DISSERTATION

CARBON STORAGE IN URBAN FORESTS ALONG THE COLORADO FRONT RANGE: AN ANALYSIS OF URBAN TREES IN CARBON CREDIT MARKETS AND THE ALLOMETRIC RELATIONSHIPS FOR DETERMINING URBAN FOREST BIOMASS

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WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY MELISSA R. MCHALE ENTITLED “CARBON STORAGE IN URBAN FORESTS ALONG THE COLORADO FRONT RANGE: AN ANALYSIS OF URBAN TREES IN CARBON CREDIT MARKETS AND THE ALLOMETRIC RELATIONSHIPS FOR DETERMINING URBAN FOREST BIOMASS” BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

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ABSTRACT OF DISSERTATION

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Urbanization is increasing globally with a majority of the world's population living in or around urban centers. It has been shown that a change in regional carbon dynamics occurs with urbanization, and that in semi-arid and arid systems, net primary productivity is stimulated. Urban trees are a potentially large carbon storage pool, but their significance is unknown.

Urban tree planting has been recognized as a possible element of carbon mitigation schemes. I used a modeling approach to investigate the cost effectiveness of these projects. I found that some urban tree projects could be cost effective in carbon markets at this time and carbon assimilation rate has the largest influence on cost effectiveness.

Urban forest studies have been limited by a lack of information on urban tree allometry. I collected volume data using LiDAR for 11 dominant species in Fort Collins, Colorado and developed allometric equations. I compared my volume estimated to volume equations developed for California's urban trees. Volume equations developed for urban trees outside of Colorado did not accurately predict urban tree volume in Fort Collins.

I conducted a sensitivity analysis to determine how important it is to use allometric relationships developed specifically for urban trees when quantifying biomass. A few equations developed for traditional forest trees predicted similar biomass to urban-based predictions, but predictions for individual trees varied by over 200%. Although relative variability declined when I scaled up to a community of street trees, these results indicate that it is important to develop allometric relationships specific for urban areas to accurately quantify carbon storage of urban trees.

Finally, I quantified potential carbon storage capacity of Front Range urban forests. My results show that mature, high-density urban forests can store as much carbon as the most productive forests in Colorado. Furthermore major cities along the Front Range cover only 1% of the land area in Colorado, but contain 55% of the human population. Colorado cities can potentially store 1-26 million tonnes of carbon in their lifetime, but that is only enough to offset local carbon emissions for three years.

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Chapter 1: INTRODUCTION TO THE DISSERTATION

Urbanization is a major contributor to global environmental change and can significantly alter regional carbon dynamics (Pataki et al. 2006). In North America, studies have shown a decline in existing carbon storage pools following urbanization, however in semi-arid and arid environments, urbanization can increase carbon storage capacity (Imhoff et al. 2004; Kaye et al. 2005; Golubiewski 2006). Humans supplement the amount of water and nutrients available to plants in these areas, increasing net primary productivity, and also change the species composition and structure from native systems to predominantly introduced horticultural species. Along the Colorado Front Range, one of the fastest growing metropolitan regions in the United States (US census 2000), urbanization represents a conversion of the native shortgrass steppe, a system dominated by grasses, to one composed of lawns and non-native herbaceous and woody vegetation.

Woody vegetation in particular can be a significant carbon storage pool along the Front Range, and its importance tends to increase with urban forest maturity (Kaye 2005; Golubiewski 2006). In urban areas, trees have been one of the most well studied organic carbon pools (Pataki et al. 2006) and studies have shown that generally urban forests store about half as much carbon as native forests (McPherson 1998). Urban trees can also reduce atmospheric CO_2 concentrations by affecting energy usage (Rowntree and Nowak 1991; Nowak 1993; McPherson 1998). When trees are close to buildings they directly reduce energy usage by shading or blocking wind. A community of trees can indirectly influence energy savings through climate effects; they keep cities cooler in the summer due to shade and transpiration, and warmer in winter by blocking wind

(McPherson and Simpson 2001, Jo and McPherson 2001). Because of the direct and indirect effects of urban trees on atmospheric carbon dioxide concentrations community foresters have been considering whether urban tree planting projects can be funded through carbon markets, particularly since carbon trading is now internationally accredited.

However, there is a potentially major issue with most of the analyses on the carbon storage capacity of urban trees: they lack direct measurement of urban tree allometry and biomass (Pataki et al, 2006; McPherson and Simpson 2001). In fact, most studies that quantify the benefits and costs associated with urban trees and their management use allometric equations to predict biomass that were developed for trees in traditional forests. Only one published study (Pillsbury et al. 1998) developed allometric equations for urban trees, and that was located in California.

In this dissertation, my goal was to address some of the key issues that have been lacking in the field of urban forestry research. My objectives were to: 1) Analyze the cost effectiveness associated with urban tree planting projects; 2) develop allometric volume equations for 11 dominant tree species; 3) test the importance of using urban-based allometric relationships vs. allometric relationships associated with traditional forest trees in estimating biomass; and 4) estimate the potential carbon storage capacity of urban forests along the Colorado Front Range. These objectives are addressed in the following four chapters. Each chapter was originally written as a manuscript for submission to peer-reviewed journal and therefore contains its own abstract, introduction, methods, results, discussion and references.

There have been some misunderstandings associated with the definitions for the terms urban, municipal, natural and traditional forests. In this dissertation an urban forest is a forest that is grown in an area dominated by humans and development, sometimes called a community forest to separate the term from strict definitions associated with the word urban. A municipal forest is an urban forest that is maintained by the municipality, and refers to street and park trees that are owned by the local government. I use traditional and natural forest interchangeable throughout this dissertation to distinguish forests that are in areas that are not dominated by humans and this can mean a forest that is in a natural area or even a forest that is maintained for harvesting lumber.

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Chapter 2: THE POTENTIAL OF URBAN TREE PLANTINGS TO BE COST EFFECTIVE IN CARBON CREDIT MARKETS

Abstract

Emission trading is considered to be an economically sensitive method for reducing the concentrations of greenhouse gases, particularly carbon dioxide, in the atmosphere. There has been debate about the viability of using urban tree plantings in these markets. The main concern is whether or not urban planting projects can be cost effective options for investors. I compared the cost efficiency of four case studies located in Colorado, and used a model sensitivity analysis to determine what variables most influence cost effectiveness. I found that some urban tree planting projects can be cost effective investments at this time. Our modeling results suggest that carbon assimilation rate, which is mainly a function of growing season length, has the largest influence on cost effectiveness, however resource managers can create more effective projects by minimizing costs, planting large-stature trees, and manipulating a host of other variables that affect energy usage.

Key Words: Carbon dioxide; carbon credits; urban trees; emissions trading; global climate change; cost effective

Introduction

Concerns over global climate change have led to an increased interest in reducing atmospheric carbon dioxide (CO_2) concentrations. Advocates for economically sensitive methods for reducing CO_2 emissions have proposed carbon credit trading as an option (Zhang and Folmer 1995; Ellerman et. al. 1998; Petty and Ball 2001). Carbon credit trading allows industries that cannot feasibly reduce CO_2 emissions to buy credits (each worth one metric ton, or tonne, of CO_2) from industries that have reduced their emissions more than the level required. In theory, the market is an economical approach for some industries because it would cost more for them to reduce emissions than to buy credits. Companies can also choose to invest in reforestation projects that remove CO_2 from the atmosphere. In voluntary markets, this is typically called a 'reduction' rather than a 'credit', but units are still measured in tonnes of CO_2. Similarly, when other greenhouse gases are reduced (methane, nitrous oxide, sulfur hexafluoride, CFC's, and PFC's), 'carbon equivalents' can be earned and traded.

The first emissions trading systems were established in 2000 (Petty and Ball 2001) and on February 16, 2005 the Kyoto Protocol officially took effect, establishing internationally accredited emissions trading. At this time the United States has not signed this treaty that requires ratifying nations to reduce greenhouse gas emissions below 1990 levels; however the treaty is endorsed worldwide, and many US companies with international markets are affected by its implementation.

Community foresters have been considering whether urban tree planting projects can be funded through carbon markets, particularly since carbon trading is now internationally accredited. Tree planting has been considered a method for reducing atmospheric CO_2 because trees sequester CO_2 and store carbon in their biomass through the process of assimilation (Trexler 1991). Many studies show that urban trees can also reduce atmospheric CO_2 concentrations by affecting energy usage (Rowntree and Nowak 1991; Nowak 1993; McPherson 1998). When trees are close to buildings they directly affect energy usage by shading or blocking wind. Trees indirectly influence energy savings through climate effects; they keep cities cooler in the summer due to shade and transpiration, and warmer in winter by blocking wind (McPherson and Simpson 2000, Jo and McPherson 2001).

Although urban trees affect atmospheric CO_2 concentrations in these two ways and it is often assumed that they should be viable for carbon credit trading, there are more requirements involved in trade agreements. Carbon credit projects must be marketable, quantifiable, and cost effective. Investors further require evidence that the atmospheric carbon reduction would not be viable without their support.

The proliferation of tools available to quantify the benefits provided by urban trees is an indication of their marketability. Recent studies have shown that urban trees provide net benefits to communities through reducing atmospheric CO_2 concentration, improving air and water quality, and increasing real estate values, as well as providing many social and psychological benefits for residents (Dwyer et. al. 1992; McPherson et. al. 1997, 1999, 2003). Because urban trees, especially those on city property, are managed and easily assessed, the carbon assimilated by these trees is inherently quantifiable. Estimating reduced emissions associated with climate related energy saving is more difficult to measure, but if in question can be considered a supplementary benefit. Also, most community forestry programs are monetarily limited and continually have to compete for funding with other departments within a city, so the associated atmospheric carbon reduction would be directly attributable to assistance provided by investors. Tree maintenance is often a higher priority than planting since the city is accountable for damages associated with lack of tree care, further limiting funding for planting.

The main concern regarding the viability of urban tree planting projects is whether such projects are cost effective investments. Understanding which variables most influence cost effectiveness can assist us in determining, whether management decisions or uncontrollable variables such as climate are playing a larger role in determining a tree planting projects viability in carbon credit markets. It is also important for community foresters to know how they can potentially create more cost effective tree planting projects; even if planting projects do not reach the market, this information is useful for city governments that are voluntarily accounting for total carbon gains and losses, and trying to minimize emissions from the community.

Our goal in this paper is to use a model sensitivity analysis to assess the cost effectiveness of urban tree planting projects. Our key questions are: 1) can urban tree planting projects be cost effective investments?, and 2) which variables influence the cost effectiveness of these projects? A host of social factors influence the range of real world values for the variables in the model; therefore, in this study I also aim to compare empirical case studies with potential cost effectiveness quantified in a sensitivity analysis.

Methods

The Model

The model "Carbon Dioxide Reduction Through Urban Forestry" (McPherson and Simpson 2000) consists of a series of calculations that predict (1) total monetary costs, (2) total carbon storage, and (3) reduced energy related carbon emissions over a 40 year period (Figure 2.1). These output variables are calculated within the model to determine total cost/tonne of atmospheric CO_2 reduced, and are dependent on input variables for a specific tree planting project. Some input variables are a function of regional factors such as climate, while others are dependent on a local community, or specific decisions by resource managers (Figure 2.1). I classified the input variables into these three main categories for the purpose of this analysis, to assess not only which variables affect cost effectiveness, but also which variables may be manipulated in future tree planting projects. Below, I describe the model using these classifications of input variables for the purpose of providing context for our sensitivity analysis; the full model is explained in detail in McPherson and Simpson 2000).

Default Values for the Input Variables

The model was created to help resource managers quantify the cost effectiveness of tree planting projects in their communities (McPherson and Simpson 2000). Since many of the input variables may be unknown or difficult to determine, default values for these variables are available with the published model; these are suggested by the authors for use when the real values are unknown. The U.S. is divided into 11 representative climate regions based on heating degree days, cooling degree days, latent enthalpy hours, and the ratio of average global horizontal radiation to average extraterrestrial horizontal radiation; default values for all input variables are based on average conditions in each of the 11 climate regions, except for assimilation, decomposition and maintenance rates which are set at a value that is a function of three main tree growth regions.

Input variables influenced by growth region

In this model, the United States is split into three main growth regions based on mean length of frost free periods: North, Central, and South regions have <180, 180-240, and >240 frost free days respectively (McPherson and Simpson 2000). The model includes suggested input values for assimilation, decomposition, and maintenance rates for each of these growth zones. Typically, a user will input default rates assigned to each growth zone because these numbers are a result of complex processes and are difficult to measure, however, different rates can be used. Default assimilation rates for large, medium, and small stature deciduous and evergreen trees were determined by McPherson and Simpson (2000) based on growth curves and biomass equations from the literature with the input of expert reviewers. The southern growth region has the highest assimilation rates per year for all tree types due to a longer growing season (Table 2.2).

In this model, McPherson and Simpson (2000) conservatively estimated that all trees removed from urban areas are converted to mulch and decompose rapidly, with up to 80 percent of the carbon being re-released into the atmosphere within a year. Although this may be a weak assumption, they note that there is little research in this field of urban forestry and based their estimate on research by Melillo and others (1989) that showed after four years, 80 percent of red pine needle litter was gone. In the model, decomposition rates are highest in the southern growth zone because decomposition tends to increase with temperature and temperatures remain higher in this region for a longer period of time. Note that here, decomposition rate is considered as a constant input variable based on growth region (Table 2.2); however, total annual decomposition is also a function of mortality rate and mature tree size. These other input variables are explained in more detail in the section that describes variables influenced by management decisions.

Maintenance rate is representative of the amount of CO_2 emissions associated with tree care activities. Default maintenance rates for each growth region were determined by a survey of wholesale nurseries, non-profit tree programs and municipal forestry programs (McPherson and Simpson 2000).

Both decomposition and maintenance rates are considered regionally based variables for the purpose of this analysis, however both of these rates can be managed for as well. Decomposition rates supplied in the model may be conservative estimates for advanced urban forestry programs that implement different methods for disposing of dead tree biomass, such as using the material for furniture or other building materials. Maintenance rates are highly variable among various urban forestry programs, however are typically only a small percentage of total carbon emissions (McPherson and Simpson 2000), but again these estimates could be very different for programs that implement atypical management regimes. Furthermore, separating the US into three tree growth regions is an oversimplification, but allometric equations and detailed research on urban tree growth rates across the country are lacking. Overall this approach, even with some broad simplifications, allowed me to understand the variance in cost effectiveness associated with broad climate regimes and potentially capture the spectrum of tree growth and management in the US.

Locally Dependent Input Variables

Local conditions, like existing tree cover, affect how much more added benefit a local community receives from additional trees. Default existing cover values for reference cities in the model range from 3-67%. The age of buildings (pre-1950, 1950-1980, and post-1980) building size (condition floor area ranging from 90.6 to 206.2 m^2), and heating and cooling equipment type (central air conditioning, evaporative cooler, room air conditioning, natural gas, electrical resistance, heat pump, fuel oil, or other heating sources) are all input variables associated with potential energy savings (Figure 2.1). Locally dependent input variables are generally dependent on conditions within a community, however some of them may at times also be considered management based variables since managers can choose to plant trees around the least energy efficient buildings in a neighborhood. The electricity emissions factor is determined by the type of fuel used by the local electricity supplier. For instance, in the model more CO_2 is released per unit of energy from coal than from natural gas. State and regional electricity emissions factors are supplied with the model and range from 0.0722 t CO_2/MWh for Vermont to 1.0456 t CO_2/MWh for North Dakota.

