A 100% Tree Inventory Using i-Tree Eco Protocol: A Case Study at Auburn University, Alabama

by

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Abstract

The Auburn University campus in Auburn, Alabama, served as a site for a case study evaluating the applicability of i-Tree Eco to complete a 100% tree inventory. The 2009-10 inventory of the managed areas of main campus encompassed 237 ha. Information collected from each tree included diameter at breast height (dbh), tree height, crown width, percent dieback, and a tree condition rating. The complete inventory included 7,345 trees on the main campus with *Lagerstroemia* spp. (crapemyrtle), *Quercus phellos* (willow oak), and *Pinus taeda* (loblolly pine) being the most numerous species. Average dbh and total height of all trees were 16.4 cm and 8.5 m, respectively, with an estimated canopy cover of approximately 16%. Tree condition ratings, recorded twice for each tree, indicated that percent dieback alone is not a sufficient measure of tree condition. Field data were analyzed by the United States Department of Agriculture Forest Service (USDA FS) using i-Tree Eco which provided vital information on ecosystem services.

Ecosystem services data estimated by i-Tree Eco for the Auburn main campus (237 ha) and Davis Arboretum (5.5 ha) were separated to provide an evaluation of the differences between an urban managed and a protected forest. The ecosystem services reported included air pollution removal and carbon storage and sequestration. Air pollutants reported were carbon monoxide (CO), ozone (O_3), nitrogen dioxide (NO_2), particulate matter < 10 microns (PM10), and sulfur dioxide (SO_2). Trees in the

arboretum had an average dbh of 24.4 cm and basal area of 12.04 m^2/ha (std. dev. = 19.4 and 0.12, respectively) as compared to 16.4 cm and 2.24 m^2/ha (std. dev. = 19.6 and 0.13, respectively) for the main campus. The managed areas of campus stored 6,652 kg of carbon per ha and sequestered 291 kg/year/ha of carbon. The Davis Arboretum stored 41,975 kg of carbon per ha and sequestered 1,758 kg/year/ha of carbon, 6x the campus amount on a unit area basis. Trees from the main campus removed 2,970 kg/year of air pollution (12.5 kg/year/ha) compared to 560 kg/year for the arboretum (102 kg/year/ha), which was 8x the amount on a unit area basis compared to the main campus. Relative tree condition ratings indicated there was little difference in tree condition between the two areas; however, the larger diameter trees in the arboretum had higher condition ratings than those on the main campus.

Models that predict ecosystem services in urban areas are useful tools for urban forest managers and arborists. Tree crown form is an important component of these equations; however, there are few equations that predict ecosystem services available for urban, open-grown trees. Predictive open-grown crown width equations were developed for three native species common in urban forests in the southeastern United States (US). The species used were *Quercus lyrata* (overcup oak), *Quercus nuttallii* (Nuttall oak), and *Quercus phellos* (willow oak). To our knowledge, these are the first predictive open-grown crown width equations developed for these species in the southeastern US. Dbh (independent variable), dbh^2 (independent variable), and average crown width (dependent variable) data were used to create the equations which yielded R^2 values of 0.96, 0.94, and 0.91 for overcup, Nuttall, and willow oak, respectively. These equations can aid urban landscape and utility planners in predicting crown width at various trunk diameters, reduce field collection time by reducing the need to measure crown width in the field, and with time, be used to validate species specific equations, e.g. leaf biomass, for these and other southeastern urban-planted tree species.

Ecosystem services information obtained from the complete inventory of the Auburn main campus and Davis Arboretum provided a dataset used to evaluate the standard plot sampling protocol of i-Tree Eco. Air pollution removal and carbon storage and sequestration values estimated by i-Tree Eco were the ecosystem services factors utilized for this assessment. To achieve an 80% estimate of the total campus value for air pollution removal and carbon storage and sequestration, 622, 870, and 483, 0.04 ha plots, respectively, with at least one tree present would have to be inventoried, as opposed to the standard i-Tree Eco sampling protocol of 200-0.04 ha plots. Based on the proportion of area with and without trees, the Auburn campus would require 20, 30, and 16% of the total area to be inventoried for air pollution removal and carbon storage and sequestration, respectively, to obtain the necessary number of plots with at least one tree present.

In this study, i-Tree Eco procedures were an effective and efficient tool, based on having not incurred any major problems, and provided valuable information regarding Auburn University's and the Davis Arboretum's urban forest structure and functions. The ecosystem services results demonstrate how important and necessary naturalized and protected areas are in our urban environments and how small areas can have large impacts, because they may contain more trees on a unit area basis, which are typically larger and in better condition due to less disturbance. This study also provided a first step in the evaluation of the i-Tree Eco sampling protocol; however, efforts to test these methods at sites throughout the southeastern US and to evaluate stratified sampling are needed to provide the most accurate evaluation for urban forests. i-Tree Eco has the potential to become the urban forest inventory standard; however, more research is needed not only throughout the southeastern US but also other regions to more completely validate i-Tree Eco.

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List of Abbreviations

AU	Auburn University
CO	Carbon monoxide
Dbh	Diameter at breast height
EPA	Environmental Protection Agency
FS	Forest Service
GIS	Geographical Information System
GPS	Global Positioning System
LIDAR	Light Detection and Ranging
MCTI	Mobile Community Tree Inventory
NO_2	Nitrogen dioxide
O_3	Ozone
PM10	Particulate matter < 10 microns
SDAP	Storm Damage Assessment Protocol
SO_2	Sulfur dioxide
STRATUM	Street Tree Resource Analysis Tool for Urban forest Managers
UFORE	Urban Forest Effects Model
US	United States
USDA	United States Department of Agriculture

Chapter I.

Introduction and Literature Review

The urban forest, defined as "ecosystems characterized by the presence of trees and other vegetation in association with people and their developments" (Nowak et al. 2001), is an ever changing landscape due to human activities and the environment. Research has been conducted to quantify the impacts of trees in urban settings (Dwyer et al. 1991; McPherson et al. 1997; Nowak and Crane 1998; Nowak et al. 2008a; Pandit and Laband 2010), but more research is needed due to the importance of trees in mitigating many impacts of urban development. Trees alleviate those impacts by moderating climate; conserving energy, carbon dioxide, and water; improving air quality; and by enhancing the attractiveness of a city (Dwyer et al. 1992).

Tree inventories

To accurately assess the urban forest and its environmental impact, one has to know its composition and structure. Tree inventories are conducted and analyzed to provide this information. Traditionally, information regarding urban forest structure was gathered from street and park trees (Hauer 1994; Welch 1994), but due to increasing concerns, inventories have been expanded to encompass vegetation in other parts of the urban forest, including residential, industrial, and abandoned lands (McPherson et al. 1997).

Inventories provide information on forest structure (i.e. tree species, number, size and/or age, location) (Nowak and Crane 1998; Nowak et al. 2008a; Nowak et al. 2008b) and are the basis for deriving measurements of ecosystem services, including carbon storage and sequestration, and energy savings (Nowak et al. 2008a). Inventories can also be used to determine compensatory values of trees, or the monetary value in the urban environment to the individual owner (Nowak et al. 2002). These evaluations also aid in determining real estate value (Dwyer et al. 1992) and assessing liabilities and risks (Matheny and Clark 2009).

In the 1990's, Light Detection and Ranging (LIDAR) was first used commercially in forestry to conduct tree inventories (Carson et al. 2004). LIDAR technology uses lasers mounted on an aerial platform, e.g., a satellite, to send pulses out and then instruments to compute the distance based on travel time of light to the object and back to the laser transmitter (Jensen 2007). This technology is now being used to isolate individual trees (Chen et al. 2006), and to determine tree heights (Suárez et al. 2005), and individual tree crowns (Koch et al. 2006; Popescu et al. 2003). This approach allows for inventories to be conducted more efficiently as well as over impassible areas. However, it does still require the use of a ground crew to verify the information gathered.

i-Tree Eco

Researchers from the United States Department of Agriculture Forest Service (USDA FS) developed a tool that can improve inventory efficiency and provide the environmental information necessary to understand urban forest structure and values (Nowak and Crane 1998). The Urban Forest Effects (UFORE) model was developed to help resource managers and researchers quantify the structure of the urban forest and the functions of urban ecosystems (Nowak and Crane 1998). The model is a science-based, peer reviewed computer model (i-Tree 2010b) that estimates structural aspects such as species composition and diversity, tree density and overall health, and leaf area, as well as volatile organic compound emissions, the total amount of carbon stored and sequestered, and pollution removal and the associated percent improvement in air quality (Nowak and Crane 1998). Currently, projects and inventories utilizing the model are referred to as i-Tree Eco projects and inventories; however, the actual computer model used at the time of this study was the UFORE model (i-Tree 2010a).

i-Tree Eco has been used in several cities in the United States (US), including Atlanta, GA, Baltimore, MD, Boston, MA, New York, NY, and Philadelphia, PA (Nowak and Crane 1998), Minneapolis, MN, and San Francisco, CA (Nowak et al. 2008a), and has provided valuable information on ecosystem services and urban forest structure. Work has been conducted to validate different aspects of the model like plot and sample size (Nowak et al. 2008b), but more research is needed. Validating the model and i-Tree Eco techniques for other regions of the US is a necessary step for i-Tree Eco to become the urban forest inventory standard.

Another urban forest analysis tool being used is the Street Tree Resource Analysis Tool for Urban Forest Managers (STRATUM), now referred to as i-Tree Streets, which was developed by an USDA Forest Service research group in California (i-Tree 2010a). It is a computer based tool that helps to quantify and assess the urban forest street trees and acts in much the same way as i-Tree Eco. Measurements are taken from the street trees and the analysis tool uses the data to help quantify the trees' value in conserving energy and controlling stormwater, and describes any management needs (i-Tree 2010c). There are also other utilities available such as MCTI (Mobile Community Tree Inventory) and SDAP (Storm Damage Assessment Protocol) which are provided by the i-

Tree Suite. The MCTI allows the community to conduct tree inventories and manage them and the SDAP gives a community an efficient way of assessing damage in the urban environment after severe storms (i-Tree 2010a).

Tree condition

Numerous natural forest assessments have been conducted (FIA 2010; FHM 2010), and urban forest assessments are becoming more common (Dwyer et al. 2000; Nowak et al. 2001). Assessments usually focus on the health and condition of the trees. Tree health defined in a pathological sense is the incidence of biotic or abiotic factors affecting trees (Ferretti 1997a); whereas tree condition refers more to the appearance of the tree (Ferretti 1997a). Many indicators are considered in determining tree health and/or condition, two terms often used interchangeably. Ferretti (1997b) defined an indicator as a measurable environmental characteristic. Primary visual tree condition indicators include dieback, leaf size and discoloration, trunk damage, root damage, and even the presence of pests or disease either individually or sequentially. There are also ways of assessing non-visible parts of trees using computer technology, along with other techniques (Matheny and Clark 2009); however these are not commonly used.

Presently, there are several methodologies for assessing tree condition with some being very well known and established (FIA 2010) while others have only been used on a limited scale (i-Tree 2010c). Existing ratings typically have several subjective aspects (CITYgreen 2010; Webster 1978), may not include all the necessary indicators (i-Tree 2010c; i-Tree 2010d), or may be too detailed for all instances (CTLA 2000).

Ecosystem services

The urban environment is a dynamic landscape where humans cause changes every day that may be beneficial, detrimental, short-lived, or long lasting. The world's human population continues to rise and the migration to cities and urban areas is increasing (MEA, 2005b). In just the last century, the urban population grew to 2.9 billion, and as of 2005 there were 388 cities worldwide with populations of 1 million or more people (MEA, 2005b). These trends of constant change and population migration are increasingly stressing our urban environments, forests, ecosystems, and ecosystem services.

To better understand the changes occurring in our urban areas, we first need to appreciate our environment and what it provides humans. Moll and Petit (1994) defined an ecosystem as "a set of interacting species and their local, non-biological environment functioning together to sustain life." Ecosystem services can therefore be defined as "the benefits human populations derive, directly or indirectly, from ecosystem functions" (Costanza et al., 1997); more concisely, "ecosystem services are the benefits people obtain from ecosystems" (MEA, 2005a).

Ecosystem services encompass numerous benefits which typically vary from region to region and city to city. Urban ecosystem services include air filtering, micro-climate regulation, noise reduction, rainwater drainage, sewage treatment, recreational and cultural values (Bolund and Hunhammar, 1999), carbon storage and sequestration, energy savings (Nowak et al., 2008), and the provision of wildlife habitats (Patterson and Coelho, 2009). Extensive research has placed values on ecosystem services (Bolund and Hunhammar, 1999; Chee, 2004; Heal, 2000; Patterson and Coelho, 2009), as well as their effects (Nowak and Crane, 2002; Nowak et al., 2006; Pandit and Laband, 2010), and techniques and models have been developed to help quantify them, such as i-Tree Eco (i-Tree 2010a).

When managing urban forests, it is important to understand that different levels of management (McDonnell and Pickett, 1990; Welch, 1994) can affect the ecosystem services provided. These range from intensively maintained areas (e.g. street trees, trees near buildings, etc.) to those where maintenance is passive and trees are protected, such as parks or arboretums (McDonnell and Pickett, 1990; Welch, 1994). It is important to understand how different levels of maintenance affect ecosystem services so appropriate management strategies and resources can be concentrated in areas where they provide the most benefit.

Predictive open-grown crown width equations for urban trees

Tree measurements such as diameter at breast height (dbh), total height, height to the live crown, and crown width can provide vital information on their own, as well as providing crucial data for other calculations such as leaf area and leaf biomass (Nowak 1996; Peper et al. 2001a; Peper at al. 2001b). These measurements are important to urban forest managers, arborists, researchers, and planners because they can aid in the development of management strategies and practices (Peper et al. 2001a; Peper et al. 2001b). Dbh, crown width, leaf area, and other information from trees also aid in assessing ecosystem processes such as evapotranspiration, light interception, and atmospheric deposition (Nowak 1996), and can help in developing predictive equations for pollution uptake (Peper et al. 2001b). Tree measurements are vital when determining ecosystem services, and having crown equations makes it possible to determine benefits such as carbon sequestration and air pollution removal. Using predictive open-grown crown width equations can also speed up data collection in the field by not having to measure crown width. Urban shade trees are vital to our environment and offer many benefits, most of which depend on their size (Frelich 1992).

Few predictive crown equations have been developed for open-grown, urban trees (Nowak 1996; Peper et al. 2001a; Peper et al. 2001b; Peper and McPherson 2003); especially for specific regions. However, researchers in the traditional field of forestry have developed numerous equations that include dbh, biomass, and crown width (Krajicek et al. 1961; Ek 1974; Hasenauer 1997; Lhotka and Loewenstein 2008). Although some of these equations have been used for urban trees, validation is lacking (Peper et al. 2001a). Tree canopy architecture differs between open-grown and forest-grown or closed canopy conditions. When grown in the open, a tree's canopy can reach its full size and not be restricted; however, in a forested situation, tree canopies often touch and are limited due to the inadequate growing space. Limited research on dimensional relationships for urban trees has been conducted on trees with crowns that were full and healthy in New Jersey (Fleming 1988), on healthy trees in St. Paul and Minneapolis, Minnesota (Frelich 1992), on trees with full tree crowns in excellent condition in Chicago, Illinois (Nowak 1996), on street trees in Santa Monica, Calilfornia (Peper et al. 2001a), and on street trees in Modesto, California (Peper et al. 2001a; Peper et al. 2001b). The research conducted by Peper et al. (2001a; 2001b) aided in the development of predictive crown width equations for urban trees in regions with longer growing seasons, varying locations, and broader ranges of condition; however, to our knowledge, there are no equations available for southeastern US tree species planted in urban locales.

