URBAN TREE GROWTH AND MORTALITY IN GAINESVILLE, FL: IMPLICATIONS FOR CARBON DYNAMICS AND GREEN WASTE

By

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Research on urban tree growth, mortality and in-growth is needed to project future urban forest structure more accurately. To provide more accurate information for urban forests in Gainesville, a subsample of 93 plots established in the summer of 2006 were relocated and re-measured during the growing season of 2009. These 65 plots provide a unique opportunity to study urban tree growth, mortality and in-growth. Comparative data provided rates of diameter growth, mortality, and in-growth that were analyzed based on initial tree and plot level conditions using general and generalized linear mixed statistical models. Growth in diameter at breast height (dbh) was modeled for three species groups and the four most frequent tree species: laurel oak (*Quercus laurifolia*; 76 trees), water oak (*Quercus nigra*; 62 trees), slash pine (*Pinus elliottii*; 62 trees) and loblolly pine (*Pinus taeda*; 57 trees). Mortality and in-growth models were developed for hardwood and softwood species. Results show that Gainesville trees are estimated to have an average annual mortality rate of 1.8%. In total there were 755 trees sampled in 2006 and by 2009, 128 (17%) trees were removed. Plot and tree level characteristics affected diameter growth in all species groups. Growth rates in Gainesville were higher

than those reported in other studies of urban tree growth. Results provide local information that can be used for improving estimates of growth, biomass, and carbon sequestration in the Southeastern United States.

CHAPTER 1
INTRODUCTION AND OBJECTIVES

Urban Forest Ecosystem Structure

Two key aspects of a healthy ecosystem are the ability of an urban forest to provide ecosystem services like tree shade and aesthetics, which can be valued as a commodity that improves quality of life while still maintaining its own biophysical integrity (Rapport 1995). The composition and structure of urban vegetation can be modified over time due to losses from deforestation and fragmentation and gains from reforestation and afforestation (Zipperer et al. 1997). Activities associated with expanding human populations can also cause modifications that alter ecosystems and impede the sustainability of resources and services provided by these ecosystems (Zurlini & Giardin 2008). As such the products/goods generated from an urban forest are the quantifiable results (money saved through energy avoidance) manifested through the services (tree shade and air temperature reduction) that are the result of a variety of functions (evapotranspiration, radiation blocked by tree canopy) as well as contribution to overall city tree canopy. These functions in turn are made possible by the structure of the urban forest (location and size of tree, overall city tree cover) and can interact at multiple scales spatially and temporally (Zurlini & Giardin 2008, Pandit & Laband 2010).

To relate the overall urban forest structure to its variety of functions in a way that includes the spatial and temporal properties of social and ecological patterns is to view the urban vegetation processes within “patches” or areas that are relatively homogeneous and that differ from their surroundings which are affected by urban influences that occur along a gradient of urbanization from the urban core to rural

(Zipperer et al. 1997). Understanding how ecosystems change over time can provide insight into identifying potential changes that may detract from the integrity of the ecosystem and its capacity to continue to provide resources and services into the future (Petrosillo et al. 2007).

Growth suppression, life span reduction, increased susceptibility to insect and disease related problems, as well as losses in aesthetics and higher replacement costs can occur in the presence of tree stresses related to site and soil conditions (Rhoades & Stipes 1999). Therefore, research on growth, mortality and removed biomass from urban forests can facilitate management techniques that can increase the net benefits of urban trees such as mitigation of atmospheric carbon dioxide (Nowak et al. 2002).

Urban forest ecosystem structural changes are influenced by tree mortality, therefore mortality rates are needed to project future populations and benefits associated with the urban forest while understanding the factors that affect urban tree mortality can help urban forest managers minimize trees costs and risks while enhancing environmental benefits (Nowak et al. 2004). Research on urban tree diameter growth is limited and often focuses on tree populations from northern regions of the US (Nowak 1994, Jo & McPherson 1995, deVries 1987), and if applied to tree populations in southern US regions, they may underestimate the projected carbon dioxide reduction functions as well as other benefits associated with tree growth. Estimates of removed tree biomass can also reveal the potential bio waste supply in Gainesville, Florida as well. Analyses of permanent plots and their re-measurement should provide site-specific mortality, growth, and subsequent biomass estimates that reflect the external factors acting upon them due to local geographical, ecological, urban form, and socioeconomic related influences (Heyen & Lindsey 2003).

Temporal Changes in Urban Forest Structure

Tree cover, or percent tree canopy cover, is used to describe city-wide tree structure and is often used as an indicator of health of urban forest structure by managers, policy makers, scientists and analysts (Heyen & Lindsey 2003, Zipperer et al. 1997). Urban tree cover has been described as the proportion of land covered by tree crowns within a municipality or other geographic or administratively defined areas (Heynen & Lindsey 2003). Tree cover definitions can include the measurement of all plant material above, on and below the ground (McDonnel & Pickett 1990). There are many drivers for changes in tree cover over time: urban development, windstorms, tree removals, and growth (Zipperer et al. 1997, Duryea et al. 2007, Escobedo et al. 2009). In Central Indiana, an urban forest canopy cover study showed that areas are likely to have more canopy cover if it: has a population consisting of more individuals with college degrees, has older housing stock, has areas with slopes greater than 15% and a network of dense streams (Heyen & Lindsey 2003). Historical tree-cover data, field vegetation sampling, and comparison of past aerial photographs have been used to quantify and describe tree cover change over time (Nowak et al. 1996). In Gainesville, tree cover has not exhibited a linear trend, decreasing over time from 66% in 1995 to 55% in 2005 and then increasing to 60% in 2007 (Szantoi et al. 2008).

Natural environment, urban morphology and human values within a city affect the amount of tree cover (Nowak et al. 1996, Escobedo et al. 2009). For example, cities developed in natural forested areas have higher tree cover than those developed in grasslands (19%), or deserts (10%) (Nowak et al. 1996). Within a city, land uses occupied by park and residential lands as well as vacant lands and forested areas generally have the highest tree cover (Nowak et al. 1996). In Gainesville, Florida, 2006, urban tree cover was 51%: higher tree cover was found in vacant and forested areas and lower tree cover was found in commercial and industrial areas (Escobedo et al. 2009). Gainesville's tree cover is higher than many other cities studied in the United States (Nowak, 1993a 1993b; Nowak 1994; McPherson 1998). Certain tree species can contribute more to an area's overall tree cover due to their large individual tree sizes. For example, live oaks (*Quercus virginiana* Mill.) contributed to 14% of the Gainesville's total leaf area while only comprising 4% of all trees (Escobedo et al. 2009).

Urban Tree Mortality

Urban tree mortality can be minimized if the factors are better understood (Nowak et al. 2004). However, urban tree mortality has been the subject of relatively few scientific studies. In the limited number of studies, urban tree mortality has been shown to be related to tree condition, size, age, land use, water and nutrient stress socio-economic status, community participation, and management practices (Nowak 1986, Foster & Blain 1978, Nowak et al 1990, Sklar & Ames 1985, Gibertson & Bradshaw 1985, Nowak et al. 2004).

In many studies, mortality research on urban trees has concentrated on the factors affecting existing and newly planted street tree populations (Nowak 1986, Foster & Blaine 1978, Nowak et al. 1990, Sklar & Ames 1985, Richards 1979, Gibertson & Bradshaw 1985). Street tree size and condition in Syracuse, New York, were found to influence average annual mortality rates; low mortality was found in stable and healthy trees (1.4%) while higher mortality was found in trees larger than 77 cm dbh (5.4%) and in trees with crown deterioration (6.4%) (Nowak 1986). Newly planted street trees in

Boston, Massachusetts had a mortality rate that averaged 9% over a ten year period, which mostly depended on tree planting methods (Foster & Blaine 1978).

In Oakland, California, annual mortality rates for newly planted street trees averaged 19% over a two-year period (Nowak et al. 1990) with lower tree mortality rates occurring in areas next to single family and rapid transit stations and high mortality rates occurred in proximity to apartments, greenspaces, and areas with low socio-economic status and high unemployment. Another study of newly planted street trees in Oakland California reported lower annual mortality rates for trees planted with the community's participation: where rates as high as 50% were reported for trees planted with no community participation versus 5.8-8.2% for trees that were planted with community participation (Sklar & Ames 1985). Richards (1979) study in Oakland, California involving street tree survival, suggests high mortality rates in small, un-established trees and a positive relationship with minor accidents and vandalism. Water and nutrient stress was the cause for mortality for 56% of newly planted trees in Northern England while other causes of mortality included vandalism (18%), girdling by tree guards (12%), soil compaction (9%) and improper staking and tying techniques (5%) (Gilbertson & Bradshaw 1985).

