* moisture							213.1	214.2	218.2
soil volume				13.8	12.3	8.7			
moisture							215.3	214.2	211.4
shorter							261.7	214.2	117.8

Chapter 7: Conclusions

Growth-prediction models for three tree species – *Z. serrata* and *Q. phellos* growing in Washington, DC and *Q. virginiana* growing in Jacksonville, FL – were developed in this study using data for thirty soil and site variables. Multiple linear regression models were developed to estimate three highly-relevant urban tree growth attributes: canopy volume (CV), canopy projection (CP), and peak-increment-area age (PIA).

Analysis of soil and site data revealed relatively low variability between tree plantings within municipalities for many, but not all, variables. This suggests that sampling a few representative sites within a municipality may be sufficient to confidently evaluate planting spaces for their tree growth suitability. Some soil variables, however, either because of their high relevance to ultimate tree growth, their high variability between sites, their ease of measurement, or all three, may be critical to evaluate at every planting site. Based on this study, those variables should include certain plant-available soil nutrients, soil pH, soil texture, and soil compaction. Soil compaction was found however to be impractical to measure via soil-core sampler, which is the most common method used to evaluate soil compaction.

The approach of estimating bulk density from soil moisture, soil texture, and soil strength data shows promise as a field measurement technique; regression analysis of soil bulk density resulted in coefficients of determination of 42% to 85%, depending on soil type. Based on these findings, it is reasonable to suggest that a method or tool could be developed to confidently predict soil bulk density using soil strength and moisture measurements. Estimating bulk density from these easy-to-measure variables would allow for fast and reliable soil assessments as well as sharing of data in a commonly used measure.

Tree growth in the urban environment can be evaluated via tree-ring analysis. Tree ring analysis has been done in various studies for the rural environment but, studies in the urban environment are limited. In addition, semi-ring porous species such as *Q. virginiana* have not been the focus of any dendrochronological analysis to date possibly due to the difficulty in identifying growth rings. The results of the current study show that *Q. virginiana* can be assessed with reasonable reliability. It is also reasonable to suggest that the high variability of urban soil and site conditions lowers the interseries correlation of tree rings from urban trees. This may lead to the recommendation to decrease the commonly accepted correlation threshold of 0.4 for dendrochronological analyses of urban trees. Further research would be needed to identify a suitable threshold for urban dendrochronological research.

Tree-ring analysis was necessary to determine the age at which the tree reaches its maximum growth (peak-increment-area age (PIA)) – one of the tree growth response variables modeled in this study. The developed models fit the data well, explaining between 25 and 83% of the observed variability in tree growth. Tree growth models for PIA resulted in the highest coefficients of determination indicating that it is most sensitive to the tree’s growth conditions and that models can be used confidently to predict the age of the tree at which its growth rate declines. This age of maximum growth is of particular interest because when growth rate declines, the level of benefits provided by the tree will as well not further increase. CV and CP are less sensitive to prevailing below-ground growing conditions presumably because, above ground, the tree is often exposed to cultural practices – such as pruning – and other abiotic and biotic conditions – such as diseases and physical injury – that affect the size of the canopy yet may or may not affect the health and growth of the tree.

Full growth prediction models were developed using all thirty soil and site variables as well as simplified models. Soil pH was found to be significant for the majority of models as well as deficiencies of some nutrients such as Fe, B, Mn, and Zn, which are also associated with soil alkalinity. However, the influence of many variables was unclear. For example, the model influence of crown clearance height, soil depth for *Q. phellos* and soil volume for *Q. virginiana* were biologically counterintuitive, which suggests a correlation to other growth-influencing conditions that were not measured in this study. In addition to the potentially complex growth-prediction models that were based on thirty soil and site attributes, growth-prediction models with easy-to-measure soil and site variables, such as tree planting pit dimensions and soil pH, were developed. These simplified models were developed to determine how much variability in tree growth can be determined by soil and site attributes that are not expensive, laborious, or technically complex and therefore accessible to most municipalities. Currently, many resources are used to plant trees without knowing whether the tree will survive or whether it will reach the desired size. Trees may die prematurely or even outgrow their site. In either case, the tree would have to be removed and replaced which does not result in the desired canopy dimensions to provide level of benefits needed.

More research needs to be done to fully evaluate the potential of bulk density estimations from practical field measurements so that urban soils can be assessed more reliably. Further research needs to be done to evaluate urban trees for their dendrochronological potential to better determine the effects of urban soils, building and pavement construction, practices such as ‘root pruning’ or ‘tree topping’, pollution and other (anthropogenic) activities on tree growth and health.

Growth prediction models for all three species included variables that may suggest a negative influence of high vehicular traffic on tree growth. Urban tree growth models that include additional growth influencing factors such as degree of urbanization and pollution could improve our ability to predict tree growth and development. In addition, including planting pit characteristics that indicate the degree of resources available to the tree such as direction of the road and distance and height of surrounding buildings for solar radiation or more detailed information on each planting pit design to estimate soil water availability or more detailed rooting space (concrete alignment, soil surface height in comparison with the surrounding pavement surface) might reveal important information on tree growth. Soil attributes affect every tree and can be modified prior to tree planting if analysis reveals the soil's inadequacy. However, further research is needed on additional tree species across a wide range of age classes, soil types, and climatic conditions to provide sufficient models for predicting tree development in diverse settings. Without these scientific tools, efforts to increase tree canopy cover in urban areas will be hampered by the uncertainty surrounding how quickly trees will grow and which soil and site constraints have the greatest impact on tree development.