Urban forest plot inventory sampling

Several methods have been used to conduct urban tree inventories, including sampling (Nowak and Crane 1998; Nowak et al. 2008a; Nowak et al. 2008b) and 100% inventories (Martin et al. In press). Sampling, or random sampling, is conducted by visiting a pre-determined number of trees or plots within a given area to provide an estimate of a larger area (McBride and Nowak 1989; Jaenson et al. 1992; Nowak et al. 2008a; Nowak et al. 2008b). One hundred percent inventories assess every tree, providing the most accurate information (Jaenson et al. 1992; Nowak et al. 2008a).

Since urban areas can encompass 1000s of hectares, complete tree inventories are not always practical. Following i-Tree Eco plot sampling protocol, 200 circular 0.04 ha randomly located plots are assigned in the study area (Nowak and Crane 1998; Nowak et al. 2008a; Nowak et al. 2008b; i-Tree Eco 2010c; i-Tree Eco 2010d). Two hundred plots were established as the standard because that was the number of plots that could be inventoried in a 14-week summer season by a two person field crew (Nowak et al. 2008b). Following this protocol, Nowak et al. (2008b) found that a 12% relative standard error (RSE) produced a reasonable estimate of the population, provided that level of error is acceptable.

Hypotheses and objectives

i-Tree Eco has the potential to become the urban tree inventory standard, presenting a valuable management tool as well as vital and accurate environmental information. The overall goal of this project was to conduct a 100% tree inventory of the managed portions of the Auburn University campus following i-Tree Eco protocol, including validating certain parameters, to help make i-Tree Eco more applicable and valid for the southeastern US. This goal was achieved after a two-year study of the Auburn University campus urban forest structure and function following i-Tree Eco protocol. Specific hypotheses and objectives were as follows:

H_{0i}: An overall tree condition rating is a more accurate indicator of tree condition than percent dieback.

H_{0ii}: The amount of ecosystem services provided by a protected forest will be greater than the amount of ecosystem services provided by an urban managed forest on a per area basis.

H_{0iii}: The number of plots needed for this project area in the southeastern region will differ from the standard i-Tree Eco protocol of 200 plots when using ecosystem services as the factors of interest.

Specific objectives were: (1) complete a 100% tree inventory of the managed areas on the Auburn University campus following i-Tree Eco protocol, (2) evaluate the differences in ecosystem services between an urban managed and protected forest, (3) develop predictive open-grown crown width equations for *Quercus lyrata* (overcup oak), *Quercus Nuttallii* (Nuttall oak), and *Quercus phellos* (willow oak), and (4) evaluate the standard i-Tree Eco plot sampling protocol.

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Chapter II.

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Abstract

The Auburn University campus in Auburn, Alabama, was used as the site for a case study on the applicability of i-Tree Eco using a 100% tree inventory. The 2009-10 inventory of the managed areas of campus encompassed 237 ha (585 ac). Information collected from each tree included diameter at breast height (dbh), tree height, crown width, percent dieback, and a tree condition rating. The complete inventory included 7,345 trees with *Lagerstroemia* spp. (crapemyrtle), *Quercus phellos* (willow oak), and *Pinus taeda* (loblolly pine) being the most numerous species on campus. Average dbh and total height of all trees were 16.4 cm (6.5 in) and 8.5 m (27.9 ft), respectively, with an estimated canopy cover of approximately 16%. Two tree condition ratings were recorded for each tree and results indicated that percent dieback alone is not a sufficient measure to evaluate tree condition. In this case study, i-Tree Eco procedures were found to be an effective and efficient tool, based on not having incurred any major problems, and provided valuable information regarding Auburn University's urban forest structure and function.

Introduction

The urban forest, defined as "ecosystems characterized by the presence of trees and other vegetation in association with people and their developments" (Nowak et al. 2001), is an ever changing landscape due to human activities and the environment. Research has been conducted to quantify the impacts of trees in urban settings (Dwyer et al. 1991; McPherson et al. 1997; Nowak and Crane 1998; Nowak et al. 2008a; Pandit and Laband 2010), but more research is needed due to the importance of trees in mitigating many impacts of urban development. Trees alleviate those impacts by moderating climate; conserving energy, carbon dioxide, and water; improving air quality; and by enhancing the attractiveness of a city (Dwyer et al. 1992).

To accurately assess the urban forest and its environmental impact, one has to know its composition and structure. Tree inventories are conducted and analyzed to provide this information. Traditionally, data regarding urban forest structure were gathered on street and park trees (Hauer 1994; Welch 1994), but due to increasing concerns, inventories were expanded to encompass vegetation in other parts of the urban forest, including residential, industrial, and abandoned lands (McPherson et al. 1997). Obviously, conducting a 100% inventory is the most accurate, but unless it is being conducted on relatively small areas, it is not as cost effective as random sampling (Nowak et al. 2008a; Nowak et al. 2008b).

Inventories provide information on forest structure (i.e. tree species, number, size and/or age, location) (Nowak and Crane 1998; Nowak et al. 2008a; Nowak et al. 2008b) and are the basis for deriving measurements of ecosystem services, including carbon storage and sequestration, and energy savings (Nowak et al. 2008a). Inventories can also determine compensatory values of trees, or the monetary value in the urban environment to the individual owner (Nowak et al. 2002). These evaluations also aid in determining real estate value (Dwyer et al. 1992) and assessing liabilities and risks (Matheny and Clark 2009).

Researchers from the United States Department of Agriculture (USDA) Forest Service developed a tool that can improve inventory efficiency and provide the environmental information necessary to understand urban forest structure and values (Nowak and Crane 1998). The Urban Forest Effects (UFORE) model was developed to help resource managers and researchers quantify the structure of the urban forest and the functions of urban ecosystems (Nowak and Crane 1998). The model is a science-based, peer reviewed computer model (i-Tree 2010b) that estimates structural aspects such as species composition and diversity, tree density and overall health, and leaf area, as well as volatile organic compound emissions, the total amount of carbon stored and sequestered, and pollution removal and the associated percent improvement in air quality (Nowak and Crane 1998). Currently, projects and inventories utilizing the model are referred to as i-Tree Eco projects and inventories; however, the actual computer model used at the time of this study was the UFORE model (i-Tree 2010a).

The overall purpose of this research project was to assess the applicability of using i-Tree Eco protocol to conduct a 100% inventory. A university campus is an ideal location for such an inventory. The data collected can be used for several purposes: identification of major tree species, evaluation of height and diameter distribution, and evaluation of tree health. In addition, the model can be used to determine various ecosystem services, including carbon storage and air pollution removal, which may be important in identifying the "human footprint" on campus. The Auburn University (AU) campus, Auburn, Alabama, was an ideal location to conduct this evaluation. Specific objectives of the study were: (1) complete a 100% tree inventory of the managed areas on the Auburn University campus using a format that is UFORE compatible and follows i-Tree Eco protocol and (2) evaluate dieback as an overall indicator of tree condition.

Materials and Methods

Study site

The study site was the Auburn University campus (32° 36' N, 85° 30' W) located in Auburn, Alabama. The core campus encompasses approximately 306 ha (755 ac). The inventory included the managed portions of campus, which covered approximately 237 ha (585 ac).

Inventory

The method of assessment for this project was a 100% tree inventory in an-i-Tree Eco compatible form (i-Tree 2010c; i-Tree 2010d). The managed areas of campus were first divided into 99 sections and numbered using spring 2008 aerial photographs (courtesy of the City of Auburn, see Illustration 1). The study area was divided into sections to

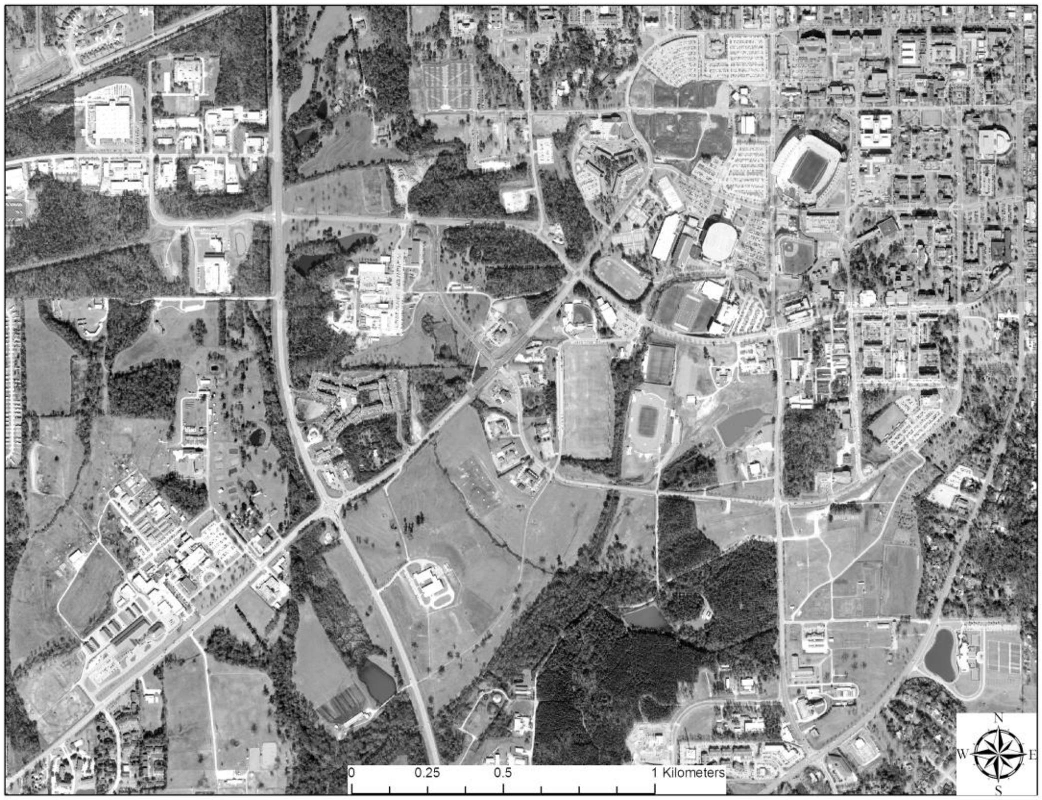


Illustration 1. Aerial photograph of the Auburn University campus-spring 2008.

provide a layout for inventory crews to follow and keep track of areas ("bookkeeping") that had and had not been inventoried. Section perimeters were determined by selecting borders such as streets and sidewalks where possible and natural borders in all other cases so that sections were easily distinguishable. Sections were numbered starting with central campus and moving outward.

Data collection

All data were collected following i-Tree Eco tree inventory protocol (i-Tree 2010c). Field data were collected by crews consisting of 1-3 members. A Global Positioning System (GPS) unit (either a Trimble GeoXM GeoExplorer® 2005 or a Trimble GeoXT GeoExplorer® 2008 series, with an external antenna on a tripod) was used to collect forest structure data in a data dictionary. The software used on the GPS units was TerraSync™ v.2.4.

The correct section was identified and the number entered into the collection unit. Total number of stems per tree was recorded and dbh was obtained using a logger's diameter tape. Minimum tree diameter at breast height (dbh) [1.37 m (4.5 ft) above the ground-line] to be included in the inventory was 2.54 cm (1 in). For multi-stem trees, up to the six largest stems were recorded at breast height. For those trees that could not be measured at breast height, the measurement was taken at 0.3 m (1 ft) from the ground-line. Crapemyrtle (*Lagerstroemia* spp.) was the only species measured at 0.3 m (1 ft) from the ground-line for all specimens, because the majority of the trees could not be measured at breast height due to their inherent form. Total tree and bole height were evaluated using a laser hypsometer (either a MDL LaserAce® hypsometer or a Laser Technology, Inc. TruPulse™ 360B rangefinder). Total tree height was determined by measuring from the ground-line to the top (alive or dead) of the tree, and bole height was recorded as the height to the lowest branch of significance. Crown width was determined by taking two measurements from the crown edges at 90 degree angles and averaging them.

Data collected were downloaded from the GPS units to a desktop computer (daily) using the Trimble GPS Pathfinder® Office v.4.1 and 4.2-software. The ESRI ArcGIS® 9 ArcMap™ v.9.3 software was used for final data presentation. Once all data were collected, it was sent to the USDA Forest Service for analysis.

Tree condition rating

Dieback and percent missing crown were determined for each tree. Dieback of branches that appeared to have died from the terminal ends was evaluated by observing all sides of the tree and assigning an overall estimate of the percent dieback. Ranges of <1, 1-10, 11-25, 26-50, 51-75, 76-99, and 100% dieback were used to assign tree conditions of excellent, good, fair, poor, critical, dying, and dead, respectively. The percent missing, or the amount of the crown that was missing, was determined the same way as percent dieback, by viewing all sides of a tree and estimating the overall percent missing in 5-percent increments. Missing crowns could be due to impacts such as directional pruning or branches being lost due to damage (ice, wind, etc.).

In addition to the i-Tree Eco protocol, an overall condition rating as a comparison was assigned by assessing all aspects of a tree that were visible, including dieback and missing crown, trunk or limb damage, the presence of insects or disease, visible root damage, and the proximity to infrastructure. The condition rating used was a modification of other ratings (Webster 1978; CTLA 2000). The condition rating scale was: 6 = excellent, 5 = good, 4 = fair, 3 = poor, 2 = very poor, and 1 = dying/dead. Excellent condition consisted of no missing crown, dieback, visible damage, or disease or pest presence. Good condition constituted < 10% dieback, missing crown, visible structural damage, and injury from diseases and pests; whereas a condition rating of fair had 10-25%, poor had 25-50%, very poor had 50-75%, and dying/dead had > 75% of the tree being affected by one or more maladies. The most noticeable (ocular observation) damaging factor was used as the deciding reason when assigning the condition rating. To reduce subjectivity, each crew member rated tree condition independently, and then all crew members would discuss and arrive at one tree condition rating.

To evaluate dieback as a tree condition indicator, we compared the rating to the overall tree condition rating for every tree on campus. To analyze the data, dieback ranges were assigned a numerical value where <1% = 6, 1-10% = 5, 11-25% = 4, 26-50% = 3, 51-75% = 2, and 76-99% and 100% = 1; and the tree condition ratings used the assigned numbers. For the analysis, trees rated as excellent and good by the dieback and overall condition ratings were combined into 1 group. A chi-square test was used to test if there was no significant difference between dieback (i-Tree Eco) and overall tree condition rating (developed by our group) for every tree on campus.

Results

Campus inventory

There were 7,345 trees inventoried on the Auburn University campus comprised of 139 species (Table 1) that averaged 16.4 cm (6.5 in) in dbh. Nine species accounted for

Table 1. Tree characteristic totals for managed areas of the Auburn University campus using i-Tree Eco inventory procedures.

Number of trees on campus	7345
Number of species on campus	139
Average dbh (cm)	16.4
Average tree height (m)	8.5
Average tree crown width (m)	6.7
Basal area (m^2/ha)	2.24
Estimated canopy cover (%)[z]	16
Estimated compensatory value ($)[y]	10,757,000

[z]Estimated canopy cover was calculated by using the total canopy-projected ground area calculated by the model and dividing it by the total area inventoried.
[y]Estimated compensatory value calculated by i-Tree Eco based on the Council of Tree and Landscape Appraisers (CTLA) method (i-Tree 2010d).

almost 64% of the total population (Illustration 2, Table 2). Crapemyrtle (*Lagerstroemia* spp.) and four oak (*Quercus*) species comprised over 40% of the total population.