Methods involving permanent, random plot re-measurement of urban tree populations are limited but one study has been used to study size, condition, species and land use effects on urban tree mortality (Nowak et al. 2004). In Baltimore, Maryland, two-year permanent 0.04 hectare plot re-measurements yielded average annual tree mortality and net change in number of live trees rates of 6.6% and -4.2% respectively, with the lowest mortality rates occurring in medium to low-density residential land uses and the highest mortality rates occurring on transportation or commercial-industrial lands (Nowak et al. 2004). Tree size and condition also affected mortality rates in Baltimore, where higher rates were found for trees in small diameter and poor condition classes.

Urban Tree Growth

Natural forest and urban tree diameter growth rates used to model urban forests are based on natural, forest-like conditions (Nowak & Crane 2000) and generally come from a study in Indiana and Illinois where comparison of permanent forest inventory plot measurements of dbh yielded growth rates that average 0.38 cm per year (Smith & Shifley 1984). Average annual growth rates for a variety of hardwoods species and a single softwood species, shortleaf pine (*Pinus echinata*) were 0.38 cm/yr and 0.36 cm/yr, respectively. This study compared growth rates by crown and diameter classes as well as species groups, finding faster growth in trees from dominant and co-dominate crown classes.

Previous urban tree growth studies have used radial growth measurements from core samples and permanent plot re-measurement to acquire urban tree growth rates. In a study of urban trees in two neighborhoods in Chicago, Illinois, growth rates determined using tree ring increments from core samples were 1.09 cm per year (N=118) for the following hardwood trees: maples (*Acer negundo, A. saccharinum, A. platanoides*), elms (*Ulmus americana, U. pumila*), mulberry (*Morus alba*), crabapple (*Malus* spp.), and cherry (Prunus spp.) and 0.51 cm per year (N=17) for softwood trees including spruces (*Picea pungens, P. abies, P. glauca*) (Jo & McPherson 1995). Another urban tree study in Chicago used radial growth increments to estimate tree growth and carbon sequestration for removed, open grown trees, and found tree growth rates ranging from 0.78 to 1.02 cm per year (Nowak 1994). In a study across five mid-western states (Illinois, Iowa, Minnesota, Missouri and Wisconsin) radial growth rings from the last ten years were used to compare growth rates across land uses and higher growth rates were found on city park sites followed by residential and commercial sites (Iakovoglou et al. 2002). In Gainesville, FL an urban tree study acquired growth rates using the five most recent annual growth rings from 12 laurel oaks (*Quercus laurifolia*) and determined a growth rate of 1.3 cm per year (Templeton & Putz 2003).

In the SE, urban tree growth has been researched on a species level with emphasis on Live Oaks, a historically important and common species and a large component of total leaf area by species in the region. In Gainesville, for example, Live Oaks provide 14% of the city's total leaf area (Escobedo et al. 2009). Not only are they excellent shade trees, live oaks are well suited to urban conditions (Grabosky & Gilman 2004) and highly resistant to hurricane damage (Duryea et al. 2007). In parking lots in Florida, one study reported that growth, described as a relationship between dbh and canopy radius size, declined as non-paved surface area was reduced for Chinese elm (*Ulmus parvifolia* Jacq.), sycamore (*Platanus occidentalis* L.), Shumard oak (*Quercus shumardii* Britton), and laurel oak (*Quercus laurifolia* Michx.); but not live oak (Grabosky & Gilman 2004). Surrounding vegetation such as other trees, shrubs and turf grass can also limit growth as they compete when space is limited (Vrecenak et al. 1989).

Soil Related Stress on Urban Tree Growth

Soil and site conditions are often used to study factors related to tree growth and reduction of life span. Factors that result in less than optimal growth rates in plants can be described as "stress" (Kozlowski & Pallardy 1997). Urban soils are altered by management regimes, disturbances, changes in surface cover, and other human influences that can result in highly variable soil characteristics distributed across the urban landscape (Craul 1999, Pouyat et al. 2007). Urbanization can cause alterations in soil bulk density, microbial biomass and organic matter resulting from physical modifications of urban soils and disturbances such as building construction, compaction from heavy equipment, foot traffic, covering of soil with impervious surfaces, and removal of grass clippings and yard wastes (Scharenbroch et al. 2005, Craul 1999). These effects are reduced by the amount of time since urbanization as natural processes improve physical, biological and chemical soil properties (Dobbs 2009, Scharenbroch et al. 2005). Soil-nutrient concentrations can also vary across the urban landscape depending on the time since urbanization, urban morphology (e.g. amount of impervious surface), land use, and land cover (Pouyat et al. 2007, Grimm et al. 2008).

Water stress is also considered a major limiting factor on vegetation in all environments (Kramer & Boyer 1995). For example urban street trees suffer from additional water and heat stresses associated with urban site conditions such as impervious surfaces, soil compaction, and built structures that radiate heat (pavement, buildings, automobiles parked under trees) (Close et al. 1996). As a result, annual diameter measurements can be negative when the tree's stem water content decreases, causing a contraction of wood and bark in the trunk (Pastur et al. 2007).

Stresses associated with poor site conditions such as impervious surfaces beneath the crown, soil compaction and pH have been shown to affect growth in sugar maples (*Acer saccharum*) where terminal growth in trees growing in woodlots was significantly higher than those grown on Michigan State University's campus and streets (Close et al. 1996). Conversely, annual rates of diameter growth were higher on trees growing on the Virginia Tech University campus than the same species growing in a forest, implying that site conditions associated with soil properties, have effects on urban tree growth that are lessened by open canopy conditions found in the urban environment (e.g. less competition for light, water and nutrients) and are similar to observed increases in branch size and survival after forest stands have been thinned (Rhoades & Stipes 1999, Kramer & Kozlowski 1979).

Carbon Storage and Sequestration of Urban Trees

Although many components such as live biomass, litter, and soil make up an urban forest's carbon stock, live biomass is most affected by human and natural disturbances and can be easily tied to tree measurement data. An urban tree cover study by Nowak & Crane (2002) estimated that urban forests across the nation collectively store 700 million tons and sequester 22.8 million tons carbon per year.

Proper management techniques can increase the role of urban trees in sequestering atmospheric carbon dioxide (Nowak et al. 2002). Planting low maintenance trees that grow at moderate or fast rates, with the potential to become large in size, usually maximize the potential quantity and duration of the carbon benefits received by a tree. Nowak (1994) reported that carbon sequestration and carbon storage was 90 and 1000 times greater, respectively in large versus small trees. When selecting trees, growth rates and life spans are equally as important as considering if the tree is appropriate for the given site conditions and maintaining the trees in a manner that increases survival (Nowak et al. 2002).

Developing uses for wood from removed trees can delay carbon decomposition emissions or contribute to community's fossil fuel energy needs (Nowak et al. 2002). In addition, Nowak et al. (2002) suggest the practices such as minimizing the use of fossil fuel burning pruning equipment and techniques, appropriate tree disposal methods, strategic planting of deciduous shade-tree providing species that require low maintenance near buildings, and proper maintenance and spacing for existing large trees need to be evaluated.

Uses of Urban Tree Biomass

The amount of wood removed due to mortality caused by urbanization, pests, hazard trees, windstorms, and other disturbances from urban forests nationally is comparable to the total annual harvests from US National Forests and can range from 16 to 38 million green tons (Bratkovich et al. 2010, Bratkovich et al. 2008). The use of urban tree “waste” wood to create useful products is gaining momentum as additional resources and initiatives are organized (Bratkovich et al. 2010).

Application of Mortality and Growth to Urban Forest Function Studies

Urban tree growth and mortality studies are being used in the Urban Forest Effects (UFORE) and the i-tree STREETS models, which are being used throughout the SE (http://www.itreetools.org/). In the UFORE model, a street tree mortality study in Syracuse, New York (Nowak 1986) is used to estimate emissions due to dead and decomposing trees when calculating carbon sequestration (Nowak & Crane 2000). Probability of mortality is determined by street tree data from Nowak (1986) where crown dieback measurements are categorized into condition ratings (good-excellent, fair, poor, dying and dead). The model also uses natural forest and urban tree growth studies from northern US regions to approximate diameter growth for individual tree carbon sequestration rates (Table 1-1). These growth rates are based on three land cover categories (forest, urban and park) and adjusted for tree condition and regional climate (Nowak & Crane 2000). Assuming growth rates from northern tree studies would likely be conservative for southern regions, despite a newer version of UFORE which uses the length of a region's growing season to determine the base growth rate standardized to Minnesota's where there are 153 frost-free days.