Management Based Input Variables

Management decisions can directly affect all three output variables associated with cost effectiveness (Figure 2.1). Total monetary costs include planting and maintenance costs combined over a 40 year period. These costs are influenced by the type and age of trees planted, how often the trees are watered, pruned, or fertilized, and whether or not volunteers are involved in these processes. Mature tree size (large>15m, medium=10-15m, small<10m) and tree type (evergreen vs. deciduous), directly control the maximum potential carbon storage; larger growing trees contain more biomass and generally half of biomass is carbon (Leith 1975). Furthermore, survival rate affects how much of the carbon stored becomes dead tree biomass and is returned to the atmosphere as CO_2 (Table 2.3). In addition to mature tree size, survival rate, and tree type, the placement of trees (azimuth and distance relative to a building) also affects energy related reductions. In the model, 24 different tree locations relative to buildings affect energy usage: N, NE, E, SE, S, SW, W, NW, at three different distances of 3-6, 6-12, and 12-18 meters.

Output Variables

Input variables are entered into the model, but these values interact within the model for the final calculation of atmospheric CO_2 reduced per total cost. Within the model, total monetary costs are calculated by simply adding the planting and maintenance costs over time; however, calculations for the other output variables, total carbon storage and energy related emissions, are more complicated (Figure 2.1). For instance, the output variable total carbon storage equals the amount of carbon stored in the trees through the process of assimilation, minus the amount of carbon lost through decomposition and maintenance emissions. I input rates of assimilation, decomposition, and maintenance, but the amount of total carbon stored and lost is also a function of mature tree size, survival rates, and whether the trees were deciduous or evergreen (Figure 2.1).

Energy related emissions reduced are associated with local shade and windbreak effects, as well as over climate effects. Only trees that are closer than 18 m are assumed to have a direct effect on building energy usage, while all trees have an impact on the general climate. Energy simulation data included as part of the model were calculated using Micropas 4.01 (Enercomp 1992) and the Shadow Pattern Simulator (SPS) following methods from Simpson and McPherson (1998) and McPherson and others (1985).

Sensitivity Analysis

I created a representation of the model in an excel spreadsheet and manipulated each input variable independently. Maximum and minimum default values published with the model were input individually into the spreadsheet while all other input variables were held constant (Table 2.1). In this part of the analysis, total monetary cost was held constant; therefore cost effectiveness is solely a function of the amount of atmospheric CO_2 reduced.

Case Study Analyses

I analyzed the cost effectiveness of four proposed tree planting projects in Colorado. In the model, Colorado is a part of the northern growth zone, and due to the short growing season, we expected this to be one of the least cost effective areas. The reference city for the supplied default values in the Rocky Mountain region was Denver, which was the first of our case studies (Table 2.4). In a second case study I evaluated an actual tree planting project in a small Denver neighborhood, called Whittier. In the other two case studies, I evaluated proposed tree planting projects in Fort Collins and Grand Junction. The Fort Collins planting consisted entirely of street trees that were in close proximity to neighboring houses, and the planting project in Grand Junction was planned for the surrounding park system. These case studies were representative of a range of potential urban tree planting projects in Colorado. In instances where variables were unknown for an area the default values for Denver were used (Table 2.4).

Results and Discussion

The Sensitivity Analysis

Assimilation rate, a variable controlled by regional growth zone, had the most influence on a project's cost effectiveness (Figure 2.2). Essentially, areas with a longer growing season (>240 days) demonstrated a greater chance to develop cost effective projects. The assimilation rates used in this model were generalized and for this reason tree growth and biomass should be more accurately quantified over time in future established carbon credit projects.

A locally dependent variable, existing tree cover, was next most important (Fig 2.2). The effects on microclimate and energy usage of additional tree cover diminished as the percent of existing cover increased. The effects of tree cover exceeded those of other variables by 100% or more, but it was only important in planting projects where energy savings were quantified. Although when tree cover is high it could have an affect on assimilation rate due to increased tree competition for light and other resources, this model did not take those effects into account.

Mature tree size was the third most important variable influencing cost effectiveness; larger-stature trees stored more carbon and had a greater effect on the surrounding microclimate than smaller trees. Studies show that large growing trees actually provide more storm water runoff reduction and air quality benefits to a community than small trees (Dwyer et. al. 1992; McPherson et. al. 1997, 1999, 2003) so favoring large trees is a positive management strategy, assuming space and resources are available.

The equipment used to keep homes cool in the summer, building age, carbon dioxide emissions associated with the electricity supplier, and building size were moderately important variables in the model and all were dependent on the locality of the tree planting project (Figure 2.2). These variables also all influenced energy usage; larger homes, older homes, and homes that have central air conditioning required the most energy to keep cool in the summer. Therefore trees shading these types of buildings had an increased effect on energy usage. Also, if I modeled the situation such that the local electricity supplier used coal as a fuel source, there was more carbon emitted per unit energy used than if a cleaner source such as wind was available. This means that more carbon will be reduced from future plantings in areas that use less efficient energy sources. However, it is important to note an effective strategy for offsetting fossil fuel emissions could be using trees planted as part of carbon credit projects as an energy source.

Decomposition rate, another variable influenced by growth zone, was a moderately influential variable. It is important to note that the rates used were highly conservative. The underlying assumption was that 80 percent of all dead tree biomass was immediately released into the atmosphere through decomposition. Although decomposition rate was a function of growth zone in the model, future planting projects designed for carbon credit markets can manipulate this high rate of decomposition by dedicating removed trees to other more slowly decomposing resources such as furniture.

Survival rate, distance and azimuth of trees relative to buildings, and tree type had smaller impacts on cost effectiveness, but if managed for in future projects, these variables together could potentially influence cost effectiveness. Maintaining the highest survival rates and strategically planting trees where they have more influence on energy usage can make a project more effective. Trees planted closer than 15m directly affected building energy usage, but if they were located E, SE, S, or SW relative to a building there were more negative energy effects in winter. This point is particularly important for communities with a short growing season, where the negative winter effects will be quantified over a longer period of time. Trees located farther than 15m still affected energy usage by changing the local microclimate, and these effects were generally positive.

Trees did not have the same effect on energy consumption in the winter as in the summer, therefore effects of evergreen trees serving as windbreaks and the type of equipment used to heat homes provided less energy related benefits than shade trees in the summer or the cooling equipment in homes (Figure 2.2). According to the model, maintenance emissions were a function of growth zone and had little impact on cost effectiveness, however studies have shown that over time maintenance emissions can significantly reduce the CO_2 mitigation potential of urban forests (Nowak et. al. 2002). The fraction of shade a tree provided for neighboring homes hardly impacted the results at all, and may be overlooked in future analyses.

Case Study Analyses

In these analyses I modified all input variables, including monetary costs. Of the four case studies in Colorado, the Denver study, consisting entirely of model supplied values, was the most cost effective ($145/tonne) (Table 2.5). Cost effectiveness was directly related to planting and maintenance costs over a 40 year period, and reported on a per tree basis, Denver had the lowest costs ($100/tree as opposed to $116, $200, and

$570 per tree for Whittier, Grand Junction and Fort Collins respectively). Fort Collins was the least cost effective case study and also had very high planting and maintenance costs. The estimated costs were higher in this study for a few reasons. First, the city's planting spaces were in the right of way (ROW) where only large caliper trees, that cost more, survive well. Second, the city pays staff to plant trees, as opposed to Whittier, which included volunteers to reduce costs. Third, I estimated high maintenance costs for Fort Collins because of the intensive management practices associated with the safety and appearance of street trees.

When I analyzed the case studies according to the amount of carbon stored or CO_2 emissions saved on the per tree basis, the Fort Collins tree planting would actually contribute the most at the end of a 40 year period (0.9 tonnes of CO_2/tree), however, all the case studies were very similar; 0.6, 0.7, and 0.8 tonnes of CO_2 per tree for Whittier, Denver, and Grand Junction. The small difference was attributable to energy related effects; when we removed these effects, and only accounted for tree growth, maintenance, and death and decomposition, all four case studies had a net assimilation rate equal to 0.3 or 0.4 tonnes of CO_2 per tree over a 40 year period.

Trees can have both direct and indirect effects on energy savings. The balance between the direct (shade) and indirect (climate) energy effects determined the overall contribution of energy effects to each study (Figure 2.3). The direct effects were not necessarily a positive contribution to net carbon saved by tree planting projects in Colorado. Where summers are short and winters are long, trees can increase heating costs more than they decrease cooling costs. In all of the case studies this was the tendency, except in Grand Junction where direct shading effects were non-existent because trees were located too far from buildings (Figs. 3 and 4). In the Denver analysis, direct shading effects were not as negative as the other studies because trees around buildings were in more ideal locations (Figure 2.3) and the positive effects associated with shading in the summer outweighed the negative winter effects (Figure 2.4).

Climate effects were high in the Denver case study (Figure 2.3), which was mostly a function of the large number of trees associated with this study. On the per-tree basis, all of the case studies had greater climate effects than the Denver study (0.66 tonnes CO_2/tree for Fort Collins and Whittier, 0.47 tonnes CO_2/tree for Grand Junction and 0.42 tonnes CO_2/tree for Denver). Climate effects were influenced by the percent cover of buildings and trees existing in an area as well as the mature size of the trees planted. A high percentage of trees in both the Fort Collins and Grand Junction plantings were large because Fort Collins is not limited by overhead wires or small planting spaces, and in Grand Junction the plantings were planned for parks.

The Case-Studies in Today's Carbon Credit Market

None of the Colorado case studies were cost effective enough to compete in today's carbon credit markets. At this time, rates in active markets range from \$3 to \$13 (www.CO2e.com) and all of these studies significantly exceeded that range in costs by \$100 or more (Table 2.5). Furthermore, if energy effects were not accounted for, cost efficiency decreased (Table 2.5).

However, a more in depth analysis of the Denver case study shows that it is not impossible for an urban tree planting project to be cost effective and perhaps even a competitive program according to today's market standards. If the Denver case study had the assimilation rate associated with the southern growth zone then the cost/tonne CO_2

was reduced to \$33. On the other hand, if the Denver study consisted of only small trees, the cost/tonne CO_2 would increase to \$1051. This huge variation created by simply changing one variable in this analysis verified that the cost effectiveness of urban tree planting projects is highly dependent on location and management decisions. Although \$33 dollars a credit is still higher than average rates in markets today, this lower rate was achieved by changing only one variable; if the Denver study was in the southern growth zone and consisted of all large trees then the cost decreased even more to \$23/tonne. Furthermore, buyers in voluntary markets have been paying relatively higher prices for credits and are willing to pay more for credits associated with highly sustainable, socially beneficial projects (www.CO2e.com).

Highly variable costs have also been found for rural based carbon offset projects. The estimated costs per tonne of CO_2 sequestered for converting agricultural land to forests throughout the eastern United States has been found to range from \$10-\$400 per tonne (Brown et. al. 2005, Walker et. al. in press). The variability is dependent on the length of afforestation, the costs associated with planting and project development, and most significantly opportunity costs, or the earning potential lost from the conversion of land from agriculture to forest. Most of the urban case studies in this analysis also fall within that range, which shows that urban projects have competitive potential with other carbon offset projects.

Conclusion

There are several key decisions that forest managers can make to influence cost effectiveness. Although community forests are potentially acceptable and marketable solutions to storing CO_2, only very few, specifically designed urban tree planting projects would be cost effective at this time. My modeling results suggest that projects in the southern growth zone and/or projects that include energy related carbon benefits are more likely to be cost effective according to today's markets. As markets become established, credit prices are expected to increase, and foresters will have a better chance of fully funding tree planting projects in communities, as well as being able to monetarily manage those forests until maturity. Moreover, it is important to consider that there are other benefits associated with urban trees, and because of these added benefits, investors may be willing to spend more per credit than they would for other projects dedicated to only reducing atmospheric CO_2 concentrations.

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Tables

Table 2.1

Input variables for the model. The main model input variables are dependent on regional processes associated with growth zones, characteristics of local communities, or are affected by direct management decisions. The variables can have sequestration effects (direct assimilation effects) or effects on energy related emissions. Minimum and maximum values for each variable were used in the sensitivity analysis to determine which variables had the greatest influence on cost-effectiveness.

Variable	**Description**	**Dependence**	**Sequestration or Energy Effects**	**Max. Values**	**Min. Values**
Assimilation/ Sequestration	The rate trees assimilate carbon, which is dependent on growth rate.	Growth Zone	Sequestration	Rates associated with the southern growth zone (Table 2)	Rates associated with the northern growth zone (Table 2)
Decomposition	Expected decomposition rate of trees that do not survive.	Growth Zone	Sequestration	Rates associated with the southern growth zone (Table 2)	Rates associated with the northern growth zone (Table 2)
Maintenance	Amount of projected maintenance emissions.	Growth Zone	Sequestration	Rates associated with the southern growth zone (Table 2)	Rates associated with the northern growth zone (Table 2)
Percent Cover	The percent of building and tree cover already existing in the community.	Local Area	Energy	100 %	0 %
Building Vintage	The age of local buildings.	Local Area	Energy	All houses are built Pre-1950	All houses are built post-1980
Conditioned Floor Area	The size of local homes.	Local Area	Energy	206.2 m	90.6 m
Cooling Equipment Adjustment	The type of equipment used to keep buildings cool.	Local Area	Energy	All houses have central air	No houses have air conditioning
Heating Equipment Adjustment	The type of equipment used to heat local buildings.	Local Area	Energy	All houses use electrical resistance	All houses use natural gas
Electricity Emissions Factor	Carbon dioxide emissions associated with the local electricity supplier	Local Area	Energy	1.0456 tonnes of CO_2 /MWh	0.0722 tonnes of CO_2 /MWh

Mature Tree Size	How large the planted trees are expected to grow at maturity.	Direct Management Decisions	Both	All large stature trees	All small stature trees
Survival	Expected rate of survival of the trees planted.	Direct Management Decisions	Both	Maximum survival rate (Table 3)	Minimum survival rate (Table 3)
Near/Far	How close a tree is to buildings.	Direct Management Decisions	Energy	All trees are near homes (closer than 15m)	All trees are far from homes (further than 15m)
Shade Effects	Azimuth of deciduous trees serving to shade buildings in the summer.	Direct Management Decisions	Energy	Trees are distributed N, NE, NW, W	Trees are distributed E, SE, S, SW
Deciduous/ Evergreen	Number of trees that do or do not lose their leaves in winter.	Direct Management Decisions	Both	All trees are deciduous	All trees are evergreen
Wind Effects	Azimuth of evergreen trees serving as windbreaks for local buildings.	Direct Management Decisions	Energy	N, NE, NW, W	E, SE, S, SW
Shade Fraction	The fraction of shade a tree will provide a neighboring home.	Direct Management Decisions	Energy	100%	0%

Table 2.2

Assimilation, decomposition, and maintenance emissions at tree maturity, by growth zone for deciduous (D) and evergreen (E) trees of large, medium, and small stature. *This table was reproduced from *Carbon Dioxide Reduction Through Urban Forestry* (McPherson and Simpson 2000).