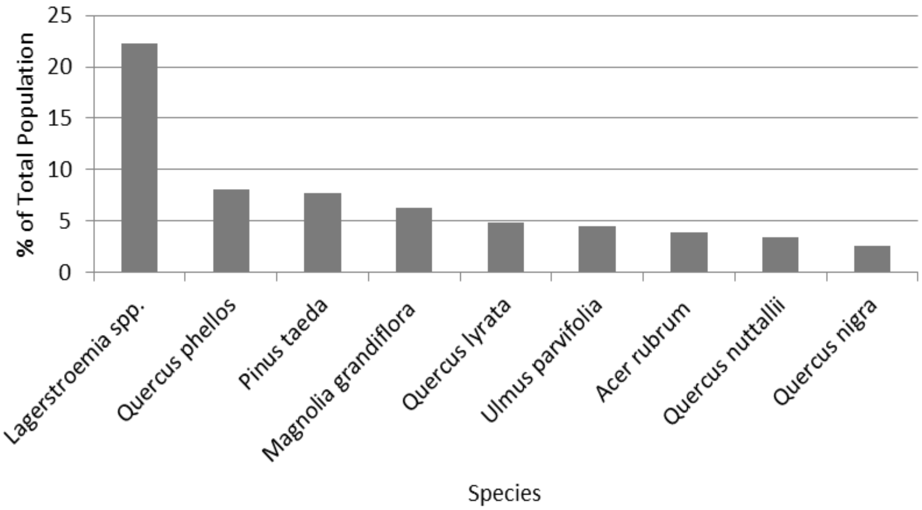


Illustration 2. Percent species composition for the most common species on the AU campus in 2009-10.

Table 2. Tree characteristic totals for the most common species on the AU campus.

Tree species	Num. of Trees	Ave. dbh (cm)	Ave. height (m)	Ave. crown width (m)
Lagerstroemia spp.	1639	12.1 (2.8-60.2) [z]	5.0 (1.8-13.7)	5.1 (0.3-12.2)
Quercus phellos	596	12.6 (5.1-142.5)	6.5 (3.4-20.4)	4.3 (1.5-21)
Pinus taeda	565	48.6 (5.1-135.6)	21.0 (3.1-41.5)	9.9 (2.1-22.6)
Magnolia grandiflora	464	15.7 (3.6-104.6)	6.0 (2.4-17.4)	5.1 (0.3-18.9)
Quercus lyrata	363	23.0 (4.8-123.7)	7.9 (3.1-22.0)	6.8 (1.8-31.1)
Ulmus parvifolia	331	9.6 (5.1-83.1)	5.3 (3.1-15.6)	4.1 (0.9-18.9)
Acer rubrum	289	17.8 (4.1-60.5)	7.6 (3.4-14.9)	6.1 (2.4-18.0)
Quercus nuttallii	250	16.4 (6.4-56.4)	7.5 (4.3-16.2)	5.9 (2.4-15.3)
Quercus nigra	194	47.6 (4.6-126.5)	16.6 (3.4-30.5)	12.7 (3.1-32.0)

[z] ( ) represents the range for each species.

Fifty six percent of the total tree population on the AU campus is < 7 m (23 ft) and < 1% are 30 m (98 ft) or more in height (Illustration 3a). Sixty four percent of the population has a diameter < 21 cm (8.2 in) (Illustration 3b). It is important to note that the large number of crapemyrtles contributes to the skewed results for both height and diameter;

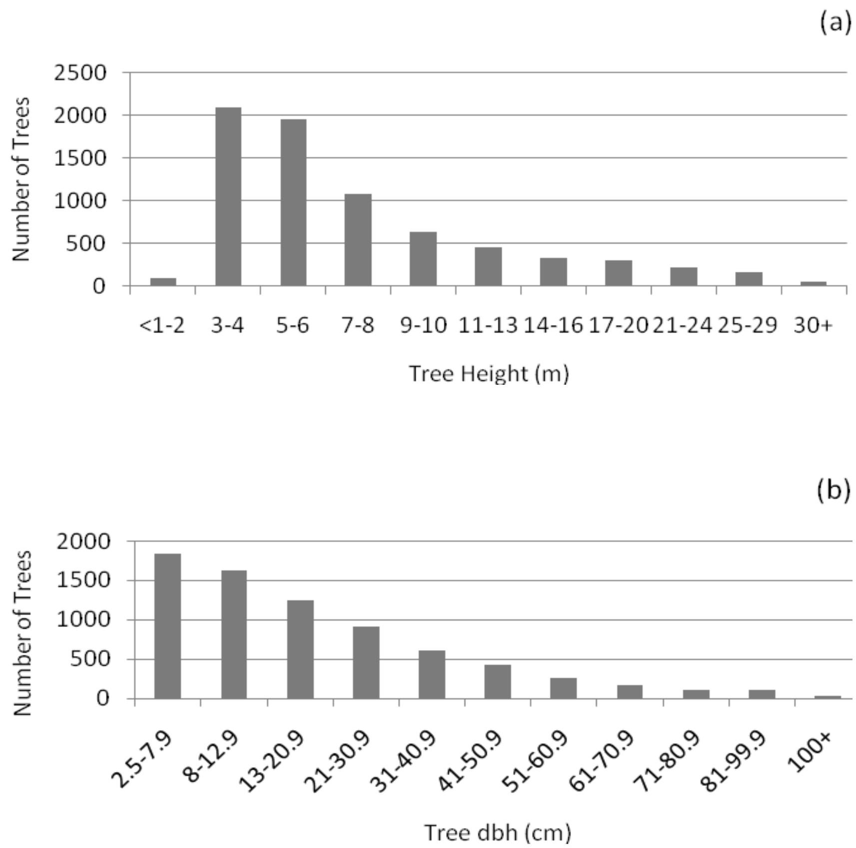
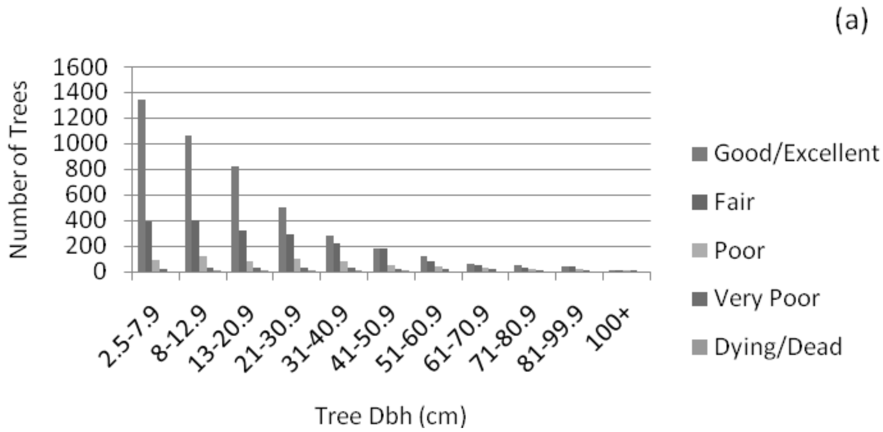


Illustration 3. Tree height distribution (a) and (b) tree diameter distribution for the AU campus (2009-10).

without these trees, the height distribution peaks in the 5-6 m (16.4-19.7 ft) (1482 trees) range and peaks in the 8-12.9 cm (3.1-5.1 in) (1230 trees) range for dbh. Total canopy cover was approximately 16%, and the overall value was estimated at approximately $10 million (Table 1).

Tree condition on the AU campus

Tree condition was a minor component of the original inventory; however, evaluating the effectiveness of using dieback as an indicator of tree condition versus overall condition became an important issue in the evaluation of i-Tree Eco. The tree condition rating for the AU campus is shown in Illustration 4a. Using our protocol, we determined that over



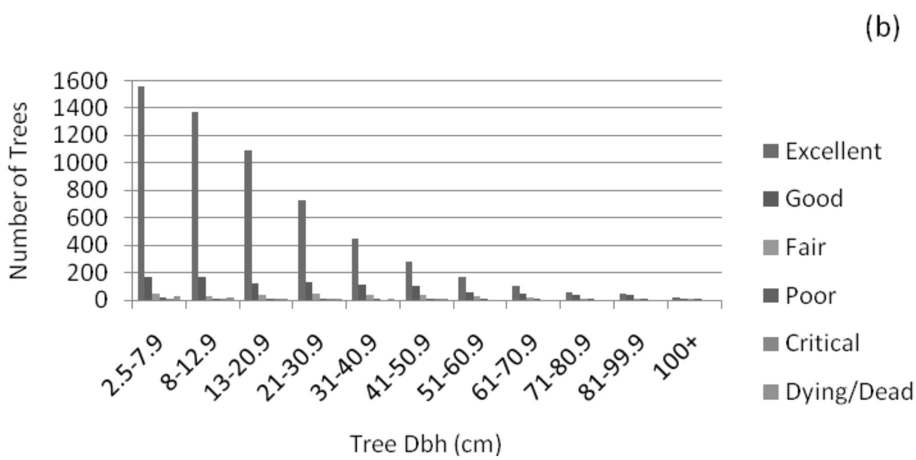


Illustration 4. Tree condition by diameter class using overall condition class (a) and percent dieback (b) for the entire population.

60% of the total tree population was rated as in excellent or good condition; however, using model-derived data (dieback) as an indicator of tree condition, 93% of the population was rated as being in excellent or good condition (Illustration 4b). The overall condition rating also ranked approximately 3% of the trees in very poor and dying/dead condition and the model rated about 1% of the trees in critical and dying/dead condition. The comparison of dieback and the overall tree condition rating using a chi-square test resulted in a statistically significant difference (p-value <0.0001) in the two rating systems (Table 3).

Table 3. Contingency table for all trees on the AU campus containing dieback rating and the corresponding overall tree condition rating.

		Overall Condition						
		E	G	F	P	VP	D/D	Total
Dieback	E^z	9	4113	1387	292	71	1	5873
	G	0	319	480	147	43	1	990
	F	0	13	130	115	68	2	328
	P	0	0	17	19	22	11	69
	C	0	0	2	13	4	10	29
	D/D	0	0	0	47	5	4	56
	Total	9	4445	2016	633	213	29	7345

^{z}E = Excellent, G = Good, F = Fair, P = Poor, C = Critical, VP = Very Poor, D/D = Dying/Dead.

Discussion

To our knowledge, this is the first published data on a 100% tree inventory using i-Tree Eco protocols. Using these data we were able to determine species composition, size distribution, and diversity. We also determined the relative value and tree condition. These data are very useful to the land manager in planning and maintaining a healthy, viable forest. The model has predominately been employed to assess the urban forests of larger cities (Nowak and Crane 1998; Nowak et al. 2002; Nowak et al. 2008a; Nowak et al. 2008b). The AU 100% tree inventory case study is small in scale when compared to other i-Tree Eco study sites; however, it is comparable in certain aspects. To compare our complete tree data with data collected using the i-Tree Eco protocol (plots), we used results from Auburn, Alabama (Huyler et al. 2010) and Gainesville, Florida (Escobedo et al. 2009a; Escobedo et al. 2009b).

In terms of species composition, all 3 study sites were similar in that they all had loblolly pine (*Pinus taeda*), red maple (*Acer rubrum*), and water oak (*Quercus* nigra) among the top ten most common species (Escobedo et al. 2009b; Huyler et al. 2010). The AU campus and the cities of Auburn and Gainesville were also similar in that the majority of the trees had a dbh of ≤ 15 cm (5.9 in) (Escobedo et al. 2009b; Huyler et al. 2010). Auburn University differed from Auburn and Gainesville in tree density (no/ha); where the campus had 31 trees/ha (12 trees/ac), Auburn had 985 trees/ha (399 trees/ac) (Huyler et al. 2010), and Gainesville had 348 trees/ha (141 trees/ac) (Escobedo et al. 2009b). The campus also differed from the other study sites in canopy cover: AU at 16%, Auburn at 49% (Huyler et al. 2010), and Gainesville at 51% (Escobedo et al. 2009a). The major differences in tree cover were due to the AU study only encompassing the managed areas of campus, whereas the other studies included vacant (unincorporated forest lands and vacant lots), residential, and industrial lands where basal area and density are generally much higher. It is hoped that in the future, data collected from 100% inventories using the i-Tree Eco protocol can be used to improve plot efficiency by improving the precision of the sampling technique for collecting information on the urban forest ecosystem structure and function.

The evaluation of dieback was important because the model assigns tree condition according to the dieback rating. As i-Tree Eco was designed to assess ecosystem services that are often related to leaf functions, it focuses its condition rating on crown condition. Dieback is an important factor when evaluating tree condition (indicator of crown integrity), but cannot alone be the determining factor since it is only one determinate of tree health. Managers who want to really understand and manage their urban forests, and especially tree condition, must examine the entire tree. The overall condition rating developed for this project included dieback as a functional rating but also considered the structural condition of the tree; the key difference between the two ratings. It was determined that using dieback as a surrogate for tree condition is a poor indicator of overall tree condition. However, our results are based on comparisons between dieback and the overall tree condition rating developed for this project to provide a simple and quick assessment of tree condition; and comparisons using other condition ratings may yield different results (CITYgreen 2010; CTLA 2000; ISA 2010). Our approach combined both crown and structural characteristics into one rating; however, providing individual ratings for crown and structure may provide a clearer picture of overall tree condition. In general, the overall condition rating resulted in a lower condition rating; however, there was a low incidence (1% of the entire population) where the overall condition rating resulted in a higher condition rating than percent dieback, which can be attributed to the observational nature of the study and the subjectivity of the crews. In the end, both the crown and structural condition of the tree need to be considered together. We recommend more research be conducted on the evaluation of tree condition by either developing a new rating system or using other established tree condition ratings (CITYgreen 2010; CTLA 2000; ISA 2010) that may yield more accurate assessments.

Conclusion

i-Tree Eco has the potential to become the urban tree inventory standard, presenting a valuable management tool, as well as vital and accurate environmental information. Our research determined that this protocol is efficient and effective for a 100% inventory of a small area. These results provide valuable information that land managers can use to help manage and maintain the evolving urban forest on the Auburn University core campus. However, for i-Tree Eco to reach its full potential, further studies and inventories are needed in other locales and areas of the country. More research dealing with the evaluation of dieback as a surrogate for tree condition is just one aspect that requires further study. With more research, i-Tree Eco can be validated for all regions of the U.S.

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Chapter III.

An Ecosystem Services Case Study: Comparison of a Protected and a Managed Forest in an Urban Setting

Abstract

The Auburn University campus in Auburn, Alabama, USA, was used as the location for a case study to compare ecosystem services of a protected and urban managed forest. Information on ecosystem services provided by the trees on campus were obtained after an i-Tree Eco analysis of data collected during the 2009-10 100% tree inventory of the managed portion of the Auburn campus and the Davis Arboretum. The ecosystem services reported for the 237 ha managed portion of campus and the 5.5 ha arboretum included air pollution removal and carbon storage and sequestration. The air pollutants removed were carbon monoxide (CO), nitrogen dioxide (NO_2), ozone (O_3), particulate matter < 10 microns (PM10), and sulfur dioxide (SO_2). Results showed that the managed portion of campus stored 6,652 kg of carbon per ha and sequestered 291 kg/year/ha of carbon. The Davis Arboretum stored 41,975 kg of carbon per ha and sequestered 1,758 kg/year/ha of carbon; almost 6x the amount for the main campus. The managed portion of campus removed 2,969,047 g/year of air pollution (12,475 g/year/ha) and the arboretum removed 560,303 g/year (101,873 g/year/ha); 8x the amount of the main campus and 8x the amount of the main campus on a per-ha basis. Results from tree condition ratings showed that overall, there was very little difference in tree condition between the two areas; however, the larger diameter classes in the arboretum had higher condition ratings. The ecosystem services results demonstrated how important and necessary naturalized and protected areas are in our urban environments and how even small areas can have large impacts; possibly because they contain more trees on a per area basis, and because the trees are typically larger and in better condition.