Research on urban tree growth, recruitment and mortality is needed to project future urban forest populations more accurately (Nowak et al. 2004). Better information on urban tree growth is needed since currently there are very few growth studies for city-wide urban tree populations from the SE US region. The Paterson's index also called the CVP (climate, vegetation, productivity) index has been used in several countries to estimate potential production for areas that are hard to inventory. This index predicts maximum growth potential of trees and is based on evaop-transpiration, annual temperature range, mean monthly temperature of the warmest month mean annual precipitation, length of growing season and is appropriate for comparisons across species and regions (Skovsgaard & Vanclay 2007). However, there are disadvantages when applying the same assumptions to different regions. Natural influences that occur on that site are specific to that geographic area; therefore, if the results are applied to an area outside of the study's realm, the resulting predictions may not be appropriate (Smith 1983).

Objectives

The overall goal of this study is to analyze temporal changes in urban forest structure by improving estimates of rates of growth, in-growth and mortality and to identify tree and plot level factors affecting these rates. Urban tree biomass removal estimates from re-measured plots will also provide information on carbon stocks and green waste potential in Gainesville.

Hypothesis 1 is that significantly higher mortality rates will be found on commercial plots versus residential plots (alpha < 0.05), because low mortality rates observed in previous studies have been found in residential areas and higher rates have been found on commercial and transportation land uses (Nowak et al. 1990; Nowak et al. 2004). Hypothesis 2 is that significantly higher growth rates (alpha < 0.05), will be found on land uses with urban-park settings such as institutional and residential that are known to have higher rates of tree and lawn maintenances as has been observed in a previous study in similar land uses (Iakovoglou et al. 2002).

Growth models are the focus of Hypothesis 3, where significant plot level factors (alpha < 0.05) will be soil water content and bulk density measurement which can indicate tree growth stress (Kramer & Boyer 1995, Close et al. 1996) and low competition from other vegetation as characterized by low tree density (trees per hectare) which also limits tree growth (Vrecenak et al. 1989). I hypothesize that tree characteristics that will be significant (alpha < 0.05) are related to crown measurements such as high crown light exposure and low percentages of missing crown, as these trends have been observed to affect the growth and survival of urban live oak trees (Templeton & Putz 2003).

Finally, hypothesis 4 is that growth rates in urban, forest, and park land cover types in Gainesville will be significantly greater (alpha < 0.05) than the growth rates used by Nowak & Crane (2002) for predicting tree growth and carbon sequestration in similar land cover types. Individual species, such as *Quercus virginiana* may also have higher growth rates that those used in Nowak & Crane (2002).

My analyses of permanent plot re-measurements will provide local mortality and growth estimates that account for local natural and human influences as opposed to assumptions based on studies from other regions. This study is unique as it describes the rates at which urban trees in Gainesville's grow and die based on actual measurements. Finally, results will also be used to briefly explore biomass and carbon stock estimates in Gainesville that account for site-specific and socio-ecological conditions.

Table 1-1. Tree diameter growth rates by land cover used in the Urban Forest Effects (UFORE) model to calculate urban tree growth and carbon sequestration from Nowak and Crane (2000)

Source	Land cover	Growth rate (cm/yr)	Tree type
Smith WB & Shifley SR (1984) Diameter growth, survival, and volume estimates for trees in Indiana and Illinois. Res. Pap. NC-257. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 10 p	Forest	0.38	Forest
Nowak, D.J. 1994. Atmospheric carbon dioxide reduction by Chicago's urban forest. In: McPherson, E.G.,Nowak, Nowak DJ (1994) Atmospheric carbon dioxide reduction by Chicago's urban forest. In Chicago's Urban Forest Ecosystem: Results of the Chicago Urban Forest Climate Project (Eds McPherson EG, Nowak DJ, Rowntree RA): 83-94. USDA Forest Service General Technical Report NE-186. Radnor, PA	Urban	0.87	Street
deVries RE (1987) A preliminary investigation of the growth and longevity of trees in Central Park. New Brunswick, NJ: Rutgers University. 95 p. M.S. thesis	Park	0.61	Park

CHAPTER 2
METHODS

Study Area

Gainesville, Florida is the largest city in Alachua County covering an area of 127 square kilometers and located at 29°39'N and 82°20'W in north central Florida. The climate is subtropical warm and humid. The city receives an average of 1370 mm per year; more than half is received June through September while the driest month is November (Metcalf 2004). Although a freeze can be expected about four times a year, the frost-free season lasts 295 days per year (Dohrenwend 1987). The elevation in Gainesville varies around 30 meters above sea level and topography changes from rolling hills in the northern part of the city to flat areas within the prairie-lands to the south where seasonally high water tables are found (Metcalf 2004, Phelps 1987). Gainesville is situated on top of two unique geological features: the northern part lies above the Hawthorne geologic formation and Plio-Pleistocene deposits of the Ocala Uplift lie below the southern part of the study area (Phelps 1987). Soils are predominantly sandy siliceous, Hyperthermic Aeric Hapludods and Plinthic Paleaquults and the texture of these soils is very sandy (95%), and the rest are composed of different fill material (Chirenje et al. 2003). Gainesville, Florida has many remnant-forested patches throughout the city that exhibit soil and vegetation characteristics similar to natural areas containing non-urban natural soils and vegetation. Also most soils in Gainesville show little signs of pollution, severe compaction or being covered by impervious surfaces (Dobbs 2009). However urbanization effects do exist; in 2006 the City of Gainesville's ground was covered 9 percent by buildings and 15 percent by impervious ground cover (roads, sidewalks, etc.) (Escobedo et al 2009).

Data Collection

Plot and Tree Measurements

In 2006 Gainesville's urban forest was sampled using the UFORE sampling protocol (Escobedo et al. 2009). Circular 0.04 ha (0.1 acre) plots were established and land use and ground cover percentages were estimated. In 2009, the Gainesville UFORE plots were re-measured following this same protocol. First, plot center was located using GPS coordinate and original reference object's distance and directions. Ground-based as well as aerial photos were also utilized while the location of individual trees within the plot and their distance and direction measurements helped reduce re-measurement error. Ground cover categories included plot percentages of impervious surfaces, grass, soil, rock (e.g., pervious rock and gravel), water, duff and mulch, herbaceous vegetation (e.g., area comprised of vegetation that is not grass or shrub cover) and maintained and un-maintained grass (e.g., grassy area with no indication of mowing or other maintenance activities). For comparison, original land uses were condensed into the following: forest, institutional, commercial and residential/vacant.

Trees with diameters larger than 2.5 cm (1 inch) were measured sequentially starting from due north and rotating clockwise around plot center; direction and distance in feet to each tree were recorded again to reduce re-measurement errors. The following data were collected by tree: species, diameter at breast height (dbh; cm), total and crown base height (m), crown width in two directions (m), crown light exposure (CLE) rating (0 to 5, where zero denotes a crown completely blocked above and on all sides and five indicates that each side of the tree as well as the top of the tree is completely exposed to direct light), and percent missing and percent dieback of foliage (compared to a full crown) to determine tree condition. Since tree dbh was of particular interest for this study, a pole marked at 1.37 m was held next to each tree where measurements were taken to reduce measurement error.

Soil Measurements

Analyses of soils on Gainesville's UFORE plot were conducted in the summer of 2007. Soil variables such as bulk density, water content, potassium concentration and pH were collected as described in Dobbs (2009). Bulk density measurements were measured from three (per plot) undisturbed 5 cm diameter by 4.5 cm deep soil samples that were then fresh weighted, oven-dried (after 48 hours) then weighed for dry weight. Chemical properties such as potassium concentrations and pH were measured from 15 (per plot) randomly located soil cores from the top 10 cm of soil and analyzed by University of Florida Extension Soil Testing Laboratory (Dobbs 2009).

Re-measurement Method Errors

Re-measurements using tree diameter tapes at breast height can differ from actual tree growth for reasons associated with measurement error and changes in tree physiology (Avery & Burkhart 1983). Even when efforts are made to reduce measurement error by using a pole for a standard breast height measurement or holding the tape tight and even, there are other sources of error that cannot be corrected. For example, annual diameter measurements can be negative due to contraction of trunk wood and bark in the presence of severe water stress (Pastur et al. 2007). In addition, changes in the height of mulch and litter below a tree can change the breast height measurement used for subsequent measurements resulting in a measurement taken at a different height. For these reasons, tree core increments are often measured to determine tree growth. In urban tree studies, however, tree coring is not appropriate since one might anticipate a high level of resistance to granting permission for coring trees on private properties due to issues of liability.