	Assimilation			**Decomposition**			**Maintenance**		
Tree type	North	Central	South	North	Central	South	North	Central	South
D Large	0.0428	0.1324	0.2937	-0.8754	-2.7107	-6.0188	-0.0051	-0.0078	-0.0106
D Med	0.0262	0.0665	0.1331	-0.5415	-1.3702	-2.7382	-0.0044	-0.0063	-0.0082
D Small	0.0055	0.0153	0.0321	-0.1138	-0.3148	-0.6618	-0.0025	-0.0037	-0.0049
E Large	0.0451	0.1204	0.3028	-0.5807	-2.4449	-6.3920	-0.0047	-0.0084	-0.0121
E Med	0.0073	0.0495	0.1049	-0.1912	-1.0598	-3.1392	-0.0032	-0.0066	-0.0100
E Small	0.0011	0.0126	0.0098	-0.0509	-0.2933	-0.8603	-0.0018	-0.0041	-0.0064

Table 2.3

Tree Survival Rates. Moderate, high and low survival rates for specific treeage intervals were used in the model analysis.

*This table was reproduced from *Carbon Dioxide Reduction Through Urban Forestry* (McPherson and Simpson 2000).

	Tree Age Intervals in Years							
	1-5	6-10	11-15	16-20	21-25	26-30	31-35	36-40
Moderate	0.75	0.71	0.68	0.64	0.60	0.56	0.53	0.49
High	0.85	0.83	0.80	0.78	0.75	0.72	0.70	0.67
Low	0.65	0.60	0.55	0.50	0.45	0.40	0.35	0.30

Table 2.4

Input variables associated with the four Colorado case studies.

	Denver	**Whittier**	**Grand Junction**	**Fort Collins**
Assimilation/ Sequestration	Northern Growth Zone (Table 2)	Northern Growth Zone (Table 2)	Northern Growth Zone (Table 2)	Northern Growth Zone (Table 2)
Decomposition	Northern Growth Zone (Table 2)	Northern Growth Zone (Table 2)	Northern Growth Zone (Table 2)	Northern Growth Zone (Table 2)
Maintenance	Northern Growth Zone (Table 2)	Northern Growth Zone (Table 2)	Northern Growth Zone (Table 2)	Northern Growth Zone (Table 2)
Percent Cover	56%	46%	56%	56%
Building Vintage	Pre-50: 42% 50-80: 48% Post-80: 10%	Pre-50: 80% 50-80: 20% Post-80: 0%	Pre-50: 42% 50-80: 48% Post-80: 10%	Pre-50: 42% 50-80: 48% Post-80: 10%
Conditioned Floor Area	Pre-50: 90.6 m 50-80: 100.3 m Post-80: 192.3 m	Pre-50: 180.7 m 50-80: 194.5 m Post-80: N/A	Pre-50: 90.6 m 50-80: 100.3 m Post-80: 192.3 m	Pre-50: 90.6 m 50-80: 100.3 m Post-80: 192.3 m
Cooling Equipment	Table 5	No cooling: 40% Room Air: 40% Evap. Cooler: 5% Central Air: 5%	Table 5	Table 5
Heating Equipment	Table 5	Natural Gas: 90% Other: 10%	Table 5	Table 5
Electricity Emissions Factor	0.908 tonnes of CO_2 /MWh	0.86184 tonnes of CO_2 /MWh	0.908 tonnes of CO_2 /MWh	1.002 tonnes of CO_2 /MWh
Mature Tree Size	Large: 49.5% Med: 36.5% Small: 14%	Large: 80% Med: 15% Small: 5%	Large: 75% Med: 0% Small: 25%	Large: 64% Med: 22% Small: 14%
Survival	Moderate (Table 3)	Moderate (Table 3)	Moderate (Table 3)	Moderate (Table 3)
Near/Far	Near = 50% Far = 50%	Near = 100% Far = 0%	Near = 0% Far = 100%	Near = 69% Far = 31%
Shade Effects	N=4%, NE=14%,E=29%, W=34%, NW=19%	N=24%, E=44%, S=11%, W=21%	Not applicable	N=21%, NE=13%, E=14%,SE=8%, S=14%, SW=8%, W=12%, NW=10%
Deciduous/ Evergreen	Dec: 90% Evr: 10%	Dec: 100% Evr: 0%	Dec: 75% Evr: 25%	Dec: 100% Evr: 0%
Wind Effects	N =4%, NE=14%,E=29%, W=34%, NW=19%	Not applicable	Not applicable	Not applicable
Shade Fraction	15%	15%	15%	15%

Table 2.5

Cost effectiveness of the four Colorado case studies with and without energy effects. *Denver and Whittier analyses did not include long term maintenance costs. The Grand Junction costs were an estimate of planting large caliper trees in parks, with a minimal amount of maintenance costs associated with short term watering. Fort Collins predicted significant maintenance costs associated with old and large street trees throughout 40 years of growth. The costs for these projects were only estimates, except for Whittier where we analyzed the project after it was completed.

	Trees Planted	Total Cost*	Net CO_2 Saved (metric tonnes) (w/energy effects)	**Cost/t (w/ energy effects)**	Net CO_2 Saved (metic tonnes) (w/o energy effects)	**Cost/t (w/o energy effects)**
Denver	10,000	$100,000	6890	$145.10	2883.6	$346.79
Whittier	232	$27,100	134.5	$201.50	84.9	$319.20
Grand Junction	460	$92,000	362.6	$253.70	150.3	$612.11
Fort Collins	1415	$807,000	1246.8	$647.26	632.1	$1276.70

Figures

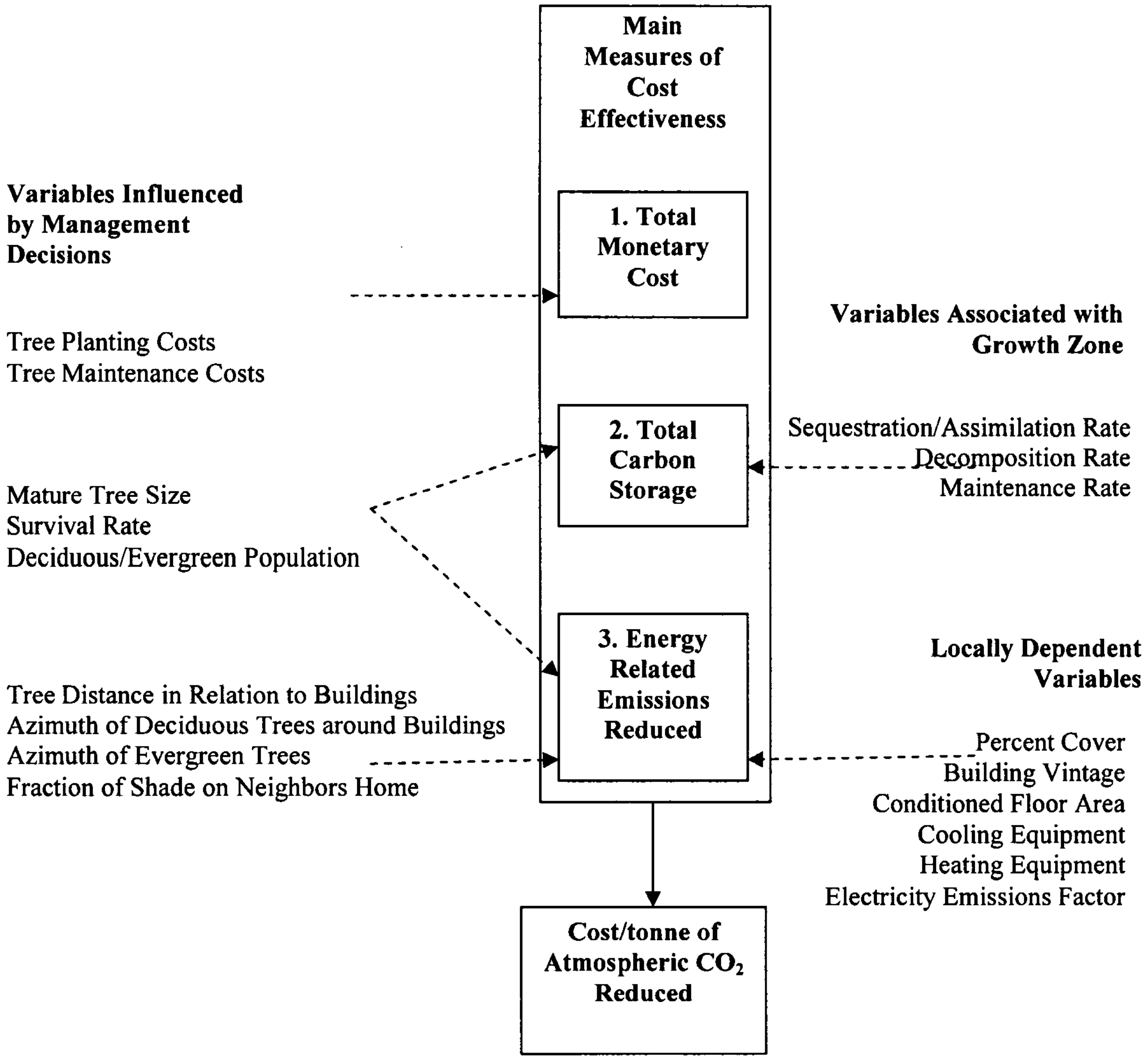

Figure 2.1

Input and output variables represented in the model. The model predicts total monetary costs, total carbon storage, and reduced energy related carbon emissions over a 40 year period. These predictions are based on input variables that are a function of regional processes, characteristics of the local community, or specific management decisions.

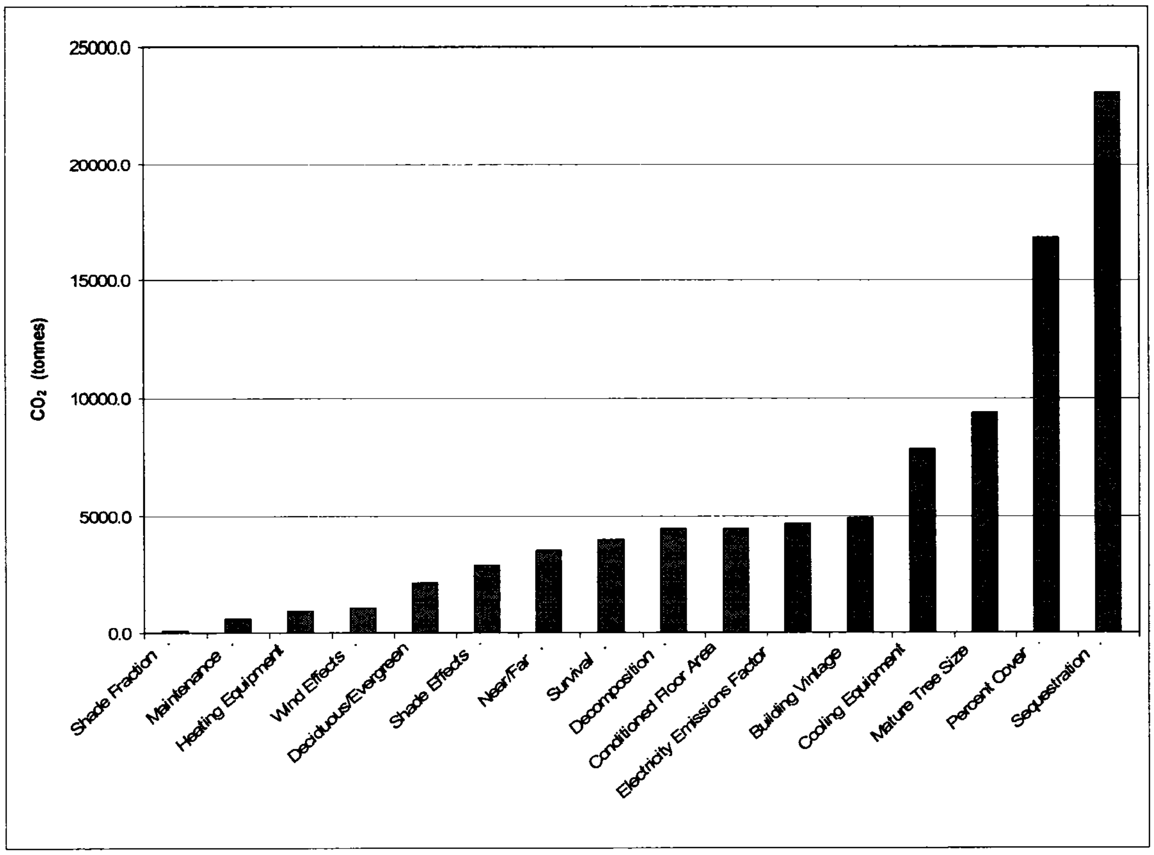

Figure 2.2

Sensitivity analysis results show the change in CO_2 (tonnes) associated with minimum and maximum values for each input variable. The values for each input variable are shown in table 1. Assimilation rate (sequestration) and the amount of existing cover (percent cover) were the two variables that had the greatest affect on cost-effectiveness in the model "Carbon Dioxide Reduction Through Urban Forestry".

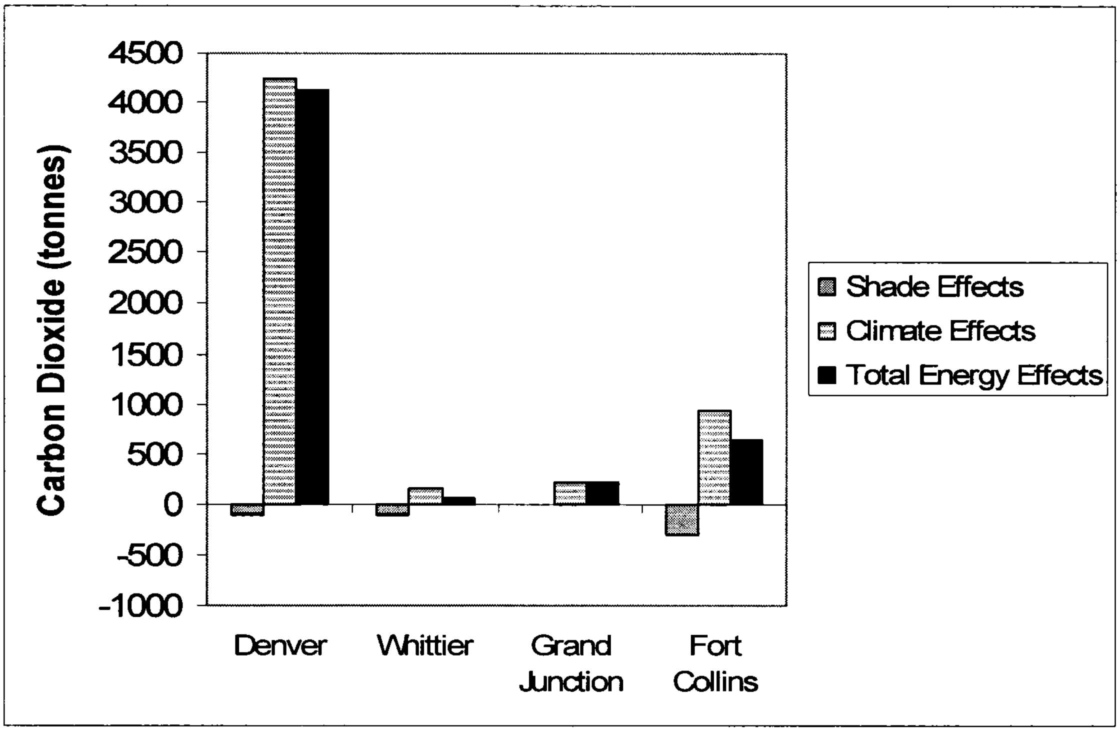

Figure 2.3

Direct (shade) and indirect (climate) effects determine total energy effects. Direct (shade) effects were not a positive contribution to net carbon saved in Denver, Whittier, and Fort Collins.