Introduction

The urban environment is a dynamic landscape where humans cause changes every day that may be beneficial, detrimental, short-lived, or long lasting. The world's human population continues to rise and the migration to cities and urban areas is increasing (MEA, 2005b). In just the last century, the urban population grew to 2.9 billion, and as of 2005 there were 388 cities worldwide with populations of 1 million or more people (MEA, 2005b). These trends of constant change and population migration are increasingly stressing our urban environments, forests, ecosystems, and ecosystem services.

To better understand the changes occurring in our urban areas, we first need to appreciate our environment and what it provides humans. Moll and Petit (1994) defined an ecosystem as "a set of interacting species and their local, non-biological environment functioning together to sustain life." Ecosystem services can therefore be defined as "the benefits human populations derive, directly or indirectly, from ecosystem functions" (Costanza et al., 1997); more concisely, "ecosystem services are the benefits people obtain from ecosystems" (MEA, 2005a).

Ecosystem services encompass numerous benefits which typically vary from region to region and city to city. Urban ecosystem services include air filtering, micro-climate regulation, noise reduction, rainwater drainage, sewage treatment, recreational and cultural values (Bolund and Hunhammar, 1999), carbon storage and sequestration, energy savings (Nowak et al., 2008), and the provision of wildlife habitats (Patterson and Coelho, 2009). The services generated also help in increasing the quality-of-life and public health. Most environmental problems found in cities are created locally, and one of the most effective ways to deal with them is through local ecosystem services (Bolund and Hunhammar, 1999).

Extensive research has placed values on ecosystem services (Bolund and Hunhammar, 1999; Chee, 2004; Heal, 2000; Patterson and Coelho, 2009), as well as their effects (Nowak and Crane, 2002; Nowak et al., 2006; Pandit and Laband, 2010). Also, techniques and models have been developed to help quantify ecosystem services, such as i-Tree Eco, originally called the Urban Forest Effects (UFORE) model, developed by the United States Department of Agriculture Forest Service (USDA FS) (Nowak and Crane, 1998). These techniques and models have been used in numerous cities in the United States and a few in other countries (Nowak et al., 2008).

When managing urban forests, it is important to understand that different levels of management (McDonnell and Pickett, 1990; Welch, 1994) can affect the ecosystem services provided. These range from intensively maintained areas (e.g. street trees, trees near buildings) to those where maintenance is passive and trees are protected, such as parks or arboretums (McDonnell and Pickett, 1990; Welch, 1994). It is important to understand how different levels of management affect ecosystem services so appropriate strategies and resources can be concentrated in areas where they provide the most benefit. The Auburn University (AU) campus, Auburn, AL was an ideal location to evaluate these differences, having large areas that are intensively managed, as well as an arboretum that is naturalized, protected, and more passively maintained. The information reported here is a part of a larger study evaluating the usefulness of i-Tree Eco protocols for a 100% inventory and validating certain i-Tree Eco parameters for southern urban forests (Martin et al., In press). Our goal was to use the Auburn University campus as a case study comparing ecosystem services of managed and protected areas in an urban forest, while specifically evaluating air pollution removal and carbon storage and sequestration.

Materials and Methods

Study site

The study site was the Auburn University campus (32° 36' N, 85° 30' W) located in Auburn, Alabama (Illustration 5). The core campus encompasses approximately 237 ha

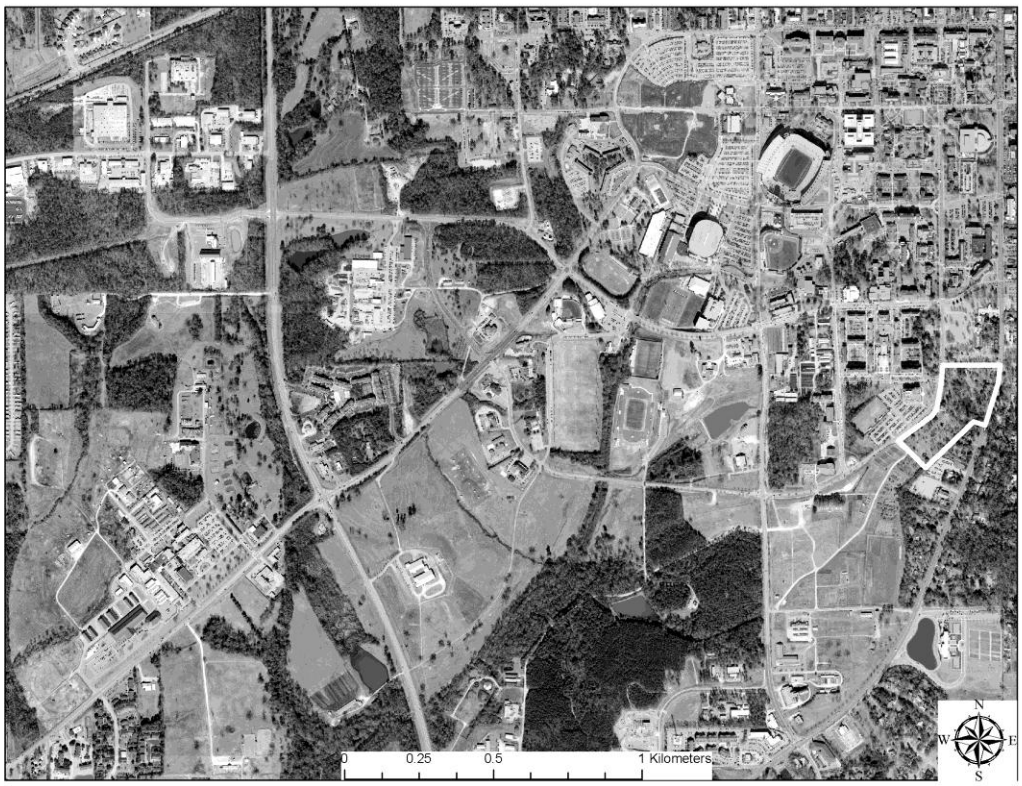

Illustration 5. Aerial photograph of the Auburn University campus and Davis Arboretum (highlighted in white)-spring 2008.

that are managed; meaning these areas are maintained on a continuous basis. The study site included the 237 ha of managed campus and the 5.5 ha Davis Arboretum.

The Donald E. Davis Arboretum (Illustration 5), established in 1963, is maintained by the College of Sciences and Mathematics (Auburn University, 2010). Its primary functions are education, conservation, and research on ecosystem preservation and diversity (Auburn University, 2010). The management philosophy of the Davis Arboretum is to encourage native species and habitats.

Field data

Field data were collected during a 100% tree inventory of the AU campus in 2009-10 (Martin et al., In press) following i-Tree Eco procedures (i-Tree, 2010b; i-Tree, 2010c) which resulted in a complete population sample of both the AU main campus and Davis Arboretum. There were 16 attributes measured for each tree including tree species, diameter at breast height (dbh) (1.37 m above the ground), tree height, average crown width, dieback, and an overall tree condition rating modified from Webster (1978) and CTLA (2000). The overall condition rating accounted for visible damage such as dieback, missing crown, and physical damage, and used a rating scale ranging from excellent (6) to dying/dead (1). A more detailed description of the sampling methodology used can be obtained by referring to Martin et al. (In press) and i-Tree Eco (i-Tree, 2010b). Tree locations were recorded with a Global Positioning System (GPS) unit (either a Trimble GeoXM GeoExplorer® 2005 series or a Trimble GeoXT GeoExplorer® 2008 series, with an external antenna on a tripod).

Data were downloaded (daily) from the GPS units to a desktop computer using the Trimble GPS Pathfinder® Office v.4.1 and 4.2 software. The ESRI ArcGIS® 9 ArcMap™ v.9.3 software was used for final presentation. Once collected, data were sent to the United States Department of Agriculture Forest Service (USDA FS)-Urban

Forestry South in Athens, Georgia for analysis. Using this information, ecosystem services for the AU urban forest and Davis Arboretum were compared.

i-Tree Eco analysis

Data provided by i-Tree Eco included carbon storage and sequestration and air pollution removal (i-Tree, 2010c). The air pollutants that i-Tree Eco estimates includes: carbon monoxide (CO), ozone (O_3), nitrogen dioxide (NO_2), particulate matter < 10 microns (PM10), and sulfur dioxide (SO_2) (i-Tree, 2010a; i-Tree, 2010c). The model uses a combination of tree cover data, United States Environmental Protection Agency (US EPA) pollution-concentration monitoring data, and hourly National Climatic Data Center (NCDC) weather data from the local area to provide amounts of air pollution removed (i-Tree, 2010c). i-Tree Eco also calculates a monetary value for the amount of each pollutant removed using median externality values for the US (i-Tree, 2010c).

Carbon storage and sequestration occur when trees fix carbon during photosynthesis and then store the excess carbon as biomass, thus removing atmospheric carbon dioxide (CO_2), a dominant greenhouse gas (Nowak and Crane, 2002). i-Tree Eco uses combinations of allometric equations for biomass, conversion factors, and species diameter equations to estimate carbon storage and sequestration amounts (i-Tree, 2010c).

Carbon sequestration comparison

To compare carbon sequestration for the managed AU campus and protected Davis Arboretum, gross carbon sequestration amounts, as determined by i-Tree Eco, were divided by the total area to obtain a carbon sequestration value on a unit area basis. Regression equations were developed for the campus and the arboretum, using carbon sequestration as the dependent variable and dbh as the independent variable. Intercepts and slopes were compared ($\alpha = 0.05$) to determine differences in carbon sequestration for the two areas.

Results

Tree characteristics for the Auburn University campus and Davis Arboretum are described in Table 4. The average dbh for the AU campus was 16.4 cm and 24.4 cm (std.

Table 4. Overall tree characteristics for managed areas of the Auburn University campus and the Davis Arboretum using i-Tree Eco inventory procedures.

	AU Campus	Davis Arboretum
Area sampled (ha)	237	5.5
Number of trees	7345	891
Number of species	139	160
Average dbh (cm)	16.4	24.4
Average tree height (m)	8.5	12.7
Average tree crown width (m)	6.7	7.6
Basal area (m^2/ha)[z]	2.24 (0.001-1.9)	12.04 (0.001-1.13)
Estimated canopy cover (%)[y]	16	62
Estimated compensatory value ($)[x]	10,757,390	1,316,806

[z]( ) represents the range for all trees
[y]Estimated canopy cover determined by dividing the total canopy-projected ground area calculated by the model by the total area inventoried.
[x]Estimated compensatory value calculated by i-Tree Eco is based on the Council of Tree and Landscape Appraisers (CTLA) method (i-Tree, 2010b).

dev. = 19.6 and 19.4, respectively) for the arboretum. The AU campus and the arboretum differed drastically (16% and 62%, respectively) in canopy cover. The arboretum exhibited larger mean total tree height, crown width, and basal area while only containing about 12% of the total number of trees on the AU main campus. On a per-ha basis, the compensatory dollar value is approximately 5.3x greater ($239,500 vs. $45,500, respectively) for the arboretum compared with the main campus (Table 4).

Lagerstroemia spp. was the most common species in the managed portion of the main campus while *Pinus palustris*, *Liquidambar styraciflua, and Quercus nigra* were the most common in the arboretum (Table 5). The five most abundant species comprised

Table 5. The five most common species for the AU campus and Davis Arboretum with total number of trees and the percent of the total population.

AU Campus			Davis Arboretum		
Species	# of Trees	% Pop.	Species	# of Trees	% Pop.
Lagerstroemia spp.	1639	22	*Pinus palustris*	37	4
Quercus phellos	596	8	*Liquidambar styraciflua*	34	4
Pinus taeda	565	8	*Quercus nigra*	33	4
Magnolia grandiflora	464	6	*Quercus alba*	27	3
Quercus lyrata	363	5	*Quercus stellata*	26	3
Total	3,627	49		157	18

approximately 49% of the total population for the AU main campus compared with 18% for the Davis Arboretum, indicating much more diversity in the arboretum, with 160 tree species present compared to 139 for the AU main campus.

Ecosystem services

Carbon storage and sequestration in the arboretum represented approximately 15% and 14%, respectively, of the main campus (Table 6). However, when calculated on a per-ha

Table 6. **Carbon storage and sequestration rates for the AU campus and Davis Arboretum as of 2009-10.**

	AU Campus	Davis Arboretum
Carbon Storage (kg)	1,576,469.88	230,864.84
	(6,652/ha)	(41,975/ha)
Gross Carbon Sequestration (kg/year)	69,063.88 (291/ha)	9,670.94 (1,758/ha)

basis, the arboretum stored and sequestered over 6x more carbon than the main campus. There were no large differences in the average amount of carbon sequestration per tree by diameter class between the AU campus and the arboretum (Table 7). Statistical analyses

Table 7. Average carbon sequestration per tree (kg/year) by diameter class (cm) for the AU campus and Davis Arboretum.

	Average Carbon Sequestration Per Tree (kg/year)	
DBH (cm)	AU Campus	Davis Arboretum
1-15	3	3
16-30	8	8
31-45	15	16
46-60	22	25
61-76	32	35
77+	54	59

(data not shown) indicated that there was no significant difference in slope (p-value - 0.0994) but there was a significant difference in intercept (p-value < 0.0001) between the AU campus and Davis Arboretum, with the campus having the larger intercept coefficient, indicating that the smaller diameter trees on campus were larger in diameter than those in the arboretum and were in better condition.

The air pollutants with the largest and smallest removal value and removal amount for both the campus and arboretum were ozone (O_3), and removal amount carbon monoxide (CO) (Table 8). On average, the managed portions of campus removed

Table 8. Air pollution removal rates and removal values for the AU campus and Davis Arboretum as of 2009-10.

	AU Campus		Davis Arboretum	
Pollutant	Removal Amount (kg/year)	Removal Value ($)	Removal Amount (kg/year)	Removal Value ($)
CO	108.5	105.05	20.8	20.29
O_3	1,439.6	9,770.78	277.1	1,887.38
NO_2	187.1	1,263.02	36.1	243.97
PM10	946.4	4,266.22	170.7	769.66
SO_2	287.5	475.22	55.5	91.8
TOTAL	2,969.1	15,880.27	560.2	3,013.10
	(12.5/ha)	(67/ha)	(101.9/ha)	(548/ha)

12.5 kg/year/ha of air pollution ($67/ha value), and the Davis Arboretum removed 102 kg/yr/ha of air pollution ($548/ha value), or approximately 8x more on a per-ha basis (Table 8).

Tree condition

Differences in tree condition between the AU campus and the Davis Arboretum were evaluated. Over 60% of the trees on the AU campus were rated as being in excellent or good condition and about 3% in very poor or dying/dead condition (Illustration 6a).