Data Organization

Data Availability

Of the original 93 plots established in 2006, 65 plots were re-measured. A complete re-measurement of all original plots was not possible in 28 plots, since access was denied to 12 and even though trees on all plots were re-measured in 16 plots, some 2006 trees could not be matched to the original plot data on these (16) plots (Table 2-1). Also, 14 of these 16 plots were forested and plot center could not be found so the plot was “re-established”, and 2 plots were located in residential plots where new construction eliminated the reference objects thus preventing measuring distance and direction information necessary to accurately re-locate plot center. Soil data was missing for 17 plots, 8 of which contained no trees. This may have been related to the previous soil plot selection criteria that eliminated plots where pervious surfaces covered at least 50% of the plot. To compare growth rates by land use categories used in Nowak & Crane (2002), plots were separated into similar categories and matched trees were found in 31, 5, and 16 plots corresponding to open, park, and forested land cover categories, respectively. Brightly painted stakes were installed on plot center for all forested plots to facilitate relocation for future re-measurements.

Matching of Individual Trees

Sample data from the 2006 and the 2009 sample were merged and individual trees present in both samples were matched if they: 1. were at the same direction and distance from plot center, 2. the same species and 3. had a larger 2009 dbh measurement. In-growth was defined as the presences of a tree in the 2009 measurement not originally measured in 2006, indicating a new planting or natural in-growth (that a small tree grew above the dbh threshold of 2.5 cm) as described in Nowak et al. (2004). Mortality represented the absence of a previously measured tree which was removed or downed since the 2006 sample. Difficulties arose while matching trees in certain plots and were mostly related to differences in the way directional information was interpreted (e.g. type of compass readings) and the differences in the order in which trees were recorded in 2006. It was considered ideal when trees were recorded starting with the tree closest to due north and plot center continuing in a clockwise direction, and compass directions were recorded in degrees from 0 to 360 from plot center.

Soil Variable Selection

Many soil variables could have been used in this study however, some soil variables were dropped because they were not available for many of the plots used in this study (Table 2-1). Additionally, many of the plots missing soils data had no trees, as the selection criteria for soil sampling required that the plot had at least 50% pervious ground cover and access was granted. Other soil variables were removed due to their high correlation with other parameters that might have led to multicollinearity that causes problems in modeling, as highly correlated variables neutralize the response of significant parameters. Multicollinearity was identified by a Principal Component Analysis (PCA) by Dobbs (2009). In this study relating urban soils to urban morphology and socioeconomic factors in Gainesville, Florida, an analysis of soil variables determined that pH, soil potassium content, and bulk density were the best variables to use for characterizing urban ecosystem structure and function in Gainesville. Soil pH was an indicator of soil water content, fertility and quality while bulk density was an indicator of socio-economic effects, and potassium an indicator of disturbance. Therefore, pH, potassium, soil bulk density and water content were used for analyses in this study based on the results from Dobbs (2009) and the documented role these soil characteristic play on urban vegetation (Scharenbroch et al. 2005, Kramer & Boyer 1995).

Species Groups

Urban forests can often have a wide variety of tree species within very localized areas. While reporting data for each species is informative, it is impractical for many species due to insufficient sample sizes. For example in this study there were 19 species where only one tree was matched for growth. Therefore, summarizing the raw data into relevant species groups is needed to make results useful for modeling. For instance urban tree mortality rates were reported for all species by size class in Baltimore, Maryland (Nowak et al. 2004). In Chicago, radial growth rates for removed urban trees were grouped into major genera by size class (Nowak 1994). These species and size grouping approaches are not suitable for this study, due to the low frequency of trees found with some size classes. For example, growth rates for trees in the larger size classes (greater than 61.1cm) could not be modeled separately, as sample sizes were as few as 4 and 5 trees (Table 2-2).

In natural settings, a tree’s average potential size at maturity and life span depend on the species’ individual characteristics (Nowak et al. 2002). The matched tree dataset was used to generate growth models where all species were grouped into one of the three following categories based on maximum height and life span characteristics as reported in the USDA PLANTS Database (www.plants.usda.gov): large size- long life span (LL), large size- moderate life span (LM), and medium and small size (M). Large size trees were those that potentially could attain a height equal or greater than 18.29 meters at maturity; medium and small size trees were those that potentially could attain a height equal or less than 18.29 meters at maturity; while a moderate life span was considered to be less than 250 years and long life span was greater than or equal to 250 years. This methodology closely follows Nowak et al. (2002) where trees were assessed for atmospheric carbon dioxide emissions. Whereas Nowak et al. (2002) was able to develop fourteen categories using life span, growth rate, and size at maturity, our data supported three categories. In addition, four growth models were created for the four most frequent tree species in the matched tree dataset. Removed and in-growth tree datasets were too small to support grouping species as for growth above; therefore mortality and recruitment models were generated by assigning trees into two classes; hardwood or softwood. Palm species were not used in any growth modeling due to their growth form and small sample size.

Land Use and Land Cover Descriptions

Re-measured plots were grouped into two sets of categories: land use and land cover (Table 2-1). This was done to compare mortality estimates to the Nowak et al. (2004) mortality study based off permanent plot re-measurement in Baltimore, Maryland, and to compare growth rate estimates to the land cover categories used to estimate growth and carbon sequestration in Nowak & Crane (2002). These studies used similar land use and land cover categories based on their differences in urban tree structure and management regimes. Land cover categories separate urban areas in a way that could be interpreted easier than when determining land use. Forest areas have high tree cover, no management activities, and minimal disturbance; park areas are managed, have lower tree cover than forests, no pervious surfaces, and minimal disturbance; and urban areas have lower tree cover than forest, more pervious surfaces, are managed, and have an increased potential for disturbances not associate with park areas. Vacant areas due to land use designations were classified as residential.

Land use categories used in this analysis were:

- Commercial (7 plots): These plots had the greatest variation in types of plots. These include business-like settings that were associated with yards, parking areas, access roads, warehouses, and also included plots in transportation routes and airports. The combination of transportation and commercial-type plots helped comparison because both types exhibited high mortality rates in the Baltimore study (Nowak et al. 2004).

- Institutional (15 plots): These plots were found on lands associated with The University of Florida, a church, a correctional facility, a community fair ground, various medical and health facilities, and elementary, middle and high schools.

- Residential (27 plots): These plots included high, low and medium density residential areas included apartments/condominiums, mobile homes/trailers, and associated drive-ways and parking areas. Vacant lots in residential areas were considered residential plots because tree cover was similar to the surrounding residential area and it was apparent that they were sometimes maintained (clearing of debris, small shrubs, and mowed grass).

- Forest (16 plots): These plots included mixed management forested areas, pine plantations and abandoned areas apart from residential areas. This category also included two plots within conserved park areas that were heavily forested, and one natural conservation area within the University of Florida.

The Land cover categories used in this study were:

- Urban-Open (45 plots): Residential, vacant, commercial and institutional plots that were near buildings, roads, or other structures that created open-canopy conditions.

- Park (4 plots): These plots had park-like structures including two cemeteries, fair grounds and a sports field in an elementary school.

- Forest (16 plots): same as forest land use (described above).

Calculations

Diameter Growth and Mortality Rates

Diameter measurements were converted into annual dbh growth (cm/yr) by subtracting the 2009 dbh from the 2006 dbh measurements and dividing by the length of time between measurements for each plot (an average of 2 years and 10 months). Mortality rates were calculated as in Nowak et al (2004), using a formula for mortality per year widely used in ecological applications (Sheil et al. 1995), where annual mortality is *m*, *t* is the time interval, and N_1 and N_0 are population counts and at the beginning and end of measurement interval *t*, respectively (Eq. 2-1).

$$m = 1 - (N_1 / N_0)^{1/t} \tag{2-1}$$

Biomass Estimates

Biomass estimates for all live trees measured in 2006 and 2009 were obtained using the same methods and allometric equations used in the UFORE model (Nowak and Crane). Allometric equations use tree characteristics such as dbh, height and species to determine above ground biomass in terms of fresh or dry weight (Jenkins et al. 2003). This dimensional analysis approach did not involve destructive sampling methods. The model UFORE uses a list of applicable diameter based biomass equations from studies across North America (Nowak 1994). This approach uses the biomass equation for an individual species if available; if not, then an average of all equations for that specie's genera are calculated. If there are no genera-specific equations for an individual species, then depending on its tree type an average from all hardwood or softwood species is calculated. Finally, all equations are converted to whole tree dry-weight biomass estimates by applying conversions for each equation's type based on the tree portion or whether fresh or oven-dried tree weight was estimated. Whole tree biomass totals can be achieved by converting from above ground biomass with the root-to-shoot ration of 0.26 (Cairns et al. 1997). Fresh weight or green weight can be achieved by using moisture content averages of 0.46 for conifers and 0.56 for hardwoods (Nowak and Crane 2002). Total tree dry weight biomass can be converted to total stored carbon by multiplying by 0.5 (Nowak & Crane 2002). Although sequestration estimates are for an analysis period of 2 years and 10 months, they were annualized for comparison purposes by dividing the estimates by 2.8 years.