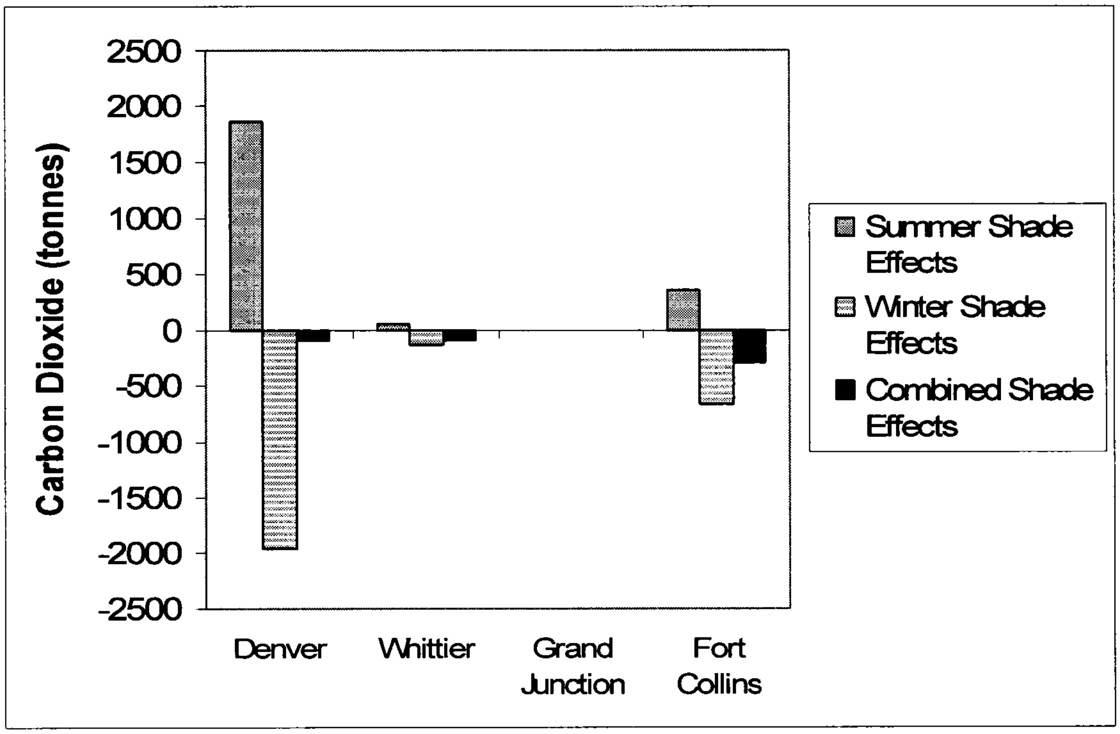

Figure 2.4

Combined direct (shade) energy effects were a function of shading in both winter and summer. In most case studies the negative effects of shade in winter outweighed the positive summer shade effects.

Chapter 3: VOLUME EQUATIONS FOR 11 URBAN TREE SPECIES IN FORT COLLINS, COLORADO

Abstract

Understanding urban environments is becoming increasingly more important as these systems are now home to almost half the global population. Studies that attempt to analyze the benefits and costs associated with urban vegetation utilize allometric relationships for quantification of volume, biomass, and carbon; however, there have been very few analyses on urban tree allometry. My overall goal was to develop equations to predict urban tree volume for more accurate quantification of the role urban forests play in potentially reducing the negative effects associated with urbanization. This study was based in Fort Collins, Colorado which is on the northern end of one of the most rapidly expanding metropolitan regions in the United States. I also conducted an in depth allometric analysis of urban trees in order to: 1) evaluate potential of predicting of height for urban trees; 2) develop clustered and general volume equations for wider applicability, and 3) analyze the relationship between a general regression developed for Fort Collins and another urban based volume study in California for potential cross site comparisons. Regression analyses for 11 species in Fort Collins using DBH were significant with R^2 values ranging from 0.816 to 0.988. Height explained less variation than DBH and was an insignificant variable for most species regressions. Predictions for each species fall within the 95% prediction interval for the general equation, however, there was a significant interaction with species, indicating equations for individual species were different from one another. Based on volume predictions, significant differences among the intercepts and slopes of all equations, and RMSE values, the urban tree species clustered into four main groups. The general equations from California were significantly different from the Fort Collins based equations, and my modeling results indicated that potentially large errors would be associated with using a general allometric relationship developed with data from both sites as opposed to using site and species specific equations. Future studies should focus on the potential of developing volume equations that would apply to regions with similar climates, the relationship between urban tree physiology and allometry, as well as the differences between urban and rural tree growth.

Key Words: urban trees; allometric equations; tree volume; tree biomass; urban carbon accounting

Introduction

Urban lands only cover about 3% of the United States, yet the majority of the population lives in or around these urban centers (Imhoff et al. 2004, Pataki et al. 2006). By 2008, half or more of the world's population will live in urban areas (Lei 2007). With increasing urbanization there is increased interest in reducing the negative impacts of urbanization while contributing to human health, through urban forests. Studies have shown that urban forests provide many quantifiable ecological services to surrounding communities, such as reducing stormwater runoff, increasing property values, and improving air quality (Nowak et al. 2002, McPherson et al. 2003, McPherson et al. 2005). Urban forest management is also often considered one of the most effective strategies for offsetting carbon dioxide emissions because urban trees have both a direct effect on carbon flux, through photosynthesis, and an indirect effect on energy efficiency, through shading, transpiration effects, and blocking winds (Trexler 1991, McPherson 1998, Nowak and Crane 2002, Nowak et al. 2002)

Models that quantify benefits provided by urban trees utilize allometric relationships for estimates of volume, biomass and carbon storage (Nowak 1991, Nowak et al. 2002, McPherson et al. 2003, McPherson et al. 2005, Pataki et al. 2006). Despite the fact that urban forests clearly differ from rural forests in both structure and function, these models have relied heavily on measurements from rural forests (McPherson and Simpson 2001). Differing environmental factors in urban vs. rural areas, including lower tree densities, additional nutrient and water inputs, and higher pollution levels, could lead to a disparity in biomass allocation and over all tree phenology; subsequently allometric equations created for trees in rural forest settings could be inaccurate predictors of urban tree characteristics.

My goal was to develop allometric volume equations for dominant urban tree species in Fort Collins, Colorado, for more accurate quantification of the benefits and costs associated with urban trees and their management. Fort Collins is located in one of the fastest growing metropolitan regions in the US, the Colorado Front Range (US census 2000). Because of the extensive urbanization occurring in this region, these equations may be useful to a number of cities along the Front Range. Previous research in the Fort Collins area by Kaye et al. (2005) established that with urbanization of the native semi-arid shortgrass steppe, carbon storage in the soils and net primary productivity increased. My study is a continuation of these efforts to better understand how carbon dynamics change when semi-arid systems are converted to urban systems and is part of an effort to evaluate the potential carbon storage capacity of urban forests along the Front Range.

It is expensive and time consuming to conduct volume and biomass studies on trees, and especially difficult in urban areas where cutting down trees for research purposes is highly undesirable; therefore little information is available on urban tree allometry. My first objective was to analyze the relationships between total volume and DBH, and total volume, DBH and height to determine if height is a significant variable in predicting total volume. Past research on rural forests has shown that height often does not predict total volume as well as DBH, however, can be a useful variable for cross site comparisons (Montagu et al. 2005, Wang 2006, Bunce 1968). Understanding height and DBH relationships can be particularly useful for urban tree studies since management techniques can influence tree growth.

My second objective was to cluster species into similar groups and to develop general volume equations for all 11 species combined. Clustered and generalized equations can be useful in areas where little information is known on species composition or urban forest structure, for regional extrapolation (Montagu et al. 2005). Some studies have indicated that combined species equations were acceptable estimates, especially because these regressions were associated with an increased sample size and a narrowing of confidence limits (Whittaker and Woodell 1968, Bunce 1968). However, what is acceptable depends on what the goals are for a volume or biomass analysis. For instance, implementing carbon trading scenarios requires accurate and verifiable procedures (Joosten et al. 2004), while a general estimate of benefits and costs of urban forests for other policy decisions may be adequate.

My final objective was to create general equations using information from one other urban based volume study conducted in California and analyze how a general volume equation from another site compares to locally developed general equations as well as an overall general equation developed for both sites. Several studies have analyzed developing generalized equations for cross site comparisons and results have been dependent on the species being analyzed (Wang 2006, Montagu et al. 2005, Pastor et al. 1984, Bunce 1968). When accurate, cross site generalizations can be valuable for testing whether site differences are solely attributable to the application of different regression equations (Pastor et al. 1984). As part of this last analysis I aimed to test statistical significance for similarities of the generalized regression equations as well as analyze the practicality and potential errors associated with implementing general regressions versus species specific equations.

Methods

Study area

Fort Collins is the most northern city along the Colorado Front Range (latitude: 40.6N, longitude: 105.1W). The city lies within a semi-arid region, receiving an average of 38.5 cm of precipitation per year, with an average mean annual temperature of 8.9 ^{O} C (100 year record at Colorado State University, CO USA). Urbanization along the Front Range converts ecosystems dominated by native drought tolerant grasses to systems consisting of lawns, herbs, shrubs and trees that typically receive and depend on large nutrient and water inputs (Kaye et al. 2005, Golubiewski 2006). Fort Collins was an ideal location for this study because it contains a large and diverse population of well-maintained street and park trees.

Field measurements

The ideal method for measuring aboveground biomass and carbon is to destructively sample and physically weigh an entire tree, however this method is time consuming (Ketterings et al. 2001), and it is not possible for acquiring data on a number of species in urban environments. It is particularly expensive to cut down urban trees and therefore trees are usually only removed when they are a hazard. So called "hazard trees" are often large and old, contain a significant amount of decomposing wood, and/or are heavily pruned and do not represent average tree form. Alternatively, past studies measure standing tree volume and convert to biomass using specific gravity values for individual tree species. I implemented a newly developed method to measure total tree volume using a terrestrial light detection and ranging system (LiDAR) (Lefsky and McHale, in prep).

I studied eleven dominant tree species in Fort Collins and used a complete inventory of the municipal forest to select a stratified random sample for each species (Table 3.1): all of my sample trees were planted along roadways and sidewalks and owned and maintained by the municipality. The trees in this study are also popular urban trees in other localities, and have a wide range of diameter distributions within the city. I selected 14-22 individual tree samples for each species, with a total sample of 184 trees (Table 3.1). I collected all data in the winter of 2002, to avoid visual interference from leaf cover. I measured diameter at breast height (DBH, 1.3 m) with a diameter tape, and measured and calculated all other tree metrics using the terrestrial LiDAR system.

I used a Cyrax 2500 LiDAR system (Cyra Technologies Inc.) to scan each tree from two different locations 90 degrees from one another. I maintained a constant resolution of 1.5 x 1.5 cm and the points clouds from both locations were later merged to create one single point cloud (Figure 3.1). The Cyrax 2500 had a 40 by 40 degree field of view, single point range accuracy within +/- 4 mm, a range of 50 m, and scanning dimensions of 1000 points per column and 2000 points per row.

Tree diameter measurements using LiDAR vs. a Barr and Stroud optical dendrometer

To test if tree diameters could be measured accurately with a terrestrial LiDAR system, I compared bole diameter measurements using LiDAR to measurements taken with a Barr and Stroud optical dendrometer. The Barr and Stroud is no longer commercially available and can only be used to take measurements of branches that are completely vertical, but has been proven to take accurate measurement of vertical bole diameters up to an inch (Clark 2000). Diameter measurements correlated well for the two species analyzed (Figure 3.2).

LiDAR point cloud processing

To measure total tree volume using LiDAR, a cylinder fitting algorithm was applied to each tree's point cloud (Lefsky and McHale, in prep). After cylinders were fit to main stems, the volume represented by the remaining points was calculated (Figure 3.3). The resolution of the points was constant and it was therefore assumed that each point in space was surrounded by a volume of 2.65 cm^3 on average (Lefsky and McHale, in prep). Total volume was a function of both the volume of cylinders and the volume surrounding each point in space.

Volume Equations for Individual Species

For each species, I evaluated the relationship between total tree volume and diameter at breast height (DBH), as well as total tree volume vs. two independent variables, DBH and height (H). There was increasing variance with tree size, so I transformed all data using the natural log function and using linear regression, I analyzed the relationships

$$\ln(tvol) = a + b*\ln(DBH) \quad (1)$$

$$\ln(tvol) = a + b*\ln(DBH) + c*\ln(H) \quad (2)$$

where ln = the natural log function, (tvol) = total tree volume (m^3), DBH = diameter at breast height (cm), H = tree height (m), and a, b and c are parameters in the model. All regressions were run using PROC REG in SAS (Version 9.1, SAS Institute Inc, Cary, NC) and the regressions displayed homoschedastic residuals after transformation.

Transforming the data and applying linear regression is a common method for developing volume equations, however it has been shown that this method may underestimate tree volume (van Laar and Akca 1997, Parresol 1999). Some studies have attempted to correct for potential underestimations, but other studies show that corrections may over-compensate for underestimation (Madgwick and Satoo 1975, Hepp and Brister 1982, Parresol 1999). Some researchers recently have chosen to use a weighted least squares regression; I chose linear over weighted nonlinear regression for several reasons. First, when I applied a weighted least squares regression using PROC NLIN (SAS, Version 9.1, SAS Institute Inc, Cary, NC), predictions for tree volume associated with smaller diameter trees were often negative; these results are not biologically realistic. Second, the weighted regressions corrected for some of the increasing variance with increased tree size for most species, however transforming the data corrected heteroschedasticity associated with all species. Third, the weighted regressions sometimes predicted less volume than the linear regressions even though the logarithmic transformation is often associated with an underestimation of tree volume. This indicated that weighted nonlinear regression did not necessarily account for potential underestimation associated with applying the log-linear method. Finally, overall both regressions predicted very similar results across the entire diameter range for all species.