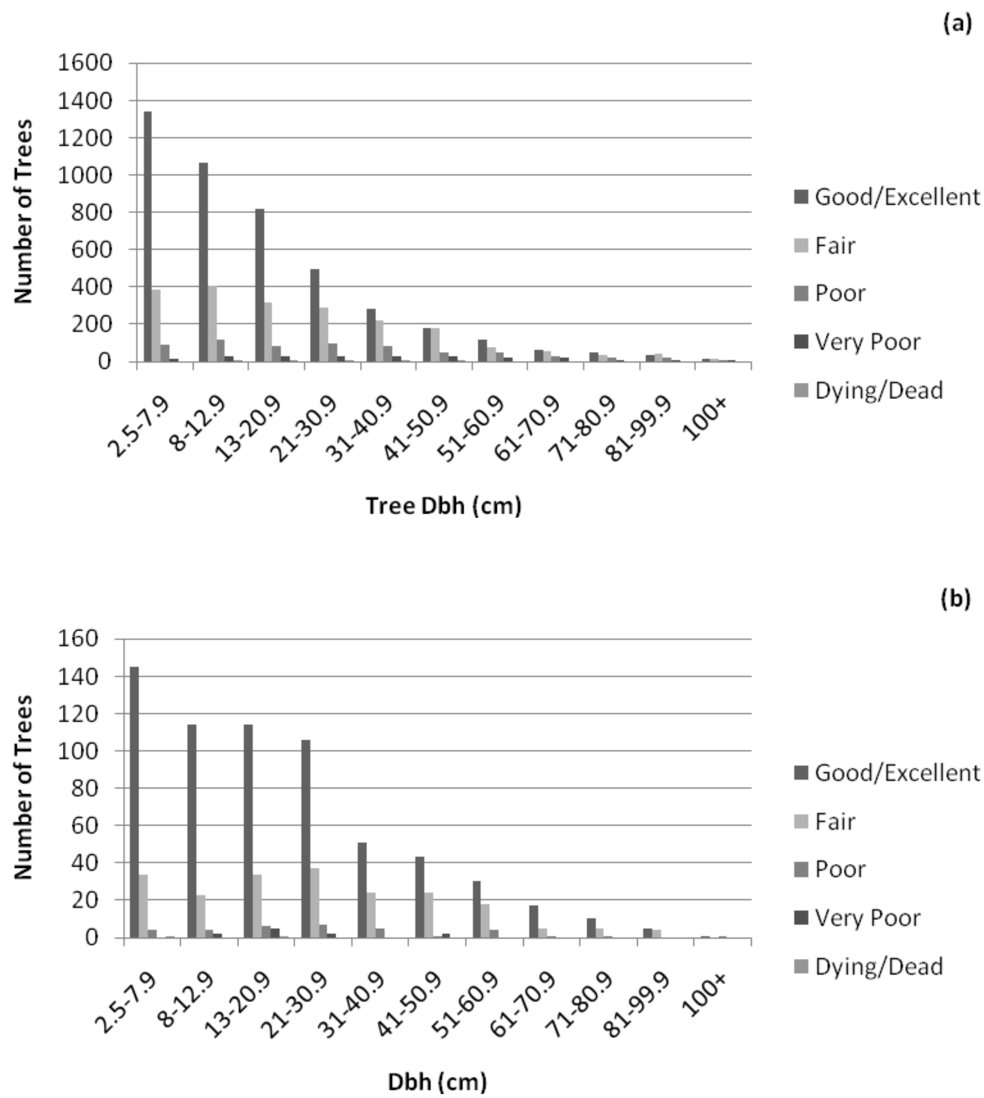

Illustration 6. Tree condition by diameter class determined by the overall condition rating for the AU campus (a) and (b) the Davis Arboretum.

Approximately 71% of the trees in the Davis Arboretum were rated as being in excellent or good condition and about 1% in very poor or dying/dead condition (Illustration 6b). Across species, for trees with a dbh of ≥ 21 cm, approximately 28% and 17% of all trees in the arboretum and on the main campus, respectively, were rated in good or excellent condition. For trees with a dbh of ≥ 31 cm, approximately 18% and 10% of the respective populations fell into these categories. The remaining trees were in fair, poor, very poor, or dying/dead condition.

Discussion

Determining the ecosystem services provided by the urban managed forest on the AU campus and the protected Davis Arboretum was the main objective of this case study. To determine the full value of the urban forest, the direct benefits they provide must be quantified and also compared to other urban areas. Those results could then be used to aid in development and planning strategies so that ecosystem services could be optimized.

Comparing the ecosystem services results from this study site to other study sites in the southeastern US is crucial for evaluation. For example, the City of Auburn had an average pollution removal value of \$0.29/tree/year in 2008 (Huyler et al., 2010) in comparison to the average removal value of \$2.29/tree/year for the managed areas of the AU campus and the Davis Arboretum combined and \$3.38/tree/year for the arboretum alone. Ozone and PM10 were the air pollutants with the highest removal amounts for both study sites (Huyler et al., 2010). The City of Auburn stored an average of 1.8 kg carbon/tree (Huyler et al., 2010), and the managed areas of the AU campus, and Davis Arboretum combined stored an average of 219 kg carbon/tree and 259 kg carbon/tree for the arboretum. The differences between the sites could be attributed to 81.9% of the trees in Auburn having a dbh of < 15.24 cm (Huyler et al., 2010), compared to only 43% for the AU campus and Davis Arboretum combined and for the arboretum alone. This indicates that areas with larger trees will provide more ecosystem services (Escobedo et al., 2009a; Escobedo et al., 2009b).

Results for carbon sequestration from the AU campus and Davis Arboretum inventory were compared to carbon sequestration results from Gainesville, Florida (Escobedo et al., 2009a). Average per tree sequestration rates by diameter class (1-15, 16-30, 31-45, 46-60, 61-76, 77+ cm) for Gainesville were 2, 9, 17, 9, 33, and 111 kg/year. Using the same diameter distribution classes, the sequestration rates for the AU campus and arboretum combined were 3, 8, 16, 23, 32, and 54 kg/year and 2, 8, 16, 25, 36, and 62 kg/year for the arboretum. Major differences in carbon sequestration were in the 46-60 and 77+ cm diameter classes, with the latter having the largest differences. These differences in the larger diameter classes could be the product of several factors, such as the small number of trees with large diameters on campus and in the arboretum, and differences in species composition and tree condition (Escobedo et al., 2009a; Escobedo et al., 2009c; Martin et al., In press).

Differences between urban managed and protected forests are important to understand so that forest structure can be manipulated to maximize desired ecosystem services. The most effective way to demonstrate differences in ecosystem services provided by the main campus and arboretum was to express our findings on a unit area basis. Results from air pollution removal indicated that the arboretum removed > 8x the amount of air pollution per ha as campus which resulted in a removal value that is $481 more per ha/year than campus. Air pollution removal would increase from 2,970 kg/year to 24,144 kg/year if the managed portions of the AU campus had a forest structure similar to the arboretum, with the removal value increasing from $15,880 to $129,837. However, a forest structure like that of the arboretum may not be practical for the campus because of the infrastructure demands like buildings, roads, and sidewalks.

Tree condition and size may play a role in the differences in ecosystem services. In general, trees in the Davis Arboretum were larger and in better condition than those of the managed AU campus. McPherson et al. (1997) reported that 60 to 70% more air pollution could be removed by large, healthy trees, indicating that these trees are vital to increasing air pollution removal. When examining tree condition by diameter class, the arboretum in general, appears to have higher tree condition ratings, especially for larger diameter trees. Reasons for this could be because these trees are in a protected area with limited disturbances from construction or campus maintenance (roads, power lines, water lines, etc.). Tree condition could also be a factor in why the intercepts for the AU campus and Davis Arboretum differed. The average condition of the trees planted on the AU campus may be higher where larger, nursery grown specimens are planted, compared to the arboretum where the smaller, younger trees are more likely regenerated naturally and may be under competition.

When evaluating canopy cover of urban and protected areas, it is important to discuss the urban heat island effect. This phenomenon occurs when there are higher air and surface temperatures because of large areas of heat absorbing surfaces in urban areas with higher energy usage amounts (Bolund and Hunhammar, 1999; Solecki et al., 2005). Natural areas with more vegetative cover can help mitigate this effect because they either don't have as many or as much heat absorbing surfaces as open urban areas, or because these areas shade the surfaces from the sun causing less heat to be absorbed. With more vegetative cover also comes more evaporative cooling which in turn lowers the air temperature (Bolund and Hunhammar, 1999; Solecki et al., 2005). If canopy cover were to be increased on the AU main campus, the urban heat island effect could be reduced, possibly leading to larger, healthier trees. This would in turn increase the ecosystem services provided.

Cost of tree maintenance and damage due to construction can also differ for protected and urban managed forests. The City of Gainesville, Florida, spent $1,559,932 (approximately $10.57/tree) on care for the public urban forests in 2007 (Escobedo and Seitz, 2009). Modesto, California, had expenditures of $2,686,516 ($29.46/tree) for its urban forest from 1997-1998 (McPherson et al., 1999). Natural areas, with less intensive management, have much lower costs of maintenance, making their net worth higher. Hauer et al. (1994) projected that the City of Milwaukee, Wisconsin, has a loss in street tree value of $792,100/year due to construction damage. Ecosystem disservices, or costs, also have to be considered (Escobedo et al., In press; Pataki et al., 2011). Disservices (pollutants from power equipment such as vehicles, saws, mowers) include the cost of maintenance, increase in allergens, and attraction of wildlife for many people. When examining differences between protected and urban managed forests, ecosystem disservices have to be estimated along with ecosystem services to fully understand net benefits (McDonnell and Pickett, 1990; Escobedo et al., In press; Pataki et al., 2011).

The trade-off between ecosystem services and disservices is very important in development planning (Escobedo et al., In press; Escobedo and Seitz, 2009). An understanding of the interactions between built and natural areas (urban-rural gradient) is also important (McDonnell and Pickett, 1990). The urban environment needs both infrastructure and green spaces; however, they have to be balanced to address the needs of the urban population. As stated earlier, if the entire urban environment had a forest structure like that of a natural area, there would be no room for the infrastructure that is necessary to sustain life in an urban setting (e.g. houses, roads, buildings). Even if infrastructure could be built in a natural setting without disturbing the area, disservices such as maintenance and damage to the infrastructure by the trees (heaving of sidewalks) would be greatly increased. Appropriate planning can address some of these issues. Because of development, not all natural areas can or should be saved; however, the most beneficial areas can be determined and then protected to help offset the loss of ecosystem services when sites are cleared for construction. New construction sites are almost always landscaped when finished and this helps to offset the loss of vegetation, but the benefits provided by the new, almost always smaller plantings, does not come close to the benefits being provided by well established natural areas. The end result of the urban setting needs to be determined first so that infrastructure and green spaces can be balanced to provide the most benefits possible.

Conclusion

With urban environments come different levels of maintenance, depending on where you are and what type of urban vegetation is present, among other factors. Areas that are more protected, not maintained as intensively, and are allowed to grow in more of a natural state provide more ecosystem services at a lower cost, so more work should be done to leave natural areas in our urban environments because of their increased value in ecosystem services. These increased services can be attributed to the fact that protected areas contain larger trees that are typically in better condition. In the future, we need to focus on preserving areas of the urban forest that provide more ecosystem services, specifically the protected areas where our mature are in better condition so that ecosystem services can be optimized. However, the entire urban forest needs to considered and evaluated during the developmental stages so that the appropriate balance of developed areas and green spaces can be sustained.

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Chapter IV.

Predictive Open-Grown Crown Width Equations for Three Southeastern US Urban Tree Species

Abstract

Models that predict ecosystem services in urban areas are useful tools to urban forest managers and arborists. Tree crown form is an important component of these equations; however, there are few equations available for urban, open-grown trees. Predictive open-grown crown width equations were developed for three native species common in urban forests in the southeastern United States (US). The species used were *Quercus lyrata* (overcup oak), *Quercus nuttallii* (Nuttall oak), and *Quercus phellos* (willow oak), and to our knowledge, these are the first predictive open-grown crown width equations developed for these species in the southeastern US. The diameter at breast height (dbh) (independent variable), dbh^2 (independent variable), and average crown width (dependent variable) data were used to create the predictive crown width equations and yielded R^2 values of 0.96, 0.94, and 0.91 for overcup, Nuttall, and willow oak, respectively. The predictive equations can aid urban landscape and utility planners by providing a means to predict crown dimensions at varying trunk diameters. Field collection time could also be minimized by reducing the need to measure crown width, and with time, these equations could be used to validate species specific equations, e.g. leaf biomass, for these and other southeastern urban-planted tree species.

Introduction

Tree measurements such as diameter at breast height (dbh), total height, height to the live crown, and crown width can provide vital information on their own, and they provide crucial data for other calculations such as leaf area and leaf biomass (Nowak 1996; Peper et al. 2001a; Peper at al. 2001b). These measurements are important to urban forest managers, arborists, researchers, and planners because they can aid in the development of management strategies and practices (Peper et al. 2001a; Peper et al. 2001b). Dbh, crown width, leaf area, and other information from trees also aid in assessing ecosystem processes such as evapotranspiration, light interception, and atmospheric deposition (Nowak 1996), and can help in developing predictive equations for pollution uptake (Peper et al. 2001b). Tree measurements are vital when determining ecosystem services, and having crown equations makes it possible to determine benefits such as carbon sequestration and air pollution removal. Urban shade trees are vital to our environment and offer many benefits, most of which depend on their size (Frelich 1992).

Limited research has been conducted on open-grown, predictive crown equations for urban trees (Nowak 1996; Peper et al. 2001a; Peper et al. 2001b; Peper and McPherson 2003), especially for specific regions. However, researchers in the traditional field of forestry have developed numerous equations that include dbh, biomass, and crown width (Krajicek et al. 1961; Ek 1974; Hasenauer 1997; Lhotka and Loewenstein 2008). Although some of these equations have been used for urban trees, validation is lacking (Peper et al. 2001a). Tree canopy architecture differs between open-grown and forest-grown or closed-canopy conditions. When grown in the open, a tree’s canopy can reach its full size and not be restricted; however, in a forested situation, tree canopies often touch and have restricted growing space. Limited research on dimensional relationships for urban trees has been conducted on trees with crowns that were full and healthy in New Jersey (Fleming 1988), on healthy trees in St. Paul and Minneapolis, Minnesota (Frelich 1992), on trees with full tree crowns in excellent condition in Chicago, Illinois (Nowak 1996), on street trees in Santa Monica, Calilfornia (Peper et al. 2001a), and on street trees in Modesto, California (Peper et al. 2001a; Peper et al. 2001b). The research conducted by Peper et al. (2001a; 2001b) aided in the development of predictive crown width equations for urban trees in regions with longer growing seasons, varying locations, and broader ranges of condition; however, to our knowledge, there are no equations available for southeastern United States (US) tree species planted in urban locales.

The goal of this study was to develop predictive open-grown crown width equations for three commonly planted urban tree species in the southeastern US: *Quercus lyrata* (overcup oak), *Quercus Nuttallii* (Nuttall oak), and *Quercus phellos* (willow oak). The three oak species were selected because of their large populations, a wide range of diameters (dbh), and a lack of diversity within the species on campus. The species selected were among the ten most numerous tree species on campus (Martin et al. In press). Overcup, Nuttall, and willow oaks have been planted on campus for decades, providing a wide range of diameters. To our knowledge, these species are overwhelmingly represented on campus as seedlings, with cultivars representing < 1% of the population. This, coupled with the size and distribution of the test population, provided a good dataset for developing open-grown crown width equations for these common southeastern US urban tree species.

Materials and Methods

Field data collection

Field data were collected on the Auburn University (AU) campus (32° 36' N, 85° 30' W) located in Auburn, Alabama. Auburn is in the 7b cold hardiness zone with minimum temperatures averaging 5 to 10°F (USDA 2003). Data collected during the 2009-10 100% tree inventory of the managed portion of campus encompassed approximately 237 ha (585 ac) (Martin et al. In press) following i-Tree Eco protocol (i-Tree 2010a; i-Tree 2010b). Data collected from each tree included dbh, tree height, average crown width, percent dieback, and a relative tree condition rating, among other attributes. i-Tree Eco, originally called the Urban Forest Effects (UFORE) model (i-Tree 2010c), was then used to estimate leaf area and leaf biomass species equations, among other ecosystem services (i-Tree 2010b).

For this study, the definition of an open-grown tree was modified after Frelich (1992), Nowak (1996), and Hasenauer (1997), where a tree was considered open-grown if it was planted in the managed landscape and the canopy was not restricted by other trees or buildings. The overwhelming majority of the species selected for this study is classified as open-grown, with possibly 1-2% of the trees having been slightly restricted (one side of the tree crown touching the side of a building or another crown) at the time of inventory; however, all trees had leaves present from the top down to the base of the crown on all sides.