Statistical Analyses

Statistical modeling of growth, mortality and in-growth were conducted using plot level factors from the original 2006 measurements and included: land use type, land cover type, trees per hectare, basal area per hectare, percent ground covers of each plot (described in this chapter's section on plot and tree measurements). In addition, tree level factors (described in this chapter's section on plot and tree measurements) from the original 2006 measurement and selected soil variables (pH, potassium, soil bulk density and water content) collected in 2007 (as described in this chapter's section on soil measurements) were also used. Seven growth models were created for each of the three species groups and the four most frequently occurring species that combined comprise 43% of matched trees: Laurel Oak (*Quercus laurifolia*; 76 trees), Water Oak (*Quercus nigra*; 62 trees), Slash Pine (*Pinus elliottii*; 62 trees) and Loblolly Pine (*Pinus taeda*; 57 trees). Two mortality and two recruitment models were generated by grouping species into hardwood and softwood types.

Due to the concentration of measured growth rate values around zero, growth rate values were transformed with the square root function for modeling by species group and the natural logarithm plus one for modeling individual species. These transformations stabilized the variance and allowed assumptions underlying statistical models to be met. There were 46 trees (8% of matched trees) that were found to have negative growth rates and were re-assigned a growth rate of zero for modeling purposes. Measurements from these trees indicated growth rates that were less than the actual biological tree growth and are likely due to errors associated with dbh re-measurement and tree bole shrinkage (describe in this chapter's section on growth measurement errors in dbh re-measurement methods). Since these errors could not be accounted for otherwise, assigning a value of 0 to these trees approximates actual biological growth in this sample.

Growth rates were modeled with a general linear mixed model with the SAS procedure PROC MIXED (SAS 2006), using the above plot and tree level characteristics as predictor variables, and a random effect to account for correlations between trees in the same plot. A Kenward-Rogers adjustment was made to the degrees of freedom to better reflect the effect of the autocorrelation structure in the data (Littel et al. 2006). Mortality and recruitment models used a generalized linear mixed model with a negative binomial distribution to characterize the response variable. Models were fit with the SAS procedure PROC GLIMMIX (SAS 2006) using the above plot level characteristics as predictor variables.

Examination and comparison of model results used the information criteria and p-values associated with each independent value. Non-significant effects and their interactions were identified by a type I error level of 0.05, and models were compared by their corrected Akaike's information criteria (AICC), which is a small sample bias-corrected version of the Akaike's information criteria fit statistic. To provide substantial evidence that the data arose from these models, the final estimated models included only those effects that were significant (alpha < 0.05) and also had the lowest AICC values. To determine significant differences in growth and mortality rates between land uses and land cover types, the Fischer's LSD (least significant difference) statistical procedure was used with an (alpha < 0.05).

Table 2-1. Status of all permanent plots in 2009 by land use and city for Gainesville, Florida.

Land Use	Residential*	Commercial**	Institutional	Forest	City Total
Plots matched	23	2	11	15	51
No trees	4	5	5	0	14
Plot re-established	2	0	0	14	16
Access denied	6	2	1	3	12
No soils data	4 (all had no trees)	9 (3 had no trees)	3 (1 had no trees)	1	17 (26% of all plots)

* Includes plots on vacant areas; **Includes plots on industrial areas

Table 2-2. Gainesville, Florida's percent annual mortality and growth rates arranged by Nowak et al.'s (2004) size classes to demonstrate differences in sample size.

	Gainesville 2006 to 2009	Nowak et al. 2004	Gainesville 2006 to 2009
DBH (cm)	%Annual Mortality (number of trees removed)	%Annual Mortality (number of trees removed)	%Annual growth rate (cm/yr) (number of trees matched)
0-7.6	18 (70)	9 (528)	0.86 (167)
7.7-15.2	9.7 (33)	6.4 (267)	1.11 (134)
15.3-30.5	3.4 (16)	4.3 (201)	1.03 (174)
30.6-45.7	1.0 (3)	0.5 (109)	0.91 (109)
45.8-61.0	5.7 (5)	3.3 (62)	2.17 (33)
61.1-76.2	7.7 (1)	1.8 (28)	0.69 (5)
>76.2	0 (0)	3.1 (33)	1.36 (4)

CHAPTER 3
RESULTS AND DISSCUSION

Results

Change in Urban Forest Structure

In 2009 the average tree height in my sample was 12.4 m, average dbh was 29.2 cm, and average crown width was 5.8 m. From 2006 to 2009 (average of 2.78 years lapse between measurements) the overall average annual mortality was 1.8% (Table 3-1). When comparing trees within the 65 re-measured plots, there was a net annual loss of approximately 13 trees, and a gain of 0.64 square meters of basal. In 2006, 755 trees were measured in Gainesville and by 2009, 128 (17%) trees were removed, which account for 64%, 26%, 5% and 5% being removed from forest, residential, commercial and institutional plots, respectively. Plots in 2009 contained a total of 718 trees; 627 matched (30 of which were dead and not used for growth modeling) and 91 trees were considered in-growth. Figure 3-1 indicates that when comparing all plots that were measured, the city's average percent change for trees per hectare and tree density increased over time by 3% and 26%, respectively. However, forest plots had a decrease in trees per hectare of 7%. Growth rates were highest on commercial plots (2.07 cm/yr) followed by residential (0.90 cm/yr), forest (0.75 cm/yr) and then institutional (0.50 cm/yr) plots (Table 3-1).

Growth Models

Growth rates for LL trees were influenced by plot level factors such as ground cover percentages of maintained and un-maintained grass as well as average tree crown width and percent missing foliage (Table 3-2). Growth was positively influenced by every tree level factor with the exception of percent missing foliage. Growth rates for

LM trees were influenced by the plot level factors of basal area per hectare, percent un-maintained grass, soil bulk density and soil water content as well as the tree factors of dbh, average crown width, percent missing foliage and crown light exposure (Table 3-2). Growth rate was positively influenced by every factor except dbh and percent missing foliage. Growth rates for M trees were only influenced by dbh and crown light exposure (Table 3-2).

Models were created for the four most frequently occurring species which, when combined, comprised 43% of matched trees. Growth rates for *Pinus taeda* were influenced by plot level factors of percent rock cover and the tree level factor of crown height (Table 3-3) where growth was negatively influenced by crown height. Growth rates for *Pinus elliottii* were influenced by dbh as well as plot level factors of land use and ground cover (percent un-maintained grass, percent maintained grass and percent herbaceous cover) (Table 3-3). Higher growth rates (1.29 cm/yr) were found on institutional land uses, followed by forest (0.86 cm/yr) and residential (0.62 cm/yr). There were no *Pinus elliottii*s found in commercial land use plots.

Growth rates for *Quercus laurifolia* (0.84cm/yr) were influenced by the plot level land use and tree level crown light exposure (Table 3-3). For *Quercus laurifolia*, the most abundant tree in Gainesville (13% of all trees), growth was found to be significantly greater in residential plots (1.34 cm/yr) compared to commercial (0.59 cm/yr) and forest (0.49 cm/yr) but not institutional (0.67 cm/yr). *Quercus nigra* were influenced by the plot level percent un-maintained grass and tree level crown light exposure (Table 3-3).

Soil variables did not result in many significant effects within the growth models when considering the lowest AICC values. However, slightly higher AICC models were explored to further investigate these variables. For LL trees, percent grass, percent un-maintained grass, dbh, percent missing foliage, potassium and pH influenced diameter growth significantly where potassium and percent missing foliage influences were negative. In a model with a higher AICC value for *Quercus nigra* growth, significant factors that negatively influenced growth were tree per hectare, bulk density, and potassium while pH had a positive effect.

Mortality and In-growth Models

Two mortality models were developed for hardwood species. These models indicate that land use and trees per hectare significantly influenced mortality (Table 3-4). While the model using trees per hectare had a lower AICC (174.9 verses 191.1), indicating more evidence that the data arose from this model, the competing model number 2 is of interest because it does not rely on field data. There were no alternative models to compete with the softwood mortality model, which had a positive influence of trees per hectare on mortality (Table 3-4). Although individual species models could not be estimated due to the paucity of data in most species, annual mortality rates for the most common species in Gainesville were found to range from 1.1% to 6.9% (Table 3-5). Both softwood and hardwood in-growth models show that in-growth increased with trees per hectare (Table 3-6). No other plot level factors were found to be significant.