Species clustering and a general urban tree volume equation

I analyzed the relationship between DBH and total tree volume for all species combined to form general allometric equations, and using PROC GLM (SAS, Version 9.1, SAS Institute Inc., Cary, NC) tested if the individual species equations had significantly different intercepts and slopes from the general equation. To group similar species, researchers can employ procedures such as FASTCLUS in SAS which cluster species based on the estimated coefficients (Akindele and Lemay 2006). For this data automated cluster analyses combined species based on similar coefficients (values a and b in the regression equations) even when the species specific equations predicted dissimilar volumes, and therefore were not very effective. To avoid this issue, I conducted a manual hierarchical cluster analysis to evaluate similarities among the predictive equations for individual species. First, I grouped species that predicted similar total volume for large diameters. I tested this grouping by analyzing significant differences between the intercepts and slopes for all equations. I then used the root mean square error (RMSE) to quantify how much the error increased when the equations were grouped together. Only equations that had the lowest RMSE values were clustered, and the values for any grouping were not allowed to exceed the RMSE of the general equation.

Generalized equations for cross site comparisons

Pillsbury et al. (1998) conducted a study in three regions of California and developed allometric volume equations for 15 urban tree species (Tables 3.2 and 3.3). The original data are not published so following methods applied by Pastor et al. (1984) I compiled a sample of 5 to 6 trees per species using the published volume equations. I then transformed the data and developed two general allometric equations (one using DBH as the only independent variable and one using both DBH and height) for all species in the California study (PROC REG, SAS Version 9.1, SAS Institute Inc, Cary, NC). I also developed general overall allometric equations by combining the sample from California with the Fort Collins sample. Using PROC GLM (SAS Version 9.1, SAS Institute Inc, Cary, NC), I compared the slopes and intercepts for the general equations, as well as compared predictions of the general equations to the sample for Fort Collins and California to estimate percent relative errors.

Finally, to evaluate how large the errors would be using the species specific predictions versus predictions associated with generalized equations, I calculated biomass for a model urban forest, that was composed of the 11 main species studied in Fort Collins, was the same size as Fort Collins, and had an average tree density of 21 trees per hectare (the national average tree density, Rowntree and Nowak, 1991). All species were equally distributed in the model so the results were not influenced by one species in particular. Since the results likely depend on DBH and mature tree size, I modeled three main urban forest types, including a young, middle aged, and mature urban forest.

Average diameter distributions for these forest types have been published by McPherson and Rowntree (1986) (Table 3.4).

Results and Discussion

The relationship between predicted volume, DBH, and height

I developed allometric equations using nonlinear regression to predict volume using DBH, as well as DBH and height, and analyzed how well each equation explained the variation associated with the sample. The logarithmic linear regressions for volume vs. DBH were highly significant (alpha<0.001) and explained 82-99 percent of the variability for each species (Figure 3.4). *Gymnocladus dioicis* and *Ulmus pumilla* displayed the lowest coefficient of variation (R^2) values, as well as the highest RMSE values (Table 3.5). However R^2 values for *Fraxinus pennsylvanica* and *Gleditsia triacanthos* were approximately equal to 0.99, and these equations were associated with RMSE values lower than 0.181 (Table 3.5).

Although diameter was a significant variable in all equations, height was only significant for *Fraxinus pennsylvanica* (alpha<0.05, p=0.0412) when I evaluated volume vs. both independent variables. Furthermore, including height as an independent variable only increased the variance explained for two species more than 3 percent (*Populus sargentii* and *Ulmus americana*); otherwise, height barely improved the predictions, increasing the variance explained by the regression equations by less than 1 percent (Tables 3.5 and 3.6). These results are comparable to many other studies that have shown including height only slightly improves the variance explained by the model, because there is a very close relationship between height and diameter (Ketterings et al. 2001, Niklas 1994, Wang 2006).

In traditional forestry, height is usually not used for volume and biomass estimations because it is more difficult to measure, and height measurements are often less accurate than DBH measurements (Mowrer and Frayer, 1986; Gower et al., 1999; Wang 2006). However, some large scale studies suggest that height adds information to diameter only equations and can show the effects of population structure, therefore, diameter only equations should be used cautiously (Joosten et al. 2004, Zianis and Mancuccini 2004, Vallet et al. 2006). In contrast to traditional forestry practices, height is easier to measure in an urban forest because of the more open spatial distribution. It may possibly add information on the specific population structure of urban forests; urban trees are often highly maintained and including height may indicate how pruning is affecting urban tree allometry.

There are potential benefits of including height when estimating urban tree volume or biomass, although these equations should be applied cautiously for several reasons. Height was only a significant variable in one out of the eleven equations and added very little to the variance explained for most species. Even though the open distribution of urban forests may allow for easier height measurements, added variance associated with sampling and random measurement errors could still have been an issue. Finally, height was determined in this study by implementing an algorithm that finds the highest points in a point cloud (Lefsky and McHale, in prep), which may produce different results than using a clinometer or laser in the field.

General urban tree equations

I compiled data for all species and applied a regression analysis relating total tree volume to DBH. Such an equation would be most useful for cities along the Front Range that do not have species specific information associated with the local urban forest. The DBH only equation explained 93 percent of the variance and had a RMSE of 0.395 (Table 3.8). The general equation predicts volumes that were very similar to those predicted by the regression equation for *Tilia cordata* (Figure 3.5). However, there was a significant species by DBH interaction (alpha <0.05, $p<0.001$); this shows that species had an influence on model parameters. Coefficients for the general equation were significantly different from those of *Quercus macrocarpa*, *Populus sargentii*, and *Ulmus pumilla*. However, all of the predictions from the species specific allometric equations fall within the 95 percent prediction interval for the general equation (Figure 3.5), indicating similar predictions among all of the equations.

Fort Collins's municipal forest was dominated by trees that are considered medium-large to large at maturity and this sample was based on that particular population of trees. This general equation, therefore, should not be applied when an urban tree population contains a large number of trees that are small to medium at maturity. It is important to note that most of the equations predict similar volumes for trees with a DBH under 50 cm (Figure 3.6); the general equation may be particularly useful for estimating total volume associated with young tree populations.

I also developed a general equation relating total tree volume to both DBH and height. The general equation using two independent variables explained 95 percent of the variance and had an RMSE of 0.330 (Table 3.8). Height was a significant variable in the regression analysis and there were significant species by DBH and species by height interactions, which showed that these variables were affected by species.

Species clustering

My objective in this analysis was to determine how similar or different the species specific equations were from one another. There may be no biological reasoning to cluster species, however, how similar certain predictive equations are to one another could have something to do with tree form or how well certain species grow in urban environments. In this analysis, the species specific predictions of volume seem to cluster into 4 main groups at large DBH values (Figure 3.5):

1. *Quercus macrocarpa*, *Fraxinus pennsylvanica*, *Gleditsia triacanthos*, *Acer saccharinum*
2. *Tilia cordata, Populus sargentii, Celtis occidentalis, Ulmus americana*
3. *Ulmus pumilla*, *Acer plantenoides*
4. *Gymnocladus dioicus*

Quercus macrocarpa, *Fraxinus pennsylvanica*, *Gleditsia triacanthos,* and *Acer saccharinum* did not have significantly different model parameters (alpha<0.05), but these four species were significantly different from most other species in this study (Table 3.7).

Gymnocladus dioicus did not significantly differ from any of the other species, even though it predicted smaller volumes associated with all DBH values (Figures 3.5 and 3.6), but clustering was also based on RMSE values. RMSEs increased from most species specific equations with each new group, however only groups with the smallest errors were clustered in this analysis. *Fraxinus pennsylvanica* and *Gleditsia triacanthos* had very similar predictive equations and when these two species were grouped the RMSE was very close to the original RMSE for the species specific equations. The RMSE associated with *Quercus macrocarpa* and *Acer saccharinum* decreased when these species were clustered in a group. *Tilia cordata* and *Gleditsia triacanthos* did have very similar parameters, however *Tilia cordata* fit well with *Populus sargentii*, *Ulmus americana*, and *Celtis occidentalis* and this cluster had a lower RMSE. These two clusters of four species were more similar to each other than *Ulmus pumilla*, *Acer plantenoides* and *Gymnocladus dioicus* (Table 3.8, Figure 3.7).

These groups were not based on biological or botanical relationships and were only a function of the volumes predicted by the equations, significant differences among the model parameters, and RMSEs associated with each species cluster. In this study there were two *Acer* and *Ulmus* species, yet in the cluster analysis these equations were less similar to each other than they were to equations for other species (Figure 3.7). Interpretation of potential correlation between species clustering and tree structure and function is beyond the scope of this study, however, these results are interesting and could be a function of how species grow in urban environments.

Studies on the growth response of trees in urban environments have shown conflicting results. Rhoades and Stipes (1999) found that trees may grow better in urban areas due to lack of competition and turfgrass fertilization programs, while other studies have shown stressful urban conditions can negatively affect tree growth (Close et al. 1996a, Close et al. 1996b). How trees grow in urban environments can also be a function of species (Celestian and Martin 2005).

Past studies suggest that there may be overarching general allometric relationships for all species across a variety of ecosystem types (Enquist 2002), although for purposes of accurately quantifying volume or biomass in a specific location, locally created species specific equations are generally recommended because of individualistic species response to different habitats (Wang 2006). In very diverse ecosystems, species are often clustered because it is too time consuming to create and implement species specific equations (Akindele and Lemay 2006). Species specific equations in one location may at times also be clustered if there are not significant differences among the parameters and species are botanically similar (Vallet et al. 2006).

Generalized equations for cross site comparisons

I developed general allometric relationships using information published on 15 urban tree species in California (Pillsbury et al. 1998), the only published review of urban tree volume in the literature that I could find. If there were similarities between general volume equations for two studies in different localities with varying species, it could mean that generalized regression could be applied across sites. Since there is very little information on regional differences on urban tree species and their growth, it would be useful if available allometric relationships were applicable in other regions.

I developed general allometric equations using DBH, and DBH and height, for the 15 California species, as well as overall general equations using both the California and Fort Collins data sets (Tables 3.8 and 3.9). The equations explained 95 to 99 percent of the variation and all had RMSE values lower than 0.489. It is not surprising that the general equation for CA explained most of the variance in the sample, since I developed a random sample using the equations supplied by Pillsbury et al. (1998), which did not show the natural variation associated with a large field sample like that of the Fort Collins data set.

All of the equations had significantly different slopes and intercepts from one another (alpha<0.001) (Figure 3.9), with one exception: the overall general equation with height compared to the California general equation with height had statistically similar intercepts (p=0.4266). Although the equations in log form were significantly different, the predictions look very similar (Figures 3.10 and 3.11).

To evaluate how well the predictions from each of the equations fit the Fort Collins sample data, I calculated and compared overall percent relative errors (sum of the observed volumes - sum of the predicted volumes / sum of the observed volumes * 100). The Fort Collins general equations had low relative percent errors ranging from 4 to 5 percent, and the error increased when height was also used as an independent variable (Table 3.10). The general equations for Fort Collins were associated with higher relative percent errors when applied to the California sample and vise versa. The predicted volumes associated with the overall general equation for the Fort Collins sample fit better than they did for the CA data (Table 3.10). Furthermore, the overall general equation including height had the lowest relative percent error of any equation (0.19 percent), even lower than the relative errors associated with the species specific equations (1.9, and 2.3 for DBH, and DBH and height respectively). This showed that even though the equations were significantly different, the generalized equations could in certain instances be used to predict total volume with acceptable accuracy. It is interesting that the overall general equation with height was associated with a much higher relative error when applied to California's sample, than the overall general equation with DBH as the only dependent variable. In fact, the same was true for the Fort Collins general equation, which suggests that including height may not increase the accuracy of using general equations across sites.

I further evaluated the potential accuracy associated with using each of the generalized equations through developing and analyzing a model urban forest. The Fort Collins general equation (without height) consistently predicted within 3-4 percent of the species specific equations for all urban forest types (Table 3.11), whereas the Fort Collins general equation that included height was only accurate for a young tree population and deviated from the species specific predictions by over 30 percent for the other two forest types. This trend of increasing deviation with forest maturity was consistent for both the overall general equation (with height) and the California general equation (with height). Furthermore, all of the general equations (except Fort Collins general equation DBH only) predicted more volume than the species specific equations for a young urban forest and increasingly less than the species specific equations as the forest matured (Figure 3.12). Overall the equations that did not include height as an independent variable predicted volumes closer to the species specific predictions (Figure 3.12), again suggesting that height is not a useful predictor variable across sites and species. This could be a function of including a broad range of species in the general equations since the Fort Collins general equation showed significant species and height interaction.

General equations that take into account data from California did not predict actual volume as well as species specific equations or the general equation developed particularly for the 11 species growing in Fort Collins; the deviations ranged from 4 to over 50 percent (Figure 3.12). The overall general equation (without height) predicted within 40 percent of the species specific equations for all forest types which may be the best accuracy one could expect for general equations across sites and species. Furthermore, the equations not only were significant different from one another, but their practicality so far seems limited. It is important to note that California and Colorado have very different climates and species that survive well in those climates, so although regional comparisons do not seem applicable between these two data sets, it could be possible that regional allometric relationships would hold well in areas with more similar climates. Therefore, I recommend the use of the Fort Collins general equation (without height) for areas along the Front Range of Colorado that do not have species specific information, but for areas outside of this region the general equations developed as part of this research should only be used in preliminary or general analyses.

Conclusion

Species specific allometric equations represent the most accurate method for determining urban tree volume. For areas along the Colorado Front Range that have limited information on species composition the Fort Collins clustered and general equations could be useful. According to my model, the general equations without height produce similar estimates to the species specific equations; however, the trees in my sample were medium to large stature at maturity and these equations may be inaccurate for urban forests that are composed of many smaller stature trees. The general equations did well at representing all the species included at lower DBH ranges (under 50 cm) and therefore could be very useful for young urban forests.

Height was not a significant variable in most species specific regression analyses, and the general equations with height were associated with larger overall percent relative errors when compared with the Fort Collins data. The equations with height also deviated more from the modeling results. Height does not seem to improve the accuracy of predictions and I recommend using DBH only equations unless specific circumstances indicate otherwise.

The clustering analysis showed that many of these urban species I studied had statistically similar regression coefficients, although there was no botanical reason for combining these species. Future analyses on urban tree volume should also analyze clustering potential to gain a better understanding of the similarity in allometric relationships. Also, to better understand the potential relationship between tree ecophysiology and allometry, more studies are needed to relate the two characteristics; this is especially important in urban forests since trees in urban areas are subjected to many of the conditions associated with global climate change, including increased temperatures and carbon dioxide concentrations.

Furthermore, Pataki et al. (2006) have indicated that in depth regional carbon analyses and comparisons between regions are needed. In order to accomplish this, we need to have more information on regional differences in growth and structure for urban vegetation. My study showed that general equations for urban trees from two areas, Fort Collins, Colorado and California, were statistically different. This is not surprising since these areas have different climates, species compositions, as well as other varying environmental variables. It seems as if the overall general equation that incorporated data from two the locations could be useful for some cross site analyses due to the low relative percent error associated with the Fort Collins sample, although in the modeling analysis its accuracy deviated from the species specific equations.

The modeling analysis also indicated large deviations from species specific volume estimates for all general equations, except the Fort Collins based general equation (without height), and these deviations increased with forest maturity. Therefore, applying these general equations to older forests outside the region may be associated with large errors and should not be used for studies outside of the region that require accurate quantification of volume, biomass, and carbon. Future regional analyses on urban tree allometry should focus on whether or not general equations would be applicable within particular climate regimes. Comparing new urban allometric data with the results from this study, as well as the one conducted in California, could provide more information on species similarities and cross site analyses. Furthermore, since many urban forest studies rely on rural forest data, new studies should also focus on the potential physiological and allometric differences between rural and urban trees. Allometric relationships are the basis for determining the benefits and costs associated with vegetation structure and management and this study provides new data for more accurate quantification of volume and biomass in urban areas along the Front Range, and potentially other urban areas within this climate region.