Dbh and mean crown width data from the inventory were used to create the predictive equations. Dbh measurements, recorded to the nearest 0.25 cm (0.1 in), were taken at 1.37 m (4.5 ft) above the ground using a ‘Loggers Tape’. Mean crown width was determined by measuring along the two cardinal directions (North-South and East-West) from the crown edges (i-Tree 2010a) with a 'Loggers Tape', and averaging the two widths; mean crown widths were rounded to the nearest 0.31 m (1 ft).

Development of predictive equations

A subset of the total population of each species was created. Each species was divided into 5 cm (2 in) classes based on dbh. Data were then truncated at the point where there were fewer than ten trees in a class [50.8 cm (20.1 in) for overcup oak, 42.9 cm (16.9 in) for Nuttall oak, 37.6 cm (14.8 in) for willow oak)]. Any outliers that could have been due to measurement or recording errors were removed from the truncated data. Outliers were determined by visually examining data and residual plots created using dbh and mean crown width and identifying those observations that were ≥ 2 units larger than the general spread of observations in the same range on the residual plots. Four outliers were removed from the Nuttall oak data, four outliers were removed from the overcup oak data, and none from the willow oak data; resulting in 323 overcup, 243 Nuttall, and 588 willow oaks being left for the development of equations. The dbh was squared for each tree to be used in developing equations to provide the best linear fit based off residual plot examinations. Dbh (independent variable), dbh^2 (independent variable), and mean crown width (dependent variable) data were used to derive a regression equation (SAS® 9.2). The equations were of the form: crown width = $\beta_0 + \beta_1 dbh + \beta_2 dbh^2$.

To further evaluate the appropriateness of using this information to develop accurate open-grown crown width equations, additional analyses were performed. The data used to develop the initial equations for each species were divided into four groups according to dbh (2.5-12.6, 12.7-17.7, 17.8-27.8, and 27.9+ cm). A 20% subsample of each group was then randomly selected (equaling 20% of the total population). The subsample was then removed from the population and the remaining 80% were used to create a new crown width equation. This equation was then used to predict the crown widths of the 20% subsample. Residual (observed-fitted) values were then plotted against the predicted average crown widths.

Results

Results regarding dbh and crown width from the 100% inventory are shown in Table 9.

Table 9. Summary table of the 100% inventory data for the 3 selected tree species.

Species	# of Trees	Min. dbh (cm)	Max. dbh (cm)	Min. crown width (m)	Max. crown width (m)
Quercus lyrata	324	4.8	51.1	1.8	16.8
Quercus nuttallii	243	6.4	42.9	2.4	14.0
Quercus phellos	588	5.1	37.6	1.5	11.9

The maximum dbh measurements used to create the crown width equations for overcup, Nuttall, and willow oak were 51.1 (20.1 in), 42.9 (16.9 in), and 37.6 cm (14.8 in), respectively. The field data suggested strong linear relationships for all species (Illustration 7) and linear models that were created were significant with all coefficients

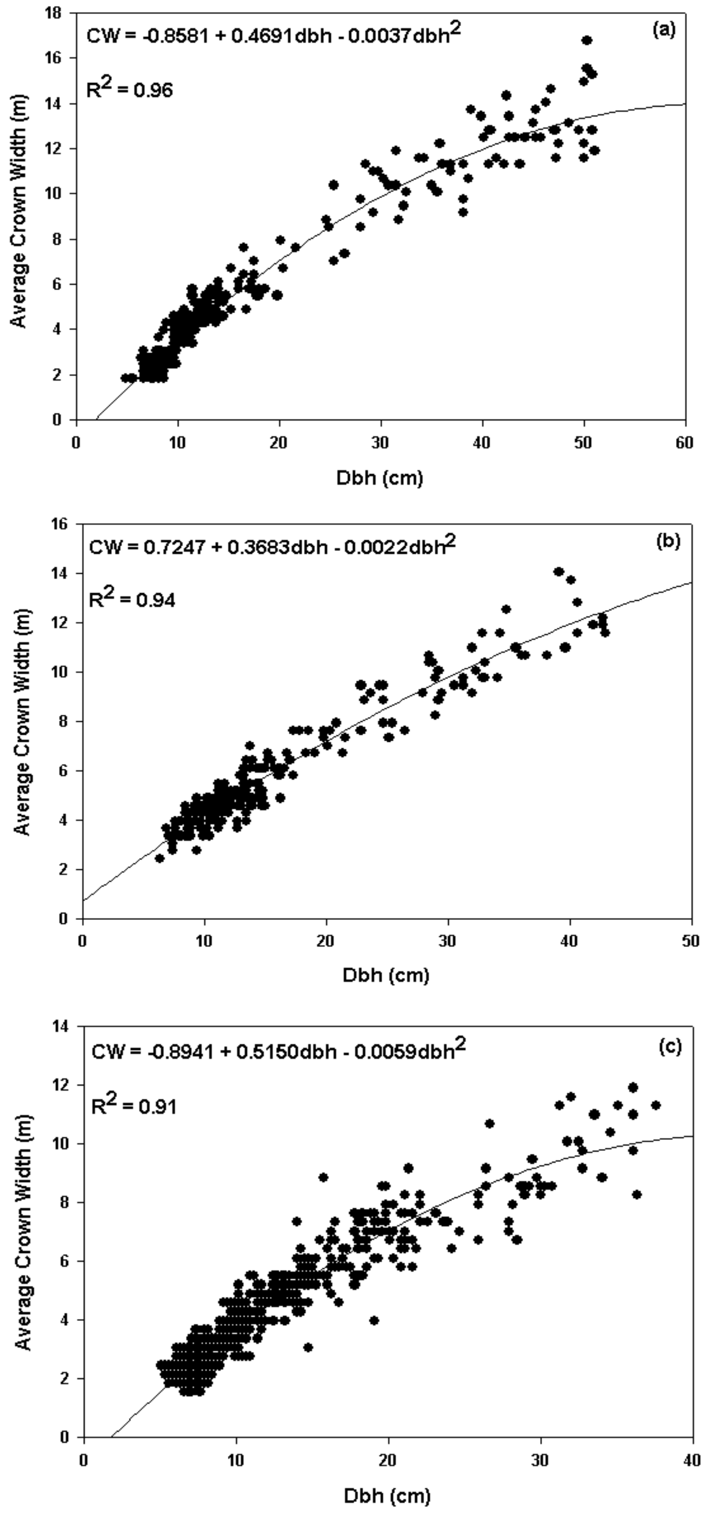
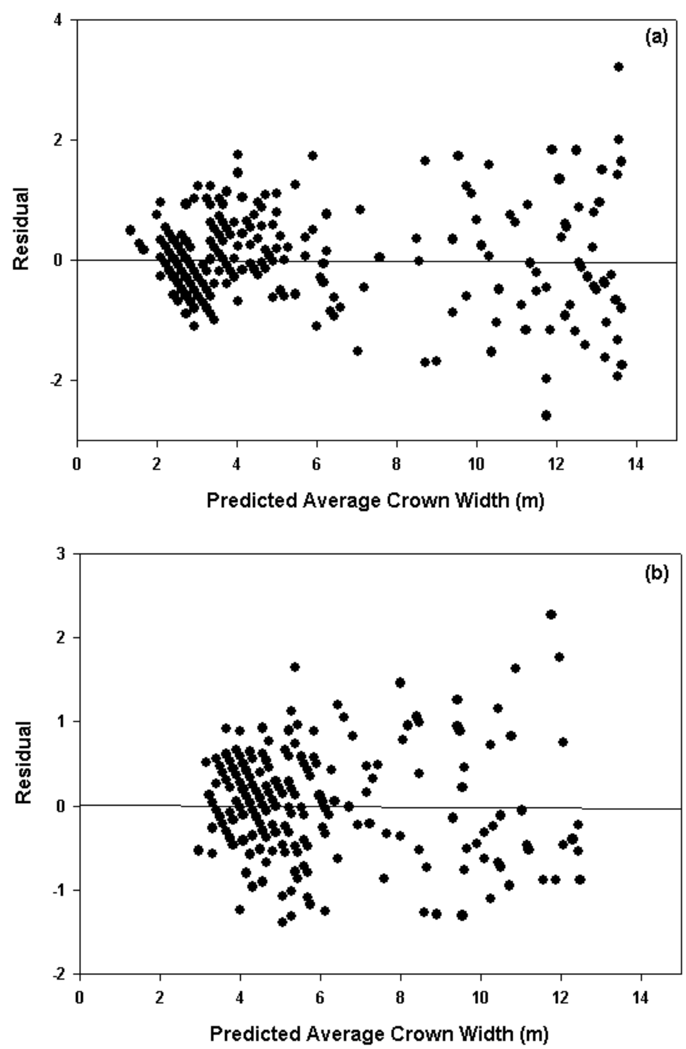


Illustration 7. Linear regression plots for (a) overcup, (b) Nuttall, and (c) willow oak with dbh (cm) against average crown width (m).

having a p-value < 0.0001 except for the intercept coefficient for Nuttall oak which had a p-value of 0.0009; however, examination of the residuals showed patterns indicating that a higher order term should be added to the model. The open-grown crown width equations developed for the three southeastern oak species resulted in R^2 values of 0.96, 0.94, and 0.91 for overcup, Nuttall, and willow oak, respectively (Illustration 7). The residual plot for each species showed no obvious pattern after including the higher order term indicating that the models are appropriate for the data (Illustration 8).



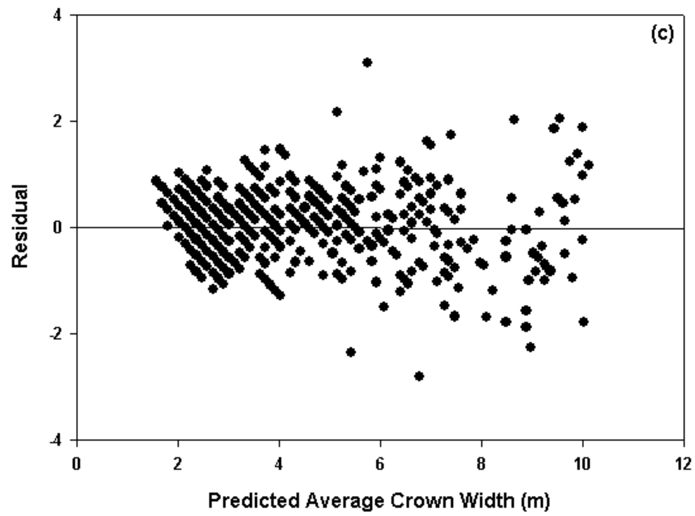
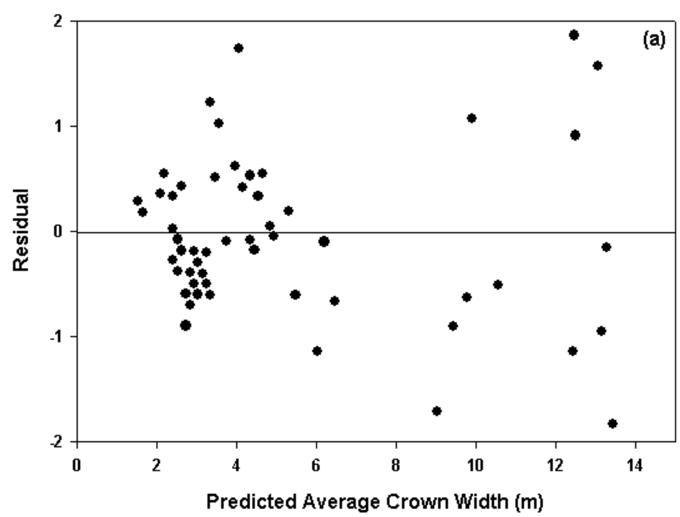


Illustration 8. Residual plots for (a) overcup, (b) Nuttall, and (c) willow oak with predicted average crown width (m) against the residual values.

A model validation for each species was then conducted by plotting the predicted average crown widths for the 20% subsample (obtained by using the 80% equation) against dbh. This yielded an R^2 value of 0.98, 0.99, and 0.98 for overcup, Nuttall, and willow oak, respectively (data not shown). Again, residual plots for the 20% subsamples showed no patterns, indicating that the models are appropriate for the data (Illustration 9).



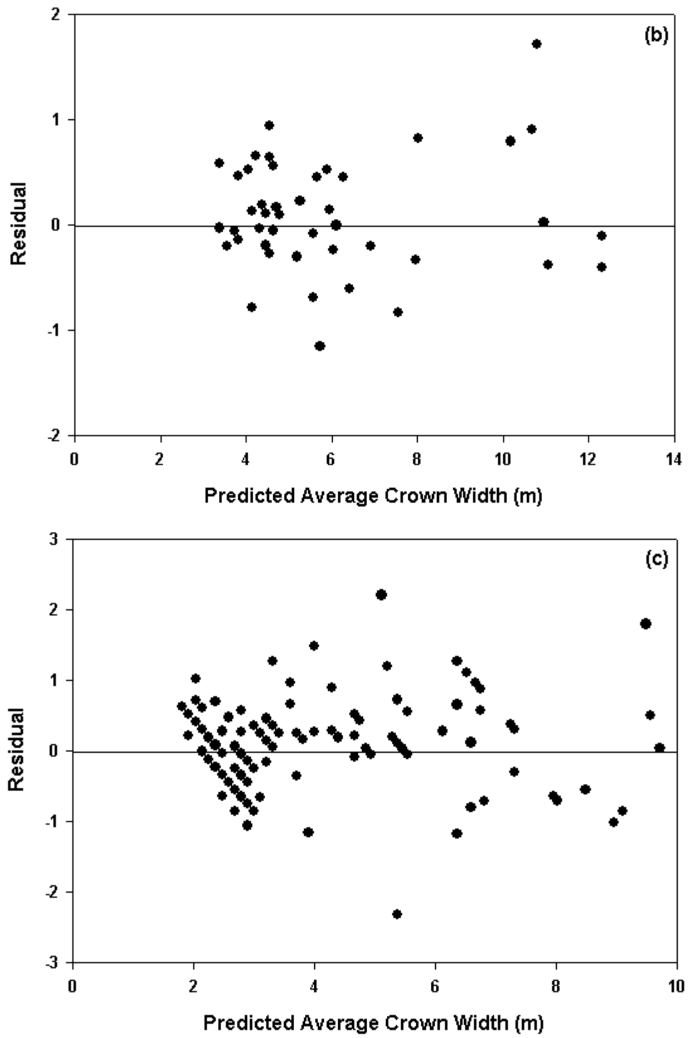


Illustration 9. Residual plots for the predicted crown widths for the 20% subsamples for (a) overcup, (b) Nuttall, and (c) willow oak with predicted average crown width (m) against the residual values.

Discussion

The development of predictive crown width equations is important not only to provide a tool for designers, managers, and arborists, but also to provide a first step in the validation of i-Tree Eco for the southeastern US. To our knowledge, these are the first predictive, open-grown crown equations developed specifically for oaks common to southeastern US urban forests. i-Tree Eco uses regression equations to derive measurements of leaf area and leaf biomass (i-Tree 2010b), and to derive accurate measurements in a certain region, equations produced from data collected from trees growing in that region are vital. To date, regression equations used in the model are based on work conducted in Chicago, Illinois (Nowak 1996). These data have been used extensively (Nowak and Crane 1998; Nowak et al. 2008) and provide good, basic information on ecosystem services; however, to regionalize the model, differences in climate, length of growing season, growth patterns, and common tree species must be considered.