Change in Biomass

Considering all trees and plots in Gainesville measured in both 2006 and 2009, I estimate that 6,082 tons of carbon was sequestered annually (Table 3-7). Carbon sequestered was largely from *Quercus virginiana*, *Quercus nigra*, and *Liquidambar* *styraciflua* (Table 3-8). Annual removed biomass per hectare was greatest on institutional and forest plots, which contained approximately 6,712 and 2,202 kg/yr, respectively (Table 3-9). Removed biomass was largely comprised of *Quercus laurifolia*, *Pinus taeda* and *Acer rubrum* (Table 3-10). Annual removed biomass in Gainesville was about 34,785 tons. Total carbon stored in urban trees in Gainesville for 2009 was about 231,950 tons (Table 3-11).

Discussion

Urban Forest Structure Changes

Despite an overall loss in number of trees, Gainesville had a net increase in basal area and biomass. Forest plots had the greatest loss in number of trees per hectare and had the second lowest increase in basal area per hectare (Figure 3-1). Conversely industrial plots had the largest increase in trees per hectare, and the lowest increase of basal area. This may imply that more trees were planted on industrial land uses than on commercial and residential land uses; while on forest plots more trees were removed/fallen than naturally re-generated. Therefore increases in basal area are primarily from growth of existing trees. While measuring trees on forest plots I observed many trees that were missing from 2006 could often be identified on the ground as downed trees (eg. large newly fallen trees of the same species with their bases near or on the location recorded for a large tree existing in 2006). This may be due to the loss of individual trees associated with the thinning stage of natural succession in remnant forest patches in urban landscapes where savanna trees enclose the canopy while changing environmental conditions due to urbanization such as fragmentation, construction or altered hydrologic processes (Zipperer et al. 1997, Tempeton & Putz 2003).

Rates of Growth and Mortality

Growth rates for trees in Gainesville ranked differently than those reported in five Midwestern states by Iakovoglou et al. (2002) where radial growth estimates were higher in city park sites followed by residential and commercial sites (Table 3-5). In Gainesville, higher diameter growth rates were found on commercial, residential, forest and then institutional sites, which is counter to hypothesis 2.

Growth rates for trees in Gainesville when analyzed by land cover types ranked differently than those used in UFORE (Table 1-1, 3-5), where the highest growth rates are found on parks, followed by open then forest (Table 3-5). Although Gainesville's urban plots did not have a higher growth rate than those in Table 1-1, growth rates in Gainesville were higher in forest and park plots than in the studies used for UFORE, which partially satisfies hypothesis 4. Growth rates for three of the most common trees in Gainesville (*Quercus laurifolia*, *Quercus nigra*, and *Pinus elliottii*) were greater than the two growth rates used in UFORE for trees grown in forest and park settings (Table 3-7).

The top six species by growth rate far exceed all three growth rate estimates used in UFORE. Growth rates by land use in Table 3-1 ranged higher than those reported in a similar study in Chicago, IL (Jo & McPherson 1995), and those used for calculating dbh growth for carbon sequestration in the UFORE model (Table 1-1; Nowak & Crane 2000). Growth rates for *Quercus laurifolia* were less than the diameter growth estimate of 1.69 cm/yr for canopy trees of this species in Templeton & Putz (2003). However, an average growth rate of 1.34 cm/yr for *Quercus laurifolia* in Gainesville's residential plots (open-canopy-like conditions) was similar to estimates found by Templeton & Putz (2003).

Overall annual mortality rates during the analysis period were less than those reported in a similar study in Baltimore (Nowak et al. 2004). Comparisons of mortality rates by size classes to the Nowak et al. (2004) study show that high mortality rates for small sized trees (0-15.2 cm dbh) and lower mortality rates for medium sized trees (15.3-61.0 dbh) were proportionally the same in both Nowak et al.'s (2004) and my study. Although there were no significant differences between land uses when comparing mortality in all plots with trees, in my study mortality was highest in forest plots, followed by commercial then residential, while institutional plots actually exhibited in-growth (Table 3-5). These trends confirm hypothesis 1 in that mortality rates are similar to those reported in Nowak et al. (2004) in Baltimore where mortality rates on transportation or commercial-industrial land uses were higher than rates in medium to low-density residential land uses.

When comparing mortality by land cover type, higher mortality rates were found on forest, then park and urban plots. Higher mortality rates were found in both *Quercus nigra, Quercus laurifolia* than in *Pinus taeda* or *Pinus elliottii* (Table 3-6). Mortality increased as trees per hectare increased for both softwood and hardwood species (Table 3-4).

Models of Growth, Mortality and In-growth

Hypothesis 3 correctly predicted tree characteristics that significantly affected tree growth, but not plot characteristics. Plot factors of soil and tree density affected growth in only one of the growth models (LM trees). However, tree factors related to crown measurements like average crown width, percent missing foliage, and tree height were significant factors in 6 out of 7 growth models and CLE was significant in 4 of the 7 growth models.

Results from the LL growth model suggest that once established (i.e. grown to 2.5 cm dbh) LL tree growth in the urban environment is affected by surrounding ground covers such as maintained grass. This is possibly due to factors caused by maintenance activities associated with maintained grass such as fertilization and increased irrigation as well as the tree's crown size and exposure to light (Zipperer et al. 1997, Tempelton & Putz 2003). Typically, vegetation such as other trees, shrubs and turf grass surrounding a tree can limit growth as they compete when space is limited as in the case of urban conditions (Vrecenak et al. 1989). The LM growth model results suggest that established LM tree growth in the urban environment is also affected by the presence of maintained grass on plots and CLE, similar to LL trees and is positively influenced by soil water content and soil bulk density, basal area and crown light exposure. For LM trees, increased growth was associated with increased soil bulk density, however this result was not expected, as deceased bulk density is known to improve soil physical properties such as water infiltration and soil biological processes which are conducive to plant growth (Scharenbroch et al. 2005). On the other hand, increased bulk density was found by Dobbs (2009) on plots with high percent maintained grass which may suggest mulitcollinearity between these variables and may have neutralized this effect. Moreover, the bulk density values for this study are from the top 10 cm of soil profile; therefore these measurements may not be affecting growth via root-soil interactions in trees with deeper roots. For better tree growth analysis, deeper soil samples might be needed.

Diameter growth was positively influenced by crown light exposure in the M growth model, suggesting that for smaller trees, the amount of light exposure is more important than any other factor that was analyzed and can be related to the tree's growing space and competition with other trees, factors that have been shown to influence tree growth (Vrecenak et al. 1989). Crown light exposure was limited in the average *Pinus taeda* where only 2 sides out of a possible 5 were exposed to light. This might explain why tree height influenced growth for this LM-categorized specie more significantly than crown light exposure (a significant factor in the LM growth model). The taller the tree, the more potential for increased crown light exposure, which can increase growth (Templeton & Putz 2003). For *Pinus elliottii*, a positive relationship between dbh growth and 2006 dbh is unusual, especially due to the fact that the average 2006 dbh of *Pinus elliottii* (32.3 cm) describes a medium-sized tree by size class in Table 2-1. This may be a reflection of the species' known rapid growth rate as well and large potential size and long life span (www.plants.gov). Similar to the dbh growth model generated for LL trees (Table 3-2), the presence of both un-maintained and maintained grass (or associated maintenance activities) positively influenced diameter growth in *Pinus elliottii*. Both oak species are categorized as LM trees and both oak growth models were positively influenced by tree level factors such as crown light exposure.

Both in-growth models showed a positive influence for trees per hectare indicating that plantings or tree in-growth to the one inch size class is more likely in areas that already contain trees. There are no other models of in-growth to compare these results to.

Plot and tree level characteristics affected diameter growth in all species groups and the individual species model, while plot level characteristics like trees per hectare and land use affected mortality and in-growth. Greater sampling intensity would likely have improved growth, mortality and in-growth models. However, due to limited access and insufficient plot re-location information, this was not possible.

Green Waste Supply Potential and Carbon Sequestration

This study's estimates account for actual biophysical and socioeconomic factors in Gainesville as opposed to modeling these assumptions. Annually, more carbon was sequestered (83%) on residential plots (which include vacant areas) than forested and commercial, while institutional plots had a net emission of carbon due to tree removals. By land cover, urban plots sequestered the most carbon followed by forest and park plots. More carbon was sequestered by live oaks (1,727 tons city-wide) than any other species (Table 3-8). Residential plots had higher carbon sequestration estimates due to the fact that vacant plots were assigned a residential land use and that forested plots decreased in trees per acre over time (Figure 3-1). Stratifying land uses differently will result in different carbon sequestration per land use estimates.