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Tables

Table 3.1

Characteristics of Sample Trees in Fort Collin, Colorado.

The common name, scientific name, species code (the first two letter of the genus combine with the first two letters of the species epithet), percent of the total street tree population in Fort Collins, sample size (n), and sample diameter range for 11 predominant urban trees.

Common Name	**Scientific Name**	**Spp. Code**	**% Pop.**	**n**	**Diameter Range (cm)**
Green ash	*Fraxinus pennsylvanica*	FRPE	22	15	14.8 - 122.6
Honey locust	*Gleditsia triacanthos*	GLTR	10	16	9.1 - 98.3
Little leaf linden	*Tilia cordata*	TICO	7	18	11.3 – 64.6
Bur oak	*Quercus macrocarpa*	QUMA	7	20	11.0 – 100.0
Hackberry	*Celtis occidentalis*	CEOC	6	22	10.9 – 119.4
American elm	*Ulmus americana*	ULAM	4	14	17.5 – 114.4
Norway maple	*Acer platanoides*	ACPL	3	17	9.7 – 102.2
Siberian elm	*Ulmus pumilla*	ULPU	3	15	15.5 – 131.6
Cottonwood	*Populus sargentii*	POSA	2	18	6.3 – 136.7
Kentucky coffee tree	*Gymnocadus dioicus*	GYDI	1	14	10.2 – 36.8
Silver maple	*Acer saccharinum*	ACSA	1	15	13.2 – 134.9

Table 3.2

The allometric relationships developed by Pillsbury et al. (1998) for 15 tree species in California. The original parameter estimates for allometric equations relating volume (ft^3) and diameter breast height (DBH, in). Parameter values are given for each individual species. The equation form is Volume = $a(DBH)^b$

Common Name	**Scientific Name**	**a**	**b**	**Adj. R^2**	**Diameter Range (in)**
Blue gum	*Eucalyptus globulus*	0.055113	2.436970	0.968	6.1-51.2
Acacia	*Acacia longifolia*	0.048490	2.347250	0.938	5.9-22.5
Monterey pine	*Tilia cordata*	0.019874	2.666079	0.969	6.6-41.5
Monterey cypress	*Cupressus macrocarpa*	0.035598	2.495263	0.980	6.2-57.7
Carob	*Ceratonia siliqua*	0.066256	2.128861	0.910	6.1-28.1
Camphor	*Cinnamomum camphora*	0.031449	2.534660	0.970	5.0-27.1
Chinese elm	*Ulmus parvifolia chinensis*	0.028530	2.639347	0.903	6.8-22.0
Holly oak	*Quercus ilex*	0.025169	2.607285	0.938	5.0-20.5
Jacaranda	*Jacaranda mimosaifolia*	0.036147	2.486248	0.949	6.8-23.5
Sweet Gum	*Liquidambar styracaflua*	0.030684	2.560469	0.979	5.5-21.4
Modesto ash	*Fraxinus velutina*	0.022227	2.633462	0.940	5.7-33.4
Sawleaf zelcova	*Zelcova serrata*	0.021472	2.674757	0.969	5.7-34.0
Chinese pistache	*Pistacia chinensis*	0.019003	2.808625	0.958	5.0-20.2
Southern magnolia	*Magnolia grandiflora*	0.022744	2.622015	0.958	5.7-29.2
London plane	*Platanus acerifolia*	0.025170	2.673578	0.965	6.1-29.1

Table 3.3

The allometric relationships developed by Pillsbury et al. (1998) for 15 tree species in California. The original parameter estimates for allometric equations relating volume (ft^3), diameter breast height (DBH, in), and height (H, ft). Parameter values are given for each individual species. The equation form is Volume = $a(DBH)^b(H)^c$

Common Name	**Scientific Name**	**a**	**b**	**c**	**Adj. R^2**	**Height Range (ft)**
Blue gum	*Eucalyptus globulus*	0.003089	2.151822	0.835731	0.983	30.6-53.5
Acacia	*Acacia longifolia*	0.014058	2.186485	0.467357	0.976	46.3-144.0
Monterey pine	*Tilia cordata*	0.005325	2.226808	0.668993	0.979	17.0-56.0
Monterey cypress	*Cupressus macrocarpa*	0.005764	2.260353	0.630129	0.989	15.3-35.5
Carob	*Ceratonia siliqua*	0.008573	1.795854	0.926668	0.933	25.0-62.0
Camphor	*Cinnamomum camphora*	0.009817	2.134803	0.634042	0.976	22.0-52.0
Chinese elm	*Ulmus parvifolia chinensis*	0.010456	2.324812	0.493171	0.915	17.0-56.0
Holly oak	*Quercus ilex*	0.004307	1.821580	1.062691	0.976	22.5-57.5
Jacaranda	*Jacaranda mimosaifolia*	0.011312	2.185780	0.548045	0.956	24.0-65.5
Sweet Gum	*Liquidambar styracaflua*	0.011773	2.315815	0.415711	0.982	26.0-91.5
Modesto ash	*Fraxinus velutina*	0.001287	1.762964	1.427822	0.978	18.5-74.0
Sawleaf zelcova	*Zelcova serrata*	0.006664	2.363178	0.551904	0.975	26.5-101.0
Chinese pistache	*Pistacia chinensis*	0.002921	2.191572	0.943669	0.969	18.0-105.8
Southern magnolia	*Magnolia grandiflora*	0.004486	2.070408	0.845627	0.973	20.0-69.0
London plane	*Platanus acerifolia*	0.010425	2.436420	0.391682	0.966	19.0-62.0

Table 3.4

Tree distribution associated with each urban forest type as documented by McPherson and Rowntree (1986).

Forest Type	Percent of trees in each DBH class					
	0-15 cm	16-30 cm	31-45 cm	46-60 cm	61-80 cm	80+ cm
Type I: Young	42	27	14	10	6	1
Type II: Midde-aged	21	29	26	8	8	8
Type III: Mature	23	15	20	16	18	8

Table 3.5

Parameter estimates for allometric equations relating volume (m^3) and diameter breast height (DBH, cm). Parameter values are given for each individual species. The equation form is Volume = $a(DBH)^b$

Tree species (Spp. Code)	**a**	**b**	**R^2**	**RMSE**
Fraxinus pennsylvanica (FRPE)	5.9 E-04	2.206	0.987	0.175
Gleditsia triancanthos (GLTR)	5.1 E-04	2.220	0.988	0.188
Tilia cordata (TICO)	9.4 E-04	2.042	0.953	0.257
Quercus macrocarpa (QUMA)	2.4 E-04	2.425	0.938	0.365
Celtis occidentalis (CEOC)	1.4 E-03	1.928	0.959	0.293
Ulmus americana (ULAM)	1.8 E-03	1.869	0.924	0.268
Acer platanoides (ACPL)	1.9 E-03	1.785	0.940	0.280
Ulmus pumilla (ULPU)	4.9 E-03	1.613	0.874	0.461
Populus sargentii (POSA)	2.1 E-03	1.873	0.991	0.181
Gymnocadus dioicus (GYDI)	4.2 E-04	2.059	0.816	0.411
Acer saccharinum (ACSA)	3.6 E-04	2.292	0.964	0.334

Table 3.6

Parameter estimates for allometric equations relating volume (m^3), diameter breast height (DBH, cm), and height (H, m) for each individual species. The equation form is Volume = $a(DBH)^b(H)^c$

Tree species (Spp. Code)	**a**	**b**	**c**	**R^2**	**RMSE**
Fraxinus pennsylvanica (FRPE)	4.1 E-04	1.847	0.646	0.991	0.152
Gleditsia triacanthos (GLTR)	4.9 E-04	2.132	0.142	0.988	0.194
Tilia cordata (TICO)	9.5 E-04	1.617	0.590	0.955	0.260
Quercus macrocarpa (QUMA)	1.7 E-04	1.956	0.842	0.946	0.369
Celtis occidentalis (CEOC)	2.2 E-03	2.118	-0.447	0.960	0.295
Ulmus americana (ULAM)	1.2 E-03	1.696	0.405	0.927	0.273
Acer platanoides (ACPL)	1.0 E-03	1.533	0.657	0.946	0.272
Ulmus pumilla (ULPU)	3.4 E-04	0.855	2.041	0.918	0.343
Populus sargentii (POSA)	1.9 E-03	1.806	0.134	0.991	0.186
Gymnocadus dioicus (GYDI)	4.6 E-04	1.545	0.792	0.845	0.395
Acer saccharinum (ACSA)	2.4 E-04	1.998	0.596	0.967	0.336

Table 3.7

Significant difference between the intercept (top portion of chart) and slope (bottom) for each individual species.

	QUMA	ACSA	FRPE	GLTR	TICO	POSA	ULAM	CEOC	ULPU	ACPL	GYDI
QUMA					**0.039**	**0.001**	**0.024**	**0.018**	**<0.001**	**0.038**	
ACSA						**0.002**	**0.070**		**<0.001**	**0.019**	
FRPE						**0.033**			**0.002**		
GLTR						**0.006**			**<0.001**	**0.052**	
TICO	**0.042**								**0.012**		
POSA	**<0.001**	**0.002**	**0.024**	**0.009**							**0.028**
ULAM	**0.012**	**0.045**									
CEOC	**<0.001**	**<0.001**	**0.044**	**0.021**							
ULPU	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**0.0152**						**0.002**
ACPL	**0.001**	**0.007**	**0.0356**	**0.020**							
GYDI									**0.062**		

Table 3.8

Parameter estimates for clustered and general allometric equations relating volume (m^3) and diameter breast height (DBH, cm). Parameter values are given for grouped species. The equation form is Volume = $a(DBH)^b$

Species Groups (Spp. Codes)	**a**	**b**	**R^2**	**RMSE**
FRPE, GLTR	5.9 E-04	2.206	0.987	0.183
ACSA, FRPE, GLTR	4.7 E-04	2.243	0.978	0.240
QUMA, ACSA, FRPE, GLTR	4.0 E-04	2.284	0.968	0.282
TICO, POSA, ULAM, CEOC	1.6 E-03	1.910	0.971	0.253
QUMA, ACSA, FRPE, GLTR, TICO, POSA, ULAM, CEOC	8.8 E-04	2.068	0.961	0.298
All species, excluding GYDI	1.1 E-03	2.004	0.950	0.356
Fort Collins general equation	7.7 E-04	2.079	0.934	0.395
California general equation	8.6 E-05	2.530	0.944	0.208
Overall general equation (Fort Collins and CA data combined)	1.4 E-04	2.434	0.950	0.489

Table 3.9

Parameter estimates for general allometric equations relating volume (m^3), diameter breast height (DBH, cm), and height (H, m). The equation form is Volume = $a(DBH)^b(H)^c$

General Equation Name	**a**	**b**	**c**	**R^2**	**RMSE**
Fort Collins general equation	4.6 E-04	1.469	1.106	0.953	0.330
California general equation	6.3 E-05	2.257	0.520	0.994	0.216
Overall general equation (Fort Collins and CA data combined)	1.1 E-04	1.961	0.856	0.960	0.458

Table 3.10

The overall percent relative error (observed-predicted/observed *100) associated with general and species specific equations versus the Fort Collins and California data sets.

	Overall	Fort Collins	California	Species Specific
	Results for DBH only Equations			
Fort Collins data	13.8	4.1	19.8	1.9
CA data	-9.2	-42.7	2.7	
	Results for DBH and Height Based Equations			
Fort Collins data	0.2	5.2	20.9	2.3
CA data	-39.0	-62.5	1.0	

Table 3.11

The urban forest model results for young, middle-aged and mature forest types. Numbers represent the results using a general equation versus species specific allometric equations (general / species specific). Values closest to one are most similar to the results of species specific based results.

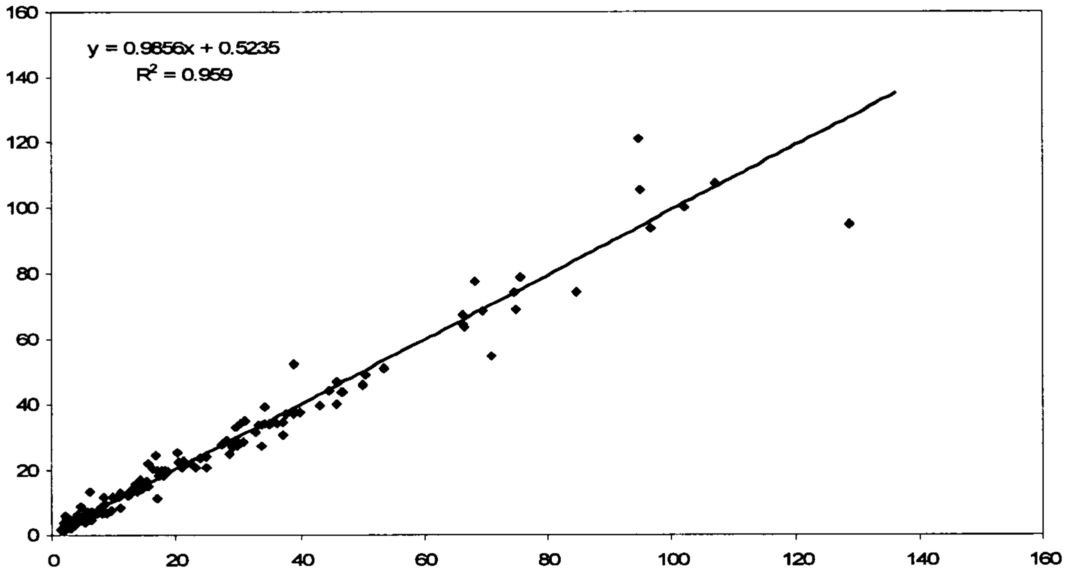
	General Equation Name	**Type I Young**	**Type II Middle-aged**	**Type III Mature**
DBH Only	Fort Collins general equation	1.04	1.03	1.03
	California general equation	1.57	0.93	0.66
	Overall general equation (Fort Collins and CA data combined)	1.39	0.83	0.60
DBH and Height	Fort Collins general equation	1.03	0.64	0.47
	California general equation	1.59	0.94	0.67
	Overall general equation (Fort Collins and CA data combined)	1.18	0.71	0.51

Figures

Figure 3.1

A point cloud scanned with the Cyrax 2500 LiDAR scanner.