The results showed strong correlations between dbh and crown width for all three species indicating that within the given range of the data, a dbh measurement entered into one of the equations will provide a good estimate of the crown width. Similar growth patterns were observed among the species where with increasing diameters, there were comparable increases in crown width for all species. The strong correlations also indicated that there was minimal management (pruning) performed to control crown spread for these species once they were planted on campus, indicated by high R^2 values and continual increase in crown width. Tree height and growth rate were not figured into the equation development and not much can be interpolated without further research.

Overcup, Nuttall, and willow oak all exhibited no pattern in the residual plots due to adding the dbh^2 term to the model. Without the term in the model, there was a pattern of over and under-predicting at different trunk diameters in the residuals for the species (data not shown). The inclusion of the dbh^2 term in the models was further justified by the fact that much of the existing literature dealing with crown width and dbh includes a dbh^2 term (Hasenauer 1997; Lhotka and Loewenstein 2008). Previously published open-grown crown width equations also use a dbh^2 term (Paine and Hann 1982; Smith et al. 1992). These results indicate that the predictive open-grown crown width equations developed for the three tree species are valid for predictive equations for use in the southeastern US. Care should be taken when extrapolating these relationships beyond the range of our data, in situations where management practices to control width exist, or where species composition includes many cultivars. It should also be noted that a large number of trees in these species have been planted within the last ten years and were balled-and-burlapped (B&B) trees from several nurseries, each having its own management methods. The source of the trees could have affected the crown width/dbh relationship; however, all small diameter trees were used in the equation development because they are now open-grown trees and are typical of what is commonly purchased from nurseries.

Predictive crown width equations developed from urban, open-grown trees are only useful if you are predicting open-grown crown widths. Using open-grown equations for trees under competition from other trees or adjacent buildings will lead to the dbh/crown width relationship being over predicted. Species specific equations should also be used when possible to reduce any error. Much research has been conducted on open-grown crown width equations (Ek 1974; Frelich 1992; Nowak 1996; Hasenauer 1997; Peper et al. 2001a; Peper et al. 2001b; Peper and McPherson 2003), but more is needed on species in urban settings, such as the three species described in this study.

Predictive open-grown crown width equations can be very beneficial to urban planners, managers, and arborists, as well as utility planners. Research has been conducted on urban (deVries, 1987; Fleming 1988; Frelich 1992) and forest tree growth estimates (Smith and Shifley, 1984), which has led to the ability to estimate diameter growth rates. Using these estimates, it is then possible to estimate crown width at various points in the future based on dbh measurements and the use of predictive open-grown crown width equations. These approximations can allow for the time until certain events to be predicted; such as the time until adequate shade is provided, when a tree crown will reach buildings and other infrastructure, when a tree may become a hazard to the public, and/or when the crown of a tree will reach power lines or other utilities. Being able to predict these events can help urban and utility planners decide if a tree will be planted or if it should be moved, and can also assist in determination and prediction of future maintenance, like pruning. Managers and arborists can benefit from predictive crown equations by not having to measure crown width while conducting field work. Eliminating the need to measure crown width, which is often the most difficult and time consuming measurement, will save valuable time. Using existing predictive open-grown crown width equations, and conducting research to develop more equations for other tree species, can provide tools that can be used by planners in the developmental stages to provide critical information which can be used to enhance the project and prevent future problems.

Conclusion

The regression equations developed to predict open-grown crown widths for overcup, Nuttall, and willow oak have the potential for use in urban planning throughout the southeastern US and may be used to validate i-Tree Eco for these species. Using data collected from a region to validate any modeling for that region is crucial and continued research should be carried out in other regions and with other tree species. Equations and models that use accurate field data to validate will help to improve our urban forest modeling and provide more accurate results. The use of predictive equations can aid urban developers and utility planners in making the best suitable decisions when it comes to urban tree placement and can provide a valuable time saving tool for managers and arborists.

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Chapter V.

Evaluation of Sampling Protocol for i-Tree Eco: A Case Study Evaluating Plot Number in Predicting Ecosystem Services at Auburn University, Alabama

Abstract

Auburn University was used as a site for a case study evaluating the standard plot sampling protocol for i-Tree Eco. A 100% tree inventory of the managed areas of campus was conducted in 2009-10 and provided a complete dataset for the evaluation. Air pollution removal and carbon storage and sequestration values estimated by i-Tree Eco were the factors utilized for this assessment. To achieve an 80% estimate of the total campus value for air pollution removal and carbon storage and sequestration, 622, 870, and 483, 0.04-ha (0.1 ac) plots, respectively, with at least one tree present would need to be inventoried, as opposed to the standard i-Tree Eco sampling protocol of 200 plots. Based on the proportion of area with and without trees, the Auburn campus would require 20, 30, and 16% of the total area to be inventoried for air pollution removal and carbon storage and sequestration, respectively. This study provides a first step in the evaluation of the i-Tree Eco sampling protocol; however, efforts to test our methods at sites throughout the southeastern United States (US) and to evaluate stratified sampling are needed to provide the most accurate evaluation for urban forests.

Introduction

In the current urban environment, changes take place every day, many of which impact the urban forest. It is critical for urban forest managers to know what changes are taking place, their impacts, and be able to evaluate those impacts in the future. Tree inventories are conducted and analyzed to provide urban forest structure and function information and to aid urban managers in evaluating environmental changes.

Traditionally, information on urban forest structure was gathered on street and park trees (McBride and Nowak 1989; Hauer 1994; Welch 1994), but due to increasing concerns, inventories have been expanded to encompass vegetation in other parts of the urban forest, including residential, industrial, and abandoned lands (McPherson et al. 1997). Besides being conducted to provide structural information (i.e. tree species, number, size and/or age, location) (Nowak and Crane 1998; Nowak et al. 2008a; Nowak et al. 2008b) on the urban forest, inventories are also the basis for deriving measurements of ecosystem services, including carbon storage and sequestration, and energy savings (Nowak et al. 2008a).

Several methods have been used in the past to conduct urban tree inventories, including sampling (Nowak and Crane 1998; Nowak et al. 2008a; Nowak et al. 2008b) and 100% inventories (Martin et al. In press). Sampling, or random sampling, is conducted by collecting data on a pre-determined number of trees or plots within a given area to provide an estimate of a larger area (McBride and Nowak 1989; Jaenson et al. 1992; Nowak et al. 2008a; Nowak et al. 2008b). With 100% inventories every tree is located and data are recorded, providing the most accurate information (Jaenson et al. 1992; Nowak et al. 2008a). However, unless the 100% inventory is being conducted on a relatively small area, it may not be as cost effective as sampling (Jaenson et al. 1992; Nowak et al., 2008a; Nowak et al. 2008b).

The United States Department of Agriculture Forest Service (USDA FS) developed a protocol in the 1990s, originally named the Urban Forest Effects (UFORE) model and now referred to as i-Tree Eco (i-Tree Eco 2010a), to be used to conduct tree inventories in urban settings and to provide information on ecosystem services (Nowak and Crane 1998; Nowak et al. 2008a). Traditionally, following this protocol, 200 circular 0.04-ha (0.1 ac) randomly located plots are assigned in the study area (Nowak and Crane 1998; Nowak et al. 2008a; Nowak et al. 2008b; i-Tree Eco 2010b; i-Tree Eco 2010c). This sampling protocol was adopted because that was the number of 0.04-ha (0.1 ac) plots that could be inventoried by a two-person crew in a 14-week summer period and would produce a good estimate of the population (Nowak et al. 2008b).

i-Tree Eco has been used in multiple cities since its development (Nowak et al. 2008a; Nowak et al. 2008b); however, little research has been conducted to validate the plot number parameter for i-Tree Eco (Nowak et al. 2008b). To evaluate the 200 0.04-ha (0.1 ac) plot protocol, ecosystem services results from the 100% tree inventory of the Auburn University (AU) campus (Martin et al. In press) were utilized. The ecosystem services variables that were examined in this case study were air pollution removal and carbon storage and sequestration. The number of plots with at least one tree present needed to provide an 80% estimate of the total campus value for all three ecosystem services was determined. Eighty percent was selected arbitrarily, based on the premise of the law of diminishing returns (Johnson 2005), as the point where the same increase in the number of plots sampled would result in a smaller increase in the estimate of the total campus value. Only ecosystem services were used for this study because i-Tree Eco inventories are typically conducted to determine the ecosystem services that are being provided by the urban forest, and the sampling protocol being followed should be one based off the variable(s) of interest.

Materials and Methods

Study site

The study site was the Auburn University campus (32° 36' N, 85° 30' W) located in Auburn, Alabama (Illustration 10). The AU main campus encompasses about 306 ha

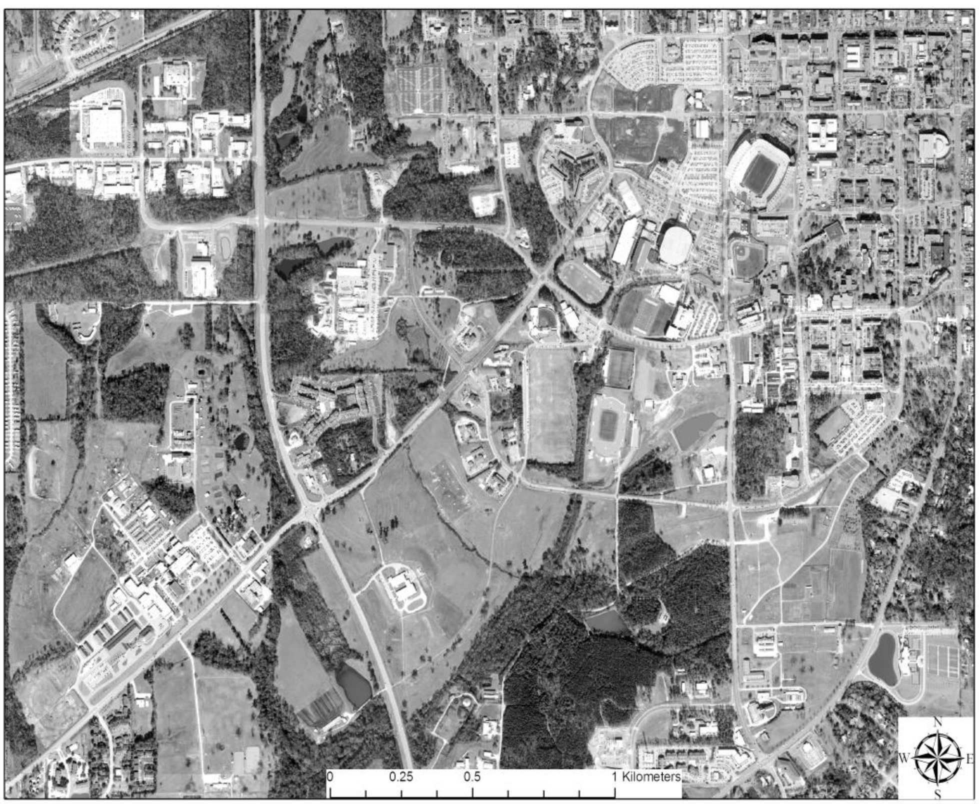


Illustration 10. Aerial photograph of the Auburn University campus-spring 2008.

(755 ac). The managed areas, meaning these areas are on a regular maintenance schedule, were the focus of this study; which covered approximately 243 ha (600 ac), including the Davis Arboretum; covering 5.5 ha. Refer to Martin et al. (In press) for more details.

Inventory

Field data were collected during the 100% tree inventory of the AU campus in 2009-10 (Martin et al. In press) following i-Tree Eco procedures (i-Tree 2010b; i-Tree 2010c). There were 16 attributes measured for each tree including tree species, diameter at breast height (dbh) [1.37 m (4.5 ft) above the ground], tree height, average crown width, dieback, and missing crown. Data collection was completed in May 2010 and all field data were analyzed by the USDA Forest Service which generated information on the ecosystem services provided by the AU urban forest. Information regarding ecosystem services provided by the Forest Service included pollution removal value ($) and carbon storage (pounds) and sequestration (pounds/year) for each tree.

Experimental Design

All spatial analyses and operations were conducted using the ESRI ArcGIS® 9 ArcMap™ v.9.3 geographic information system (GIS) computer software. First, an aerial photograph of the AU campus was used to create a new shapefile of the boundaries of the study site. No infrastructure (buildings, parking lots, sidewalks) was excluded from the shapefile to provide an accurate picture of the urban environment. All field data and tree locations collected during the initial 100% inventory (Martin et al. In press) were then used to create a new tree point shapefile with the collected tree data in an associated attribute table. The ecosystem services data for each tree were then appended to the tree attribute table created in the tree point shapefile.

Three thousand random points, created as plot centers, were then generated inside the study area with at least 22.54 m (77.4 ft) between the points to make sure that no plots would overlap. The 3,000 plot centers were created to have a large enough sample to where the variance between plots could be calculated and produce a sufficient estimate of the proportion of area with trees to the area without trees on the AU campus. A 0.04-ha (0.1 ac) buffer was created around each point (plot center). All 0.04-ha (0.1 ac) buffers were then spatially joined with the tree point shapefile created from the inventory field data to select the trees that fell within each buffer.

Plot Number Analyses

Once all buffers were created, the proportion of plots with trees to those with no trees was determined so that the number of hectares with trees on campus could be estimated. For each plot with at least one tree present, the air pollution removal and carbon storage and sequestration value totals were determined and extrapolated to provide values on a per hectare basis. The per hectare totals of plots with trees were then used to determine the average value/hectare for air pollution removal and carbon storage and sequestration and to calculate the total variance between plots with trees for those factors. Only plots that had at least one tree present were utilized because the plots that did not have any trees present had a zero value for all three factors and the variance between plots with trees was the desired result. The coefficient of variance for each factor was then determined by taking the square root of the variance and dividing it by the average of all the plots with trees. The equation used to determine the number of plots necessary to provide an 80% estimate of the total value was a standard equation used to determine the sample size needed for a finite population given a certain amount of allowable error (Shiver and Borders 1996).