Results from this study show that if all removed trees were collected from these analyzed plots in Gainesville, there would be about 34,785 tons of fresh above ground biomass removed each year and most (77%) of this biomass would come from *Quercus laurifolia*, *Pinus taeda*s, and *Acer rubrum* (Table 3-9 and 3-10). When analyzed by land use, most removed biomass came from institutional plots (42%) then forest (36%), residential (21%) and commercial (0.1%) If removed trees were only harvested from non-forest plots, this estimate would be reduced to 28,350 tons of fresh above ground biomass a year. In 2009, more carbon was being stored in forested plots (42%) than on residential plots (35%) followed by institutional (18%) and commercial plots (4%; Table 3-11).

Table 3-1. Plot count, average annual growth (AGR) and mortality rates (AMR) for all re-measured trees between 2006 and 2009 in Gainesville, Florida by land use and cover categories

Land Use	Commercial	Forest	Institutional	Residential	City Total
Plots matched	7	15	16	27	65
Plots with trees	2	15	11	23	51
AGR (cm/yr)	2.07	0.75	0.50	0.90	0.84
AMR	0.86%	2.70%	-1.86%	0.66%	1.79%
Land Cover	Urban	Park	Forest		
AGR (cm/yr)	0.81	1.49	0.75		
AMR	-0.37%	1.56%	2.70%		

Table 3-2. Test of fixed effects for model of annual diameter at breast height (dbh) growth by species group in Gainesville, Florida from 2006 to 2009

Large potential size, long life span (LL) N=126					
Effect	Estimate	Nm DF*	Den DF*	F value*	Pr>F*
%Maintained grass	0.0058	1	121	28.50	<0.0001
%Un-maintained grass	0.0060	1	121	7.20	0.0083
Average crown width	0.0039	1	121	6.59	0.0114
% Missing foliage	-0.0024	1	121	7.35	0.0077
Large potential size, moderate life span (LM) N=284					
Effect	Estimate	Nm DF*	Den DF*	F value*	Pr>F*
Basal area per hectare	0.0008	1	26	16.18	0.0004
%Un-maintained grass	0.0055	1	26	34.14	<0.0001
Dbh	-0.0173	1	249	18.12	<0.0001
Average crown width	0.0078	1	249	16.98	<0.0001
% Missing foliage	-0.0017	1	249	6.96	0.0089
Crown light exposure	0.0498	1	249	16.65	<0.0001
Soil bulk density	0.2673	1	26	11.19	0.0025
Soil water content	0.0096	1	26	13.35	0.0011
Medium potential size (M) N=120					
Effect	Estimate	Nm DF*	Den DF*	F value*	Pr>F*
Dbh	-0.0186	1	117	6.04	0.0155
Crown light exposure	0.0839	1	117	20.82	<0.0001

* Interpret as with numerator and denominator degrees of freedom (Nm DF and Den DF, respectively) the critical value of the F distribution (F-value) means the estimate is significant at the 5% level as determined by the p value (Pr>F).

Table 3-3. Test of fixed effects for model of annual diameter at breast height (dbh) growth of four most frequent species in Gainesville, Florida from 2006 to 2009

Effect	Estimate	Nm DF*	Den DF*	F value*	Pr>F*
Loblolly pine (*Pinus taeda*) N=57					
Effect	Estimate	Nm DF*	Den DF*	F value*	Pr>F*
%Pervious rock	0.0499	1	54	4.92	0.0307
Crown height	-0.0032	1	54	5.70	0.0205
Slash pine (*Pinus elliottii*) N=62					
Effect	Estimate	Nm DF*	Den DF*	F value*	Pr>F*
Land use- forest	0.2476	2	55	7.58	0.0012
Land use- institutional	0.2850	2	55	7.58	0.0012
Land use- residential	0	2	55	7.58	0.0012
%Maintained grass	0.0085	1	55	51.45	<0.0001
%Un-maintained grass	0.0064	1	55	18.28	<0.0001
%Herbaceous cover	-0.0015	1	55	6.00	0.0175
Dbh	0.0134	1	55	15.00	0.0003
Laurel oak (*Quercus laurifolia*) N=76					
Effect	Estimate	Nm DF*	Den DF*	F value*	Pr>F*
Land use forest	-0.1471	3	71	19.07	0.0324
Land use institutional	-0.0974	3	71	19.07	0.0324
Land use residential	0	3	71	19.07	0.0324
Land use commercial	-0.1569	3	71	19.07	0.0324
Crown light exposure	0.0679	1	71	3.09	<0.0001
Water oak (*Quercus nigra*) N=62					
Effect	Estimate	Nm DF*	Den DF*	F value*	Pr>F*
%Un-maintained grass	-0.0158	1	59	8.46	0.0051
Crown light exposure	0.0646	1	59	14.56	0.0003

* Interpret as with numerator and denominator degrees of freedom (Nm DF and Den DF, respectively) the critical value of the F distribution (F-value) means the estimate is significant at the 5% level as determined by the p value (Pr>F).

Table 3-4. Test of fixed effects for model of mortality for hardwoods and softwoods in Gainesville, Florida from 2006 to 2009

Hardwood mortality #1					
Effect	Estimate	Nm DF*	Den DF*	F value*	Pr>F*
Trees per hectare	0.0058	1	63	18.40	<0.0001
Hardwood mortality #2					
Effect	Estimate	Nm DF*	Den DF*	F value*	Pr>F*
Land use- forest	0.9478	3	61	3.74	0.0156
Land use- institutional	-1.0217	3	61	3.74	0.0156
Land use- residential	0	3	61	3.74	0.0156
Land use- commercial	-1.0862	3	61	3.74	0.0156
Softwood mortality					
Effect	Estimate	Nm DF*	Den DF*	F value*	Pr>F*
Trees per hectare	0.0072	1	63	5.03	0.0284

* Interpret as with numerator and denominator degrees of freedom (Nm DF and Den DF, respectively) the critical value of the F distribution (F-value) means the estimate is significant at the 5% level as determined by the p value (Pr>F).

Table 3-5. Annual mortality rates for the ten most common trees found in 2006 ranked by total number of trees

Rank	Species (Trees removed)	Annual mortality rate
1	*Quercus laurifolia*	4.67%
2	*Quercus nigra*	5.72%
3	*Pinus taeda*	3.55%
4	*Pinus elliottii*	1.14%
5	*Acer rubrum*	3.73%
6	*Prunus caroliniana*	6.89%
7	*Liquidambar styraciflua*	1.01%
8	*Nyssa biflora*	5.85%
9	*Gordonia lasianthus*	6.10%
10	*Celtis laevigata*	3.38%

Table 3-6. Test of fixed effects for model of in-growth for hardwoods and softwoods in Gainesville, Florida from 2006 to 2009

Hardwood in-growth					
Effect	Estimate	Nm DF*	Den DF*	F value*	Pr>F*
Trees per hectare	0.0047	1	63	14.08	0.0004
Softwood in-growth					
Effect	Estimate	Nm DF*	Den DF*	F value*	Pr>F*
Trees per hectare	0.0056	1	63	5.75	0.0194

* Interpret as with numerator and denominator degrees of freedom (Nm DF and Den DF, respectively) the critical value of the F distribution (F-value) means the estimate is significant at the 5% level as determined by the p value (Pr>F).

Table 3-7. Annual carbon sequestered per hectare (CSPH) and city total (CSCT) estimates by land use and land cover for trees in Gainesville, Florida from 2006 to 2009

Land Use	CSPH (kg/ha)	CSCT (tons)	Land cover	CSPH (kg/ha)	CSCT (tons)
Commercial	399	557	Forest	402	1278
Forest	379	1106	Urban	434	3801
Institutional	-195*	-619*	Park	1290	983
Residential**	955	4973			
Grand Total	479	6082		479	6082

*Carbon emitted though removals exceeded carbon sequestered through growth;
**Includes plots on vacant and residential areas.