(A) Celtis occidentalis



(B) Fraxinus pennsylvanica

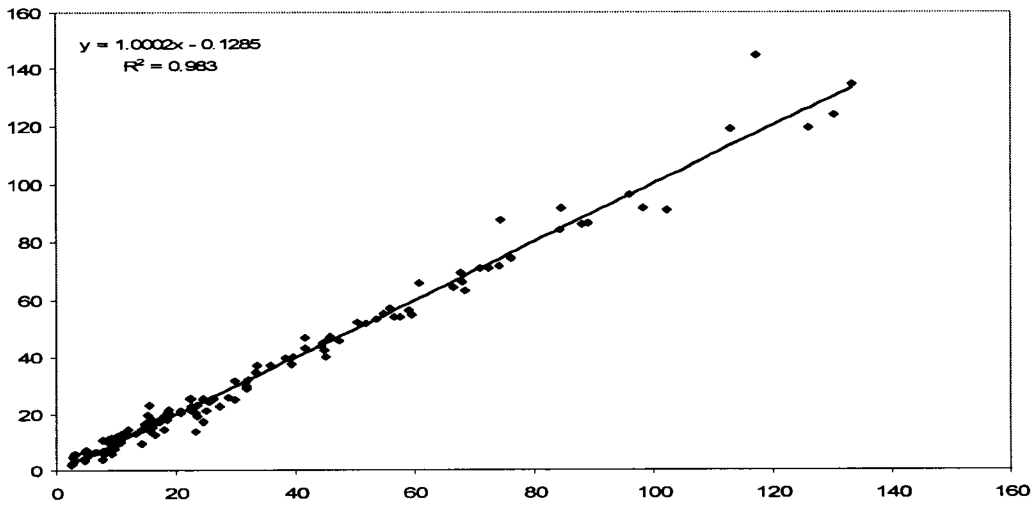


Figure 3.2

Measurement for tree diameters using LiDAR and the Barr and Stroud optical dendrometer.

Figure 3.3

Lidar Processing. Cylinders were fit to the main part of the stem using an automated algorithm, while the remaining points were analyzed based on the average volume determined from a set resolution. Total volume equals the volume contained in cylinders and the volume associated with each point.

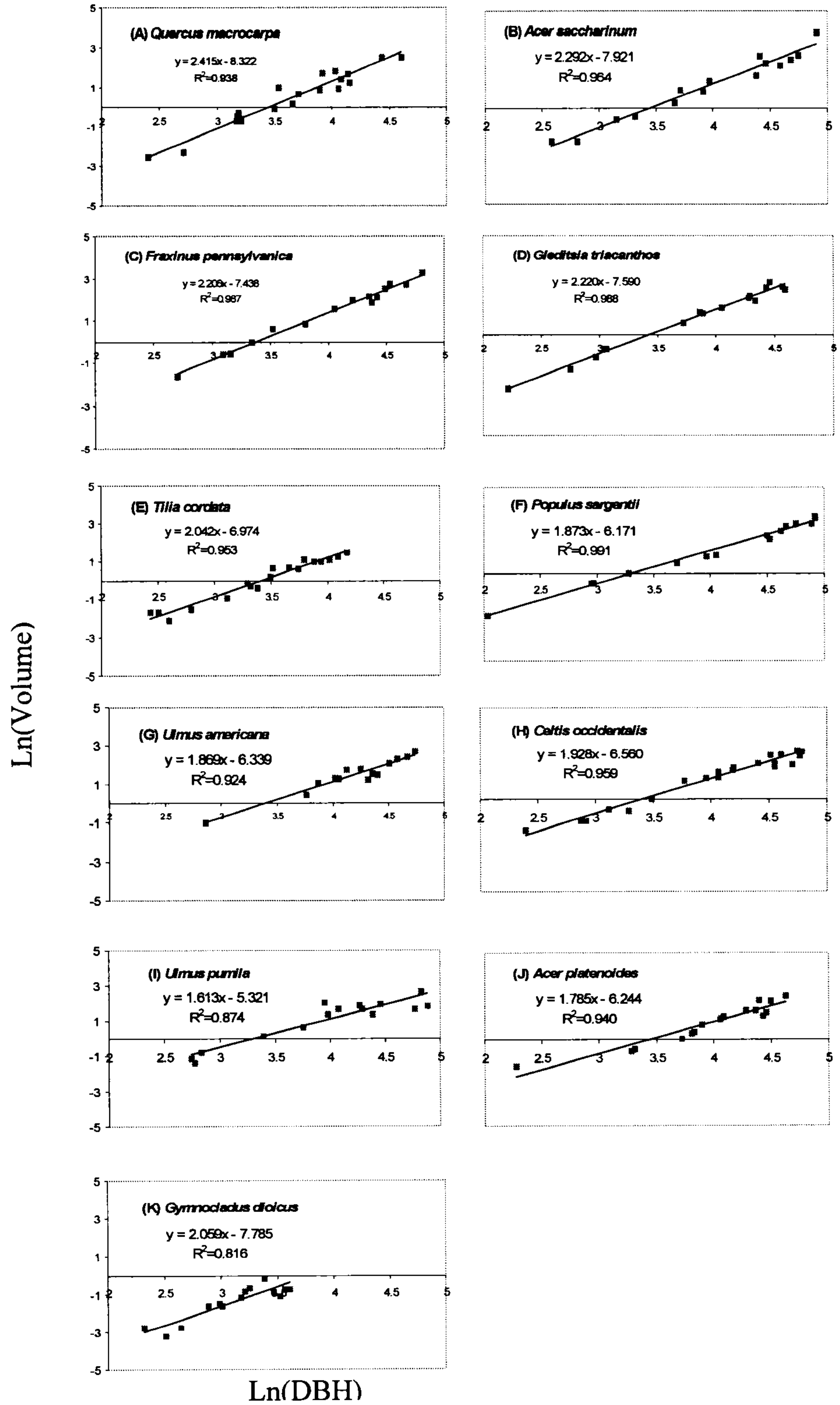


Figure 3.4

Logarithmic form of volume equations for 11 urban tree species.

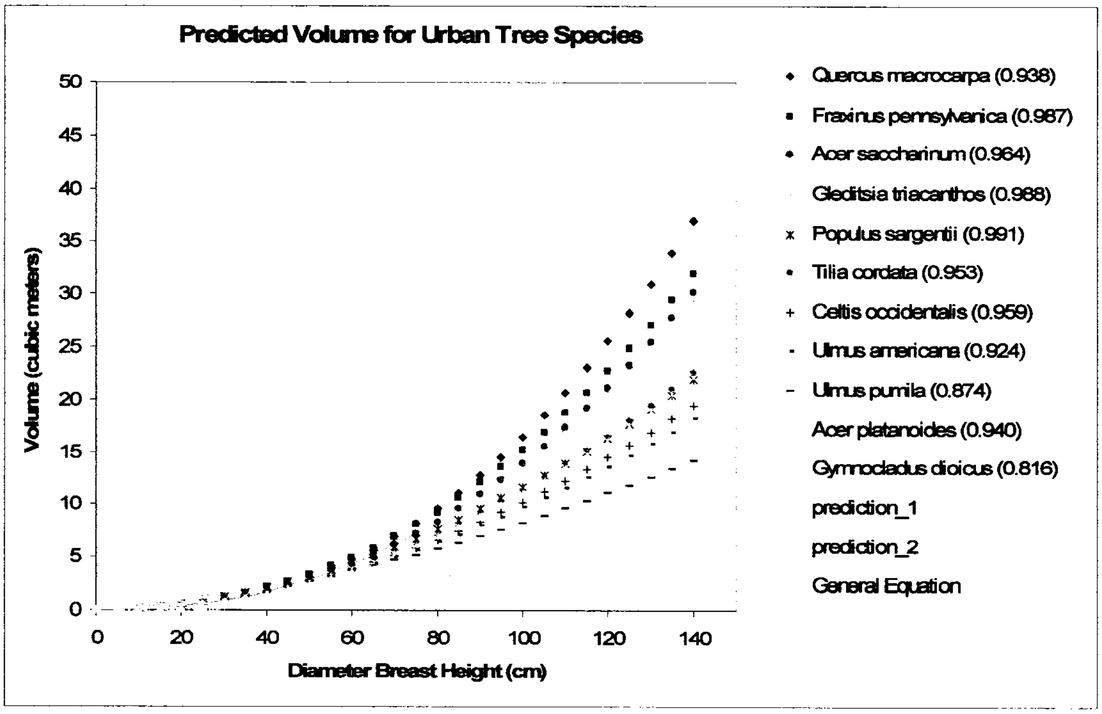


Figure 3.5

Predicted volumes for 11 urban tree species. The general equation that predicts volume relative to DBH across all species predicted similar volumes to the equation for *Tilia cordata*. Predictions associated with each equation fall within the 95 percent prediction interval for the general equation, indicated by prediction line 1 and 2. At the large DBHs, equations are clustered into 4 basic groups that predict similar volumes.

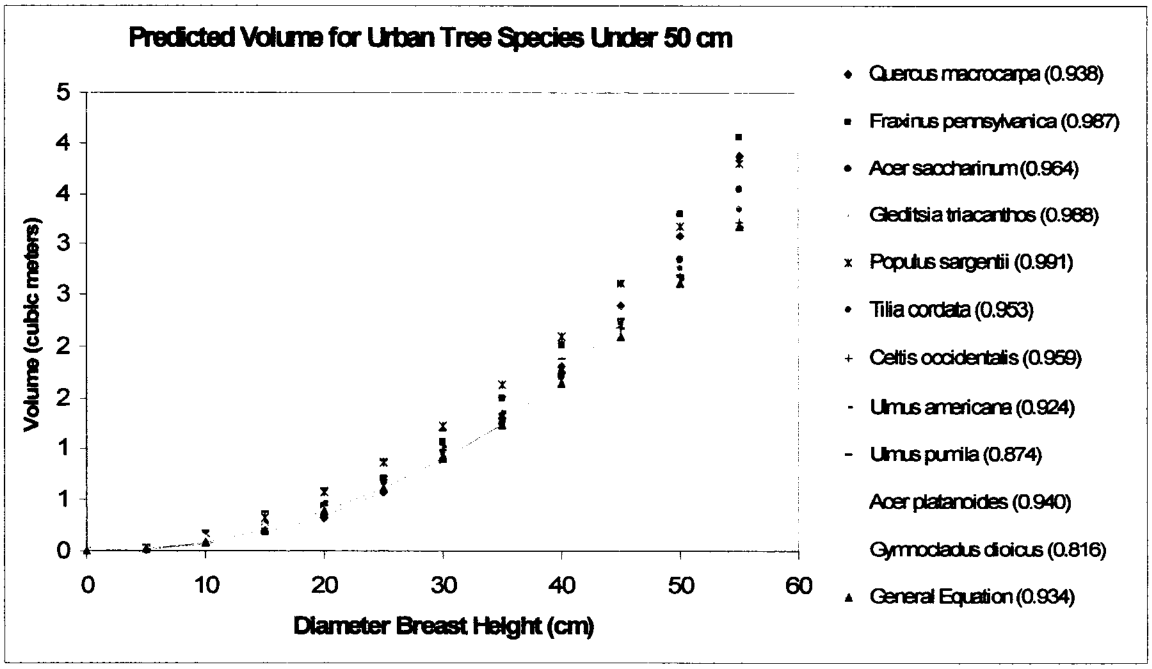


Figure 3.6

Predicted volumes for 11 urban tree species under 50 cm DBH. Most species specific equations, excluding *Gymnocladus dioicus*, predict similar volumes for trees in this size range.

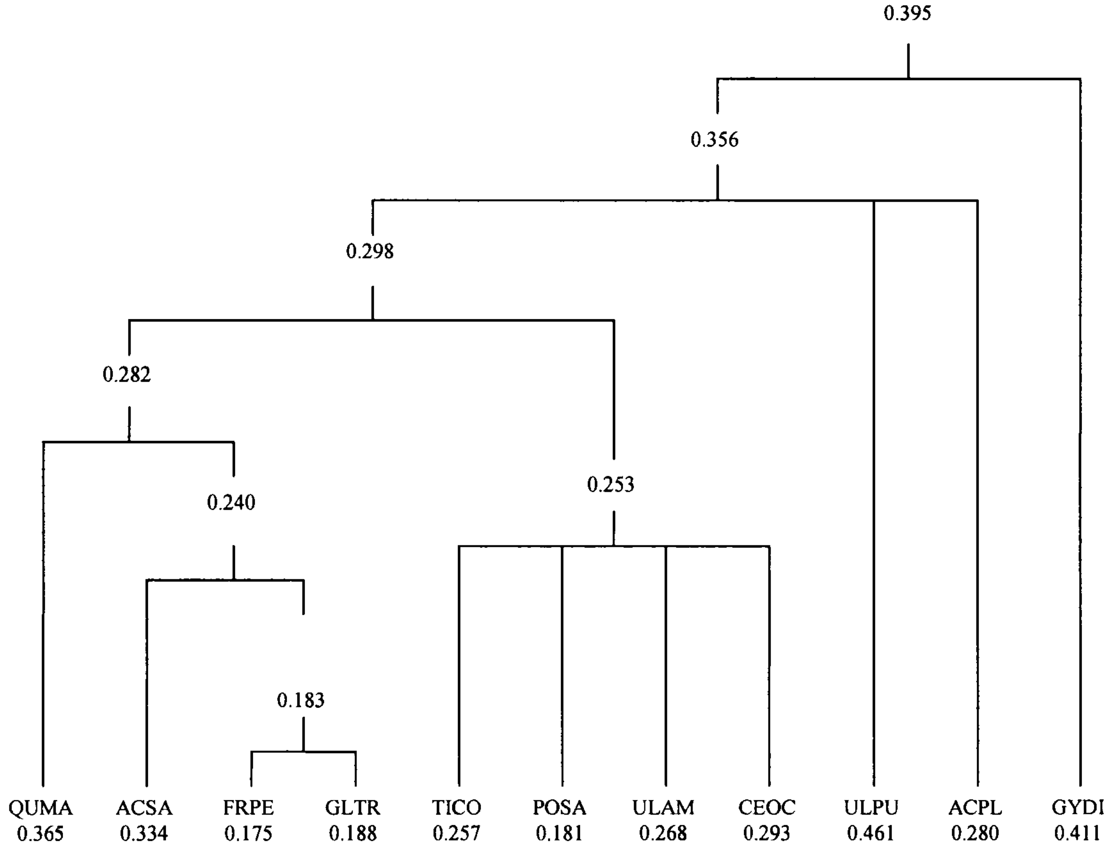


Figure 3.7

Root mean square errors (RMSEs) associated with each individual species and their associated groups. Species codes consist of the first two letters of the genus and first two letters of the species epithet.