Results

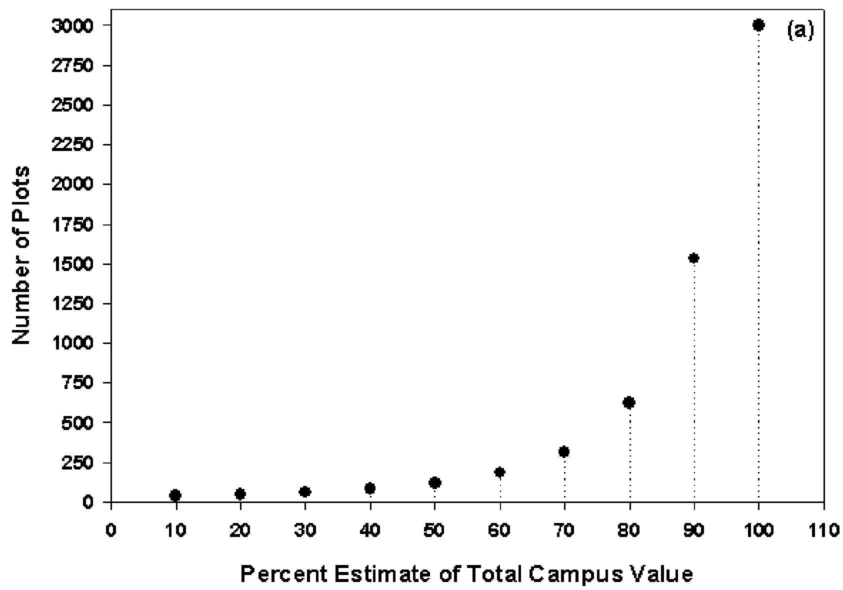
Of the 3,000 plots created, approximately 1,500 had at least one tree present, indicating that 50% of the AU campus area had trees present. Equations used to determine the number of plots necessary to estimate 80% of the total value for air pollution removal and carbon storage and sequestration are shown in Table 10. The equations were then

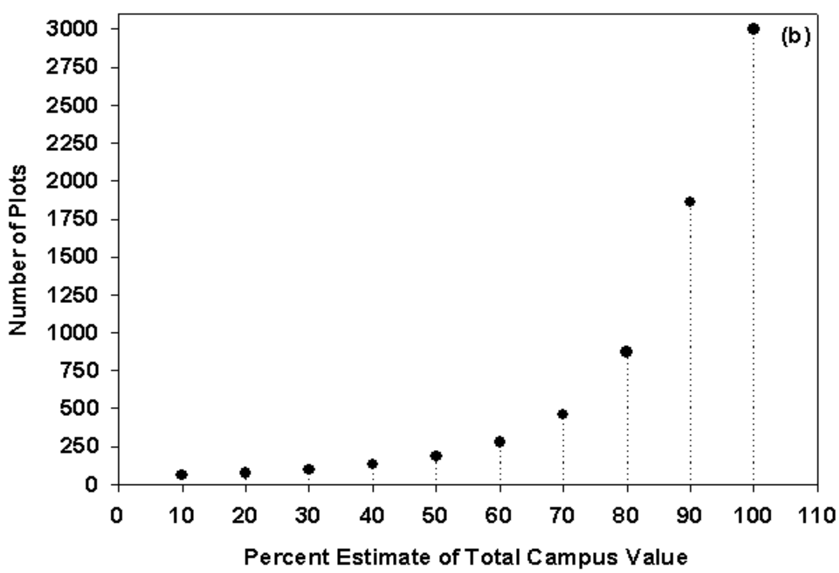
Table 10. Equations determining the total number of plots with trees needed for the AU campus to estimate 80% of the total value for air pollution removal and carbon storage and sequestration.

Ecosystem Service	Sample Size Equation
Air pollution removal	$[4(120)(1.4^2)] / [120(0.1^2) + 4(0.04)(1.4^2)]$
Carbon storage	$[4(120)(1.75^2)] / [120(0.1^2) + 4(0.04)(1.75^2)]$
Carbon sequestration	$[4(120)(1.2^2)] / [120(0.1^2) + 4(0.04)(1.2^2)]$

Note: Equations are of the form: sample size = $[4A(CV^2)] / [A(E^2) + 4P(CV^2)]$ where 4 represents the t-value squared at $\alpha = 0.05$, A is the total hectares with trees determined by the total hectares on campus multiplied by the proportion of plots with trees, CV is the coefficient of variance, E is the allowable error determined by an 80% estimate which is 10% allowable error, and P is the plot size used for this study which was a 0.04 ha (0.1 ac) plot.

manipulated to produce plots showing the ideal number of 0.04-ha (0.1 ac) plots necessary to achieve the desired percent estimate of the total campus value (10-100%) for all three factors (Illustration 11). We then determined that to estimate 80% of the total air


(a)
Number of Plots
Percent Estimate of Total Campus Value
0
250
500
750
1000
1250
1500
1750
2000
2250
2500
2750
3000
0
10
20
30
40
50
60
70
80
90
100
110


(b)
Number of Plots
Percent Estimate of Total Campus Value
0
250
500
750
1000
1250
1500
1750
2000
2250
2500
2750
3000
0
10
20
30
40
50
60
70
80
90
100
110

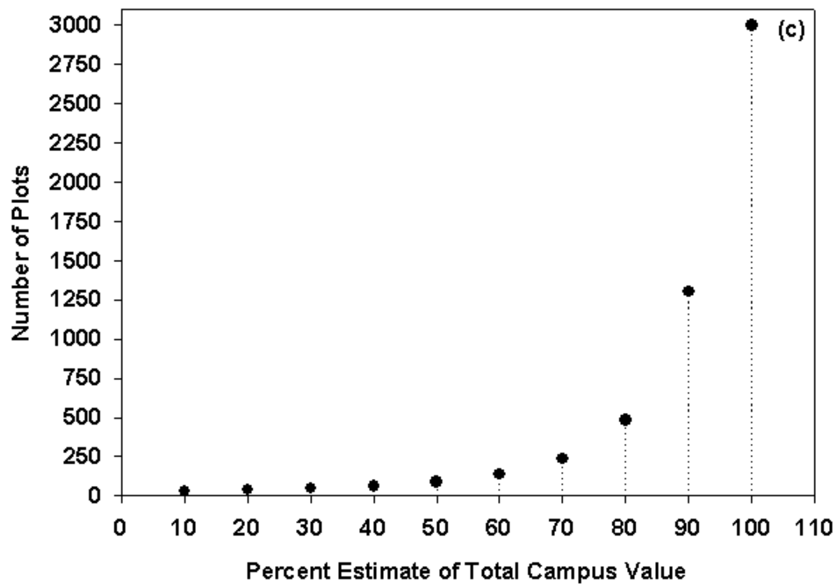


Illustration 11. Plots showing the percent estimate of the total campus value against the ideal number of plots (with at least 1 tree present) necessary to achieve the desired percent estimate for (a) air pollution removal, (b) carbon storage, and (c) carbon sequestration values based off the 3,000 plot generation.

pollution removal value of the 243 ha (600 ac) AU campus, you would need to inventory 622 0.04-ha (0.1 ac) plots that have at least one tree present. For carbon storage and sequestration you would need to inventory 870 and 483 plots, respectively, that have at least one tree present.

Discussion

Ecosystem services were used as the basis for a sampling protocol because i-Tree Eco inventories are conducted to quantify the ecosystem services provided by the urban forest. Therefore, sampling conducted using i-Tree Eco should follow a protocol in which the number of 0.04-ha (0.1 ac) plots sampled is based on the ecosystem service(s) of interest so that the inventory is providing accurate results. A sampling protocol based on an ecosystem service of interest could also aid in determining management goals by providing an estimate of the current value of that service by the urban forest. Decisions, like more trees need to be planted, could then be made so that the desired value of an ecosystem service can be reached.

The standard sampling protocol for i-Tree Eco is 200 0.04-ha (0.1 ac) plots (Nowak et al. 2008b; i-Tree 2010b). Two hundred plots were established as the standard because that was the number of plots that could be inventoried in a 14-week summer season by a two-person field crew (Nowak et al. 2008b). Following this protocol, Nowak et al. (2008b) found that a 12% relative standard error (RSE) provided a reasonable estimate of the population, if that level of error is acceptable. Nowak et al. (2008b) evaluated the effects of different plot sizes not only on the precision of the estimate of the total population but also on time and cost; however, these evaluations did not take into consideration the ecosystem services provided. Our study did not evaluate plot size effects to maintain consistency with standard practice.

Results from this study indicate that to achieve an 80% estimate of the air pollution removal and carbon storage and sequestration values for the AU campus, you would need to inventory approximately 20, 30, and 16 % [# of plots with at least one tree present determined by using the equation / proportion of acres with trees for the AU campus (50%)] of the total area in order to obtain the necessary number of plots with at least one tree present. According to i-Tree Eco, a 200 plot sample would equate to approximately 3% of the AU campus. The 3% sample would also be a combination of plots with and without trees. Our results indicate that you would need a total sample size (plots with and without trees) approximately 7, 10, and 5x larger than the standard protocol to achieve an 80% estimate of the air pollution removal and carbon storage and sequestration values, respectively, for the AU campus. Following standard i-Tree Eco protocol to estimate ecosystem services such as air pollution removal and carbon storage and sequestration could lead to an underestimation of the values being presented. The results also indicate that carbon sequestration values can be estimated by the fewest samples followed by air pollution removal and carbon storage which would require the most samples. This information could be used by managers to evaluate sampling intensity and associated costs so that the most desirable ecosystem service can be focused on.

The decision to focus on an 80% estimate of the total value was justified by the number of 0.04-ha (0.1 ac) plots that would be necessary to achieve higher estimates of the total value. All three factors demonstrated relatively small increases in the number of plots to obtain a percent estimate up to 80%. Once above 80%, the necessary number of plots increased dramatically when compared to the increase in number of plots at and below 80%, indicating that to achieve percent estimates above 80%, there would be large increases in the work and sampling that may not be justified by additional increases in the estimate.

Further research is needed regarding this evaluation. Our method was designed for the AU campus and care should be exercised if using these results for a different study site. Our method and results were based on a known tree population (100% tree inventory) and the proportion of hectares with trees to those without trees. This approach needs to be tested on several other sites throughout the southeastern US to provide the most accurate estimate of numbers of plots to inventory because of differing forest structures, species, and densities that are present in urban settings.

The managed portions of campus and the Davis Arboretum were sampled together to arrive at a total number of plots for the entire campus. The Davis Arboretum is a natural area that has a different forest structure than the rest of the AU campus (Martin et al. In press), which could reinforce the need for stratified sampling. Many urban tree inventories have been conducted using stratified sampling (Nowak and Crane 1998; Peper et al. 2001a; Peper et al. 2001b; Nowak et al. 2008a), which is an option when using i-Tree Eco (i-Tree 2010b). Future efforts should look at the AU main campus and the Davis Arboretum separately to determine the necessary number of plots to be inventoried for each area so that sampling can be minimized and the most efficient sampling protocol determined. Not stratifying the campus may also have caused the variation coefficients among plots for all three factors to be higher, resulting in a larger necessary sampling size. The number of plots needed for carbon storage could also have been affected by non-stratification because of the forest structure of the Davis Arboretum and that fact that it contains a large number of mature trees versus the campus which has a large number of small diameter trees (Martin et al. In press). Determining a sample size to be used throughout the southeastern US and evaluating stratified sampling were beyond the scope of this study.

Conclusion

As more and more cities and urban areas begin to inventory their urban forests, more research is needed to determine how much of the urban forest must be inventoried to produce an accurate estimate of the total population, if a 100% inventory is not feasible. The sampling protocol should be based on the factors of interest. The amount of time available to conduct an inventory and the cost associated with it should be considered when determining what protocol to follow; however, the desired results from the inventory, e.g. ecosystem services, should also play a key role. This case study conducted using a small campus setting, begins to validate plot sampling protocol for i-Tree Eco; however more studies using ecosystem services results that i-Tree Eco was developed to provide are needed.

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Chapter VI.

Summary

In 2009-10, the Auburn University campus, including the Davis Arboretum, was used as the study site to perform a 100% tree inventory of the managed areas of campus following i-Tree Eco protocol (i-Tree 2010a; i-Tree 2010b). Once all field data were collected, the information was sent to the USDA Forest Service for analysis, and information regarding ecosystem services was obtained. The overall goal of this project was a complete tree inventory of the managed areas of campus; however, examining ecosystem services of an urban managed and protected forest, developing open-grown crown width equations for three common southeastern urban tree species, and evaluating the plot sampling protocol of i-Tree Eco (Nowak et al. 2008; i-Tree 2010a) were the main objectives.

The 100% inventory of the Auburn campus was conducted to provide vital information on the current urban forest that could be used for management objectives by Auburn University's Landscape Services and to provide data that could be used to estimate the ecosystem services that are provided by the trees. Management personnel now know the species composition on campus, diameter and height distributions, tree condition, and the location of all managed trees on campus. Information on the urban forest structure and functions can be used by university personnel in planning and to constantly monitor the urban forest and its condition, providing a very valuable management tool. To our knowledge, there have been no 100% inventory data published that has used i-Tree Eco, especially in the southeastern US, and the results of this project could be used to demonstrate how important inventories are and how valuable knowledge can be gained so that future inventories are conducted throughout the region.

Ecosystem services such as air pollution removal, carbon storage and sequestration, and micro-climate regulation that are provided by our urban trees are vital to our urban existence. i-Tree Eco was used for this inventory because it provides quantitative estimates of the benefits provided by the urban forest (Nowak and Crane 1998; Nowak et al. 2008a). The ecosystem services results for the AU main campus (urban managed) and the Davis Arboretum (protected) were separated so that the ecosystem services provided by an urban managed forest could be compared to those provided by a protected forest to demonstrate the effectiveness of providing such services. Knowing what types of areas can best provide a particular ecosystem service can help urban managers in determining how and where to use their resources. The protected Davis Arboretum removed 8x as much air pollution and stored and sequestered 6x as much carbon as the AU main campus. Areas with forest structures like that of the arboretum could become more valuable in urban environments because they could be used to offset the costs to the environment by industrialization and could become even more valuable because of the large amounts of ecosystem services that they provide while occupying a relatively small area. The results on air pollution removal and carbon storage and sequestration can be used by other locales in the southeastern US as a reference as to how areas can provide different amounts of ecosystem services, thereby providing a basis as to how resources could possibly be allocated.

Limited research has been conducted on predictive open-grown crown width equations for urban trees (Nowak 1996; Peper et al. 2001a; Peper et al. 2001b; Peper and McPherson 2003), especially for specific regions. Three southeastern US urban tree species that had a large presence on the AU main campus were selected to create predictive open-grown crown width equations. The selected species were *Quercus lyrata* (overcup oak), *Quercus Nuttallii* (Nuttall oak), and *Quercus phellos* (willow oak). The dbh, dbh^2, and average crown width data for the selected species were used as the input variables to create the predictive equations. The predictive open-grown crown width equations that were developed during this study can be used by urban managers, planners, and arborists who want to conduct inventories in the southeastern US to reduce their field collection time. Instead of having to measure both dbh and crown width for each open-grown tree, predictive equations could allow the field personnel to only measure dbh and then use the predictive models to estimate the crown width after the fact, thereby reducing the amount of time spent inventorying. Urban forest planners could use the equations to predict a tree's crown spread at different diameters to help determine when potential hazards may arise or to determine if the tree should be planted at that location to further aid planners in making decisions. The predictive equations could also be used in estimation models such as leaf area and biomass to provide more accurate estimates for the species in the southeastern US.

Along with the importance of knowing what ecosystem services are being produced and their associated amounts, it is also important to know the most efficient means of inventorying a given area to obtain those results. Since more inventories are being conducted in urban areas to determine the ecosystem services, the sampling protocol for those inventories needs to be based off of the desired results, e.g. air pollution removal value. If the air pollution removal value is the driving factor for the inventory being conducted, then a sampling protocol that will provide accurate estimates in the most efficient manner needs to be used. Air pollution removal and carbon storage and sequestration values for the AU campus that were estimated by i-Tree Eco were used to determine a sampling protocol that was based on ecosystem services.

Traditionally, i-Tree Eco calls for 200 random 0.04-ha (0.1 ac) plots to be assigned throughout a study area (Nowak et al. 2008b; i-Tree 2010a). Our evaluation determined between 5 and 10x more samples than specified by the standard i-Tree Eco protocol are needed to provide an 80% estimate of the total value of three ecosystem services. These results provide the first step in the evaluation of the i-Tree Eco sampling protocol and allows for more research using our methods on other study sites, as well as extending the scope of research to incorporate the evaluation of stratified sampling. Continuing the research that was started in this project, as well as looking at stratified sampling will aid in determining the most efficient sampling protocol. However, our results provide vital information and a first look at an appropriate sampling protocol that is based on results obtained from an i-Tree Eco inventory.

In conclusion, the completion of the 100% tree inventory of the managed areas of the Auburn University campus and the subsequent evaluations provided vital information on several fronts. The information obtained during the project will not only aid managers and planners on the AU campus and in the Davis Arboretum, but the results as a whole can benefit people throughout the southeastern US. Conducting regional analyses using a model such as i-Tree Eco is crucial when that model is used over a widespread area. If i-Tree Eco is to become the urban forest inventory standard, more regional research will be needed, as well as follow-up research in those same regions so that i-Tree Eco can accurately estimate the urban forest benefits and costs.

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