Table 3-8. Top four species ranked by frequency and top six species ranked by highest average growth rate (AGR) and standard error (SE), with corresponding carbon sequestration per hectare (CSPH) and city total (CSCT) estimates for trees in Gainesville Florida from 2006 to 2009

Rank	Species (Number of trees)	AGR (cm/yr)	SE	*CSPH (kg/ha)	*CSCT (tons)
By Frequency					
1	*Quercus laurifolia* (76)	0.84	0.17	-34	-428
2	*Quercus nigra* (62)	0.90	0.28	91	1155
3	*Pinus elliottii* (62)	0.84	0.18	3	38
4	*Pinus taeda* (57)	0.53	0.12	-6	-76
By growth rate					
1	*Juniperus virginiana* (4)	1.69	0.51	10	127
2	*Lagerstroemia indica* (12)	1.66	0.49	15	190
3	*Quercus virginiana* (16)	1.33	0.51	136	1727
4	*Celtis laevigata* (20)	1.13	0.43	2	5
5	*Ostrya virginiana* (5)	1.00	0.38	-1	-13
6	*Acer rubrum* (36)	1.00	0.38	-20	-254
10	*Liquidambar styraciflua* (35)	0.64	0.26	42	533
12	*Cinnamomum camphora* (19)	0.51	0.17	13	165

* Negative values represent carbon emissions due to removals

Table 3-9. Annual removed above ground fresh weight biomass per hectare (RBPH) and city total (RBCT) estimates by land use and land cover in Gainesville, Florida from 2006 to 2009

Land Use	RBPH (kg/ha)	RBCT (tons)	Land cover	RBPH (kg/ha)	RBCT (tons)
Commercial	14	20	Forest	2230	7080
Forest	2203	6435	Urban	3714	32546
Institutional	6712	21311	Park	835	636
Residential	1708	8894			
Grand Total	2739	34785		2739	34785

*Carbon emitted though removals exceeded carbon sequestered through growth

Table 3-10. Annual removed above ground fresh weight biomass per hectare (RBPH) and city total (RBCT) for species comprising 90% all removed biomass in Gainesville, Florida from 2006 to 2009

Species	RBPH (kg/ha)	RBCT (tons)
All trees	314	3888
Quercus laurifolia	118	1499
Pinus taeda	73	927
Acer rubrum	50	635
Platanus occidentalis	21	266
Pinus elliottii	13	165
Quercus nigra	8	102

Table 3-11. Carbon stored in 2009 per hectare (CSTPH) and city total (CSTCT) estimates by land use and land cover in Gainesville, Florida

Land Use	CSTPH (kg/ha)	CSTCT (tons)	Land cover	CSTPH (kg/ha)	CSTCT (tons)
Commercial	7411	10353	Forest	32839	104263
Forest	33256	97141	Urban	12111	106129
Institutional	13306	42246	Park	29197	22248
Residential**	15688	81687			
Grand Total	18264	231953		18264	231953

*Carbon emitted though removals exceeded carbon sequestered through growth;
**Includes plots on vacant and residential areas

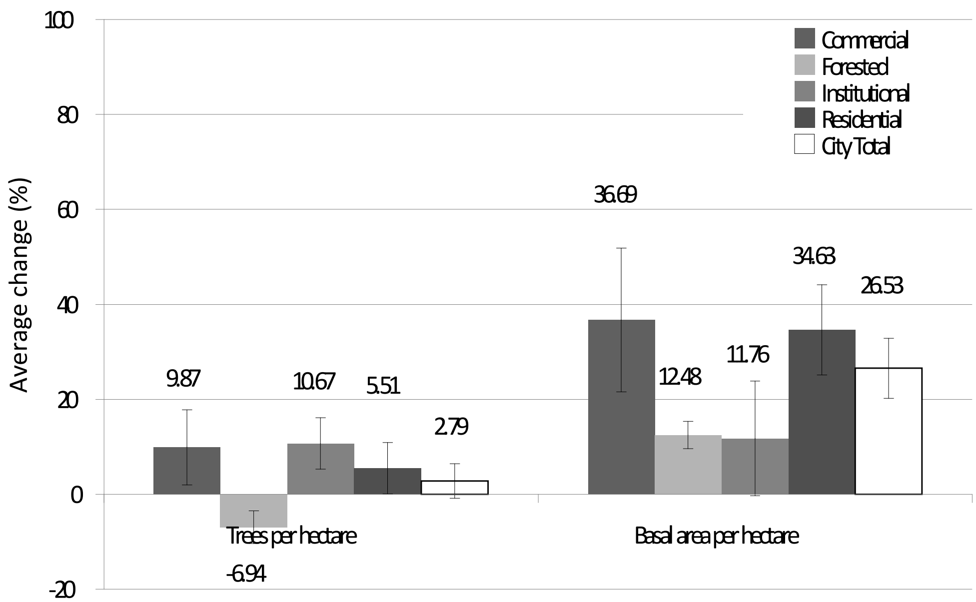

Figure 3-1. Average percent change in trees per hectare and basal area per hectare by land use and city total for Gainesville, FL from 2006 to 2009

CHAPTER 4
CONCLUSION

Growth rates presented in this study should be appropriate to apply to urban trees in other cities with growing conditions similar to Gainesville. Using this study's local growth rates in urban forest functional models would reduce bias and variance in the resulting carbon estimates for Gainesville. My results indicate that mortality rates were similar by size class and land use to a similar permanent-plot re-measurement study in Baltimore, Maryland (Nowak et al. 2004). Based on the re-measurement of permanent plots, Gainesville trees were estimated to have an average annual mortality rate of 1.8%. Of the 755 trees in our sample in 2006, by 2009, 128 (17%) trees had been removed. Plot and tree level characteristics combined can be used to estimate diameter growth as found in all growth models except the M growth model.

This study provides information on how site characteristics affect growth in trees common to Gainesville, Florida according to their different size and potential age. In *Pinus elliottii* and LL models, maintained grass was significant in enhancing growth while in the LM model, un-maintained grass was a significant factor. In addition, crown characteristics were often significant in my growth models. For example, characteristics such as average crown width, percent missing foliage, and tree height were significant factors in 6 out of 7 growth models while CLE was significant in 4 of the 7 growth models. These results could be used to develop urban tree planting strategies, such as selecting crown size and available light source as important factors to facilitate tree growth. Maintained grass (as an alternative to other ground cover vegetation types) might enhance growth because it does not compete for light and may be associated with maintenance activities that contribute to the growth of surrounding trees such as irrigation, fertilization, and edging of new vegetation or vines that can grow around a tree. Although extra resources will be spent on maintaining grass, benefits associated with enhanced tree growth might contribute to offsetting these disadvantages.

This study also provides green waste estimates for Gainesville by type and quantity as well as where it is being generated and where it is being stored as biomass. Higher growth rates found in Gainesville than those from previous studies used for estimating tree growth and carbon sequestration reveal the possibility that projected estimates in Gainesville might be underestimated. Carbon sequestration through growth was higher in residential plots (which include vacant areas) while removed biomass potential was greatest on institutional plots. Carbon stored in urban trees was higher in residential areas than institutional or commercial.

Suggestions for selecting trees based on their functional ability to store and sequester carbon can also be inferred from these results. Although only a small sample of *Quercus virginiana* was analyzed, its sequestration rate was the highest and growth rate was third highest over the other species examined in this study. This study highlights that both *Quercus virginiana* and *Quercus nigra* provide the benefit of being a large and sustainable potential sink for carbon in Gainesville's urban forest while *Quercus laurifolia* is the largest source of carbon emissions due to tree removals.

Urban forests need to be managed in a way that enhances their secondary carbon dioxide reduction functions of conservation and avoidance of building energy usage though reduced ambient air temperatures and shading by trees and decreased need for energy from fossil-fuel-based power plants (Hesiler 1986, Nowak 1993a, Simpson & McPherson 2001, Akbari 2002, Pandit & Laband 2010). The primary carbon dioxide emission reduction functions (carbon storage and sequestration in biomass through growth) can surpass the emissions produced through tree maintenance activities and emissions produced by decomposition of dead and removed trees (Nowak et al. 2002). Regional difference in energy savings from trees near buildings can differ based on differences in emission factors, building construction, climate, tree sizes and growth rates (Simpson & McPherson 2001). In the summertime, large and dense shade trees in energy-saving locations (close proximity to buildings particularly on southwest, west or east side of a building) can significantly reduce energy consumption (Simpson & McPherson 2001, Pandit & Laband 2010). The benefits from urban trees will continue to improve the quality of life in cities if the factors that affect their growth and mortality are better understood and applied urban tree management.

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BIOGRAPHICAL SKETCH

Throughout her education, Alicia Lawrence's personal goal was to contribute to the research and conservation of the natural resources of Florida, her home state. After high school in Venice, FL, she studied agricultural and biological engineering with a focus in land and water resources at the University of Florida. Later her interests shifted towards the courses she enjoyed the most in natural sciences and graduated in the fall of 2007 with a Bachelor of Science in forest resources and conservation as a Natural Resource Conservation Major with a focus in forest hydrology. In 2008 she began a Graduate Research Assistantship where she collected soil field measurements in Miami-Dade County, Florida, established permanent tree and vegetation plots in Pensacola Florida, and relocated and re-measured permanent urban forest plots in Gainesville, Florida. She also analyzed urban forest data from Houston, Texas to assess the effects of Hurricane Ike. She received her Master of Science in forest resources and conservation in the summer of 2010.