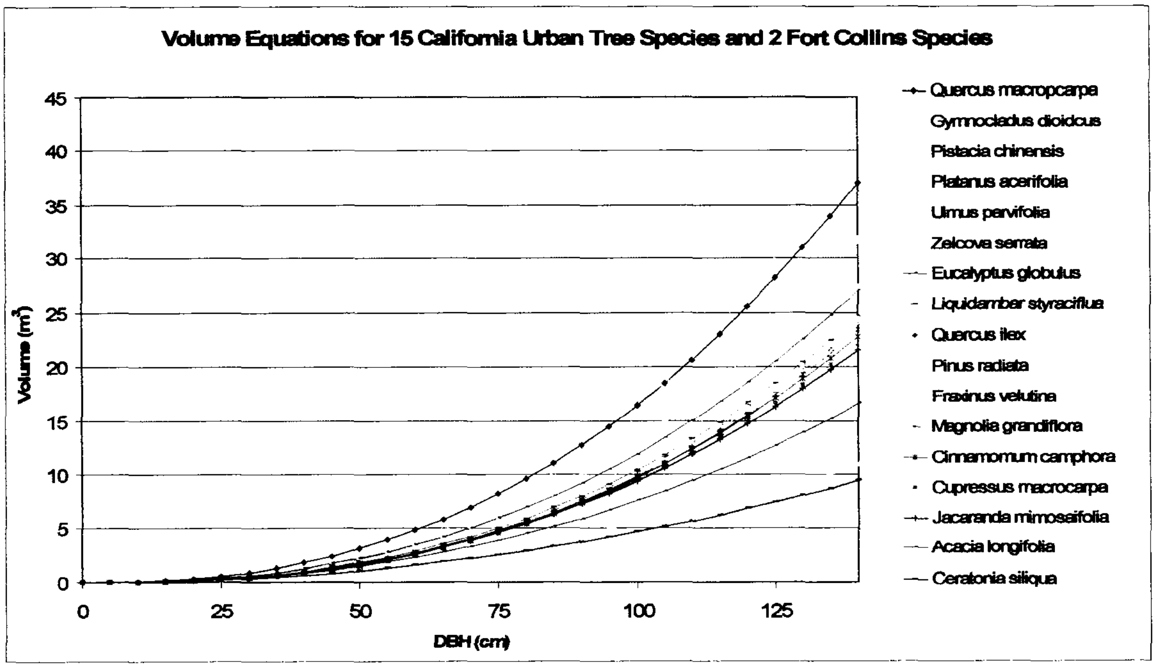


Figure 3.8

Volume predicted by 15 volume equations for California species as published by Pillsbury et al. (1998). Included are two volume equations from the Fort Collins study, *Quercus macropcarpa* and *Gymnocladus dioicus*. These two species represent the largest and smallest species studied in Fort Collins, while all other predictions for other species fell in between these predictions. The predictions associated with the California study fall within the same range.

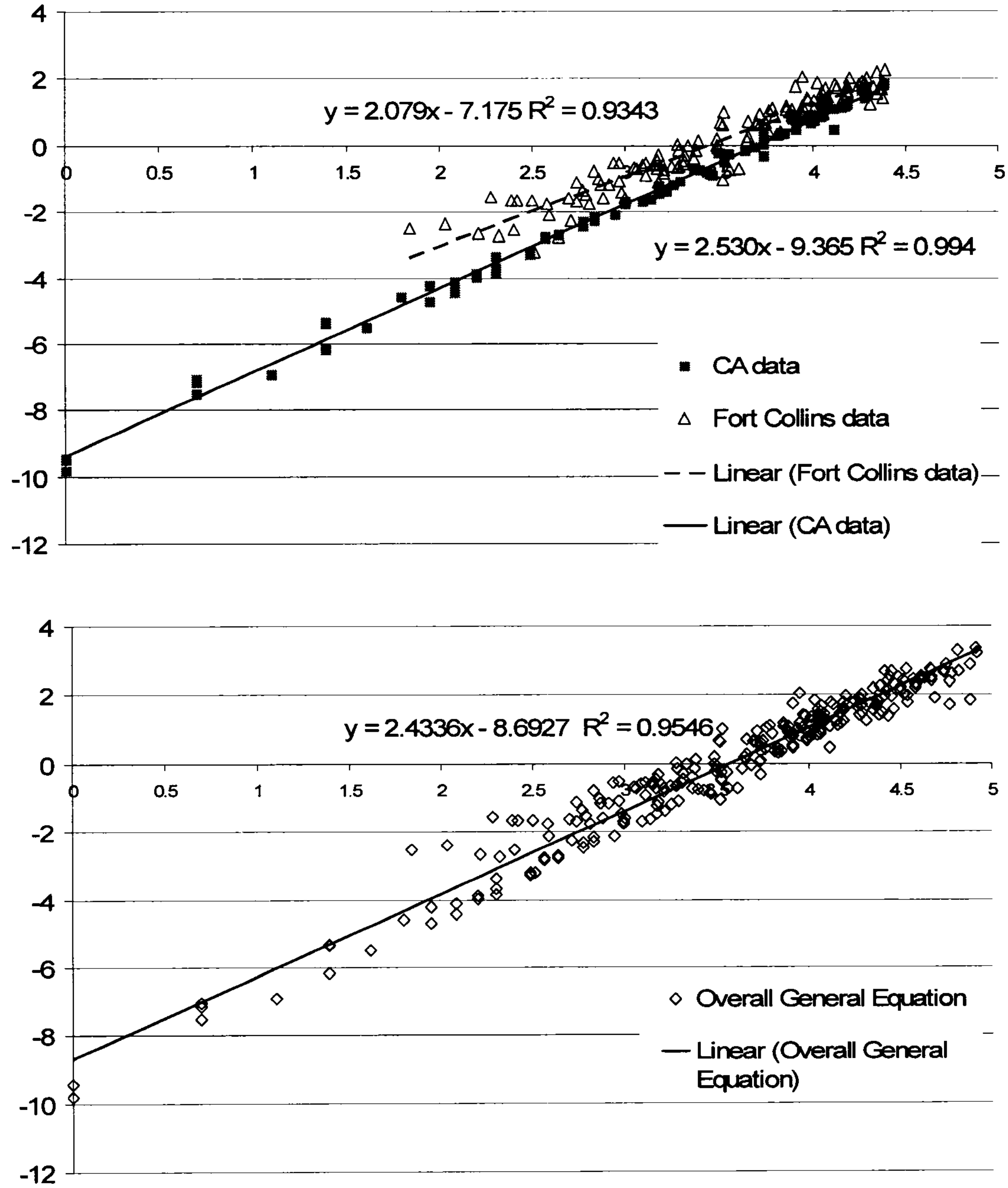


Figure 3.9

Logarithmic form of the general volume equations (without height).

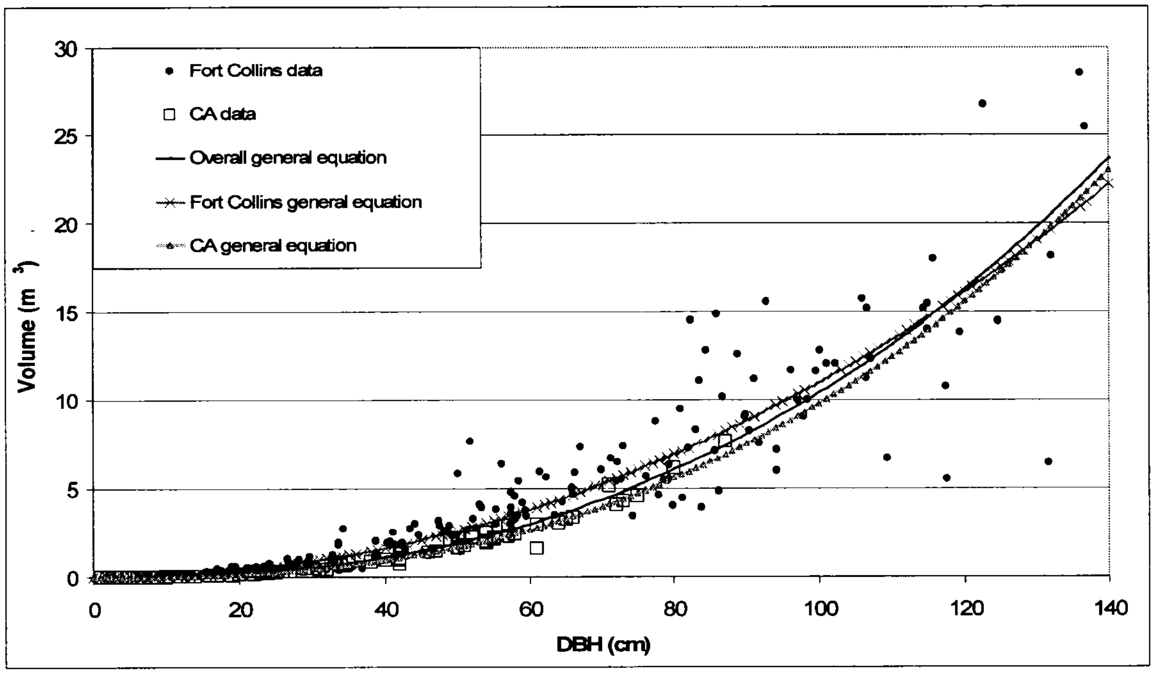


Figure 3.10

Predictions associated with the general equations (without height) and the data points for both the Fort Collins and California studies.

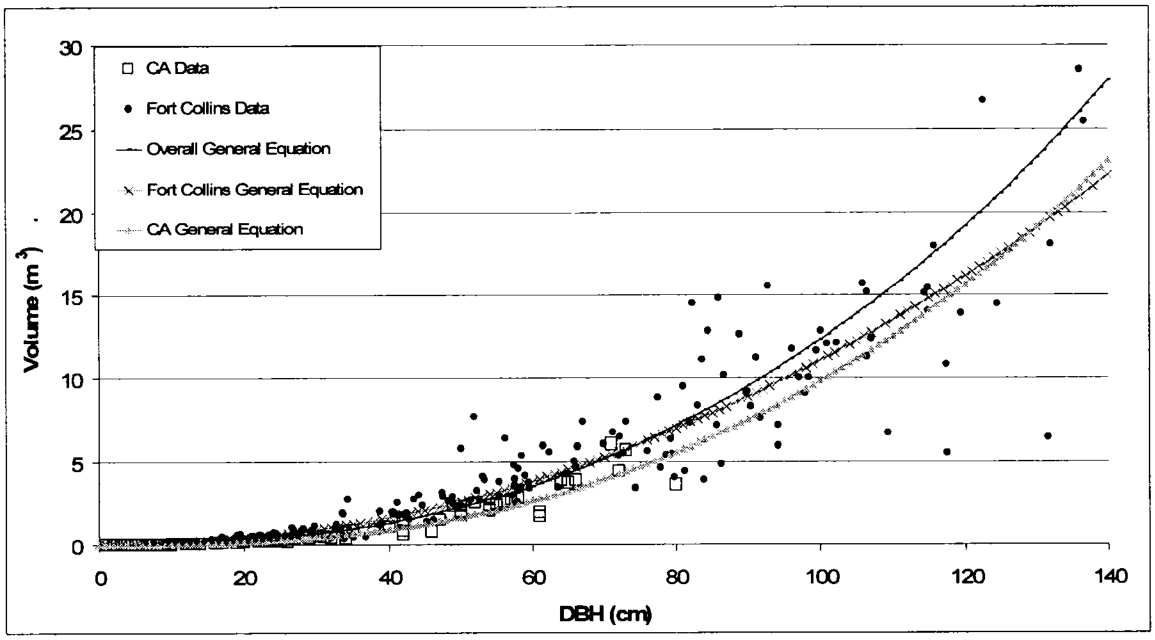


Figure 3.11

Predictions associated with the general equations (with height) and the data points for both the Fort Collins and California studies.

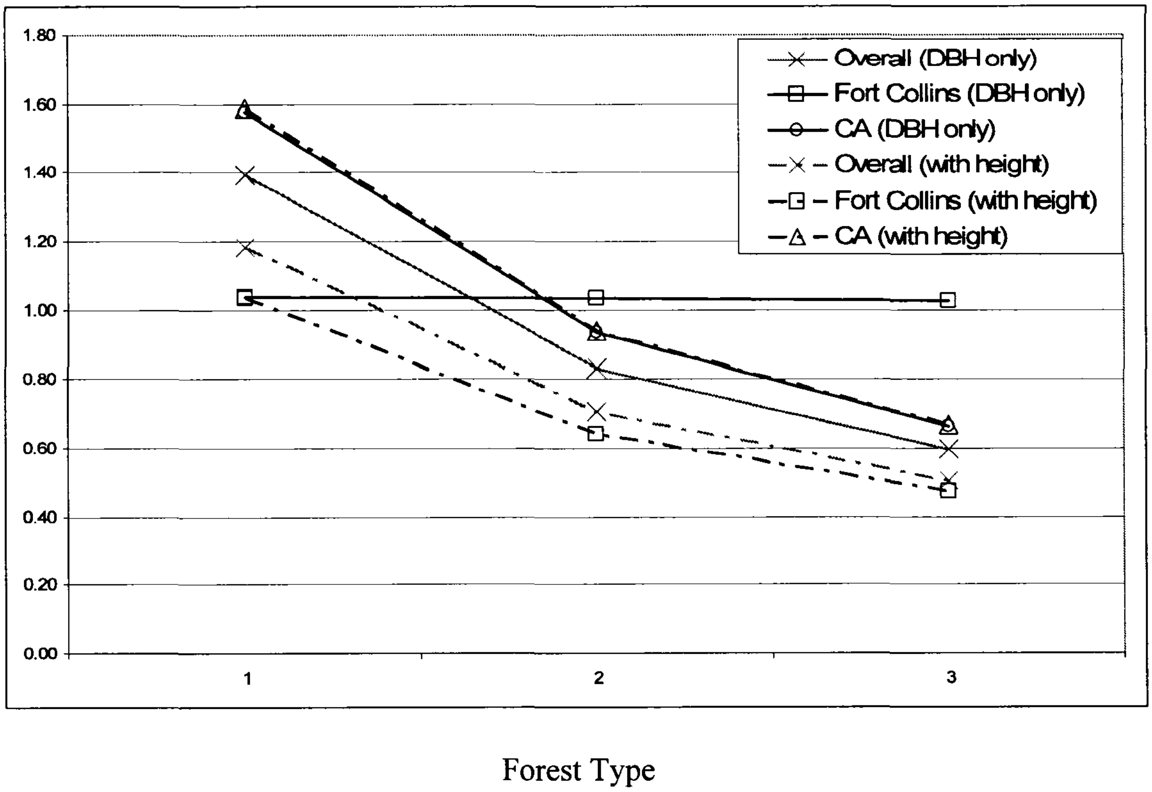


Figure 3.12

Results associated with the modeling analysis comparing the general equation predictions to species specific predictions for a model urban forest. The more a line deviates from a ratio of 1, the larger the potential error associated with using that equation relative to species specific equations.

Chapter 4: URBAN FOREST BIOMASS ESTIMATES: IS IT IMPORTANT TO USE ALLOMETRIC RELATIONSHIPS DEVELOPED SPECIFICALLY FOR URBAN TREES?

Abstract

Many studies have analyzed the benefits and costs, and carbon storage capacity associated with urban trees; but these have been limited by a lack of research on urban tree phenology, biomass, and growth. To date, estimates of carbon storage in urban systems have relied upon allometric relationships developed in traditional forests. As urbanization increases globally, it is becoming more important to accurately evaluate carbon dynamics in these systems. It was my goal to understand the variability and range of potential error associated with using allometric relationships developed outside of urban environments. To achieve this goal, I compared biomass predictions from allometric relationships developed for urban trees in Fort Collins, Colorado to predictions from allometric equations from traditional forests that have been used in past studies on urban forests. I analyzed the deviations of literature-based allometric equations for individual trees of 11 dominant urban tree species. To understand how variability changes at larger scales, I further analyzed deviations for populations of trees. The results show that a few of the equations from the literature may predict similar biomass to the urban-based predictions, but the range in variability for individual trees was over 300%. This variability declined at increasingly course scales, reaching as low as 60% for a street tree population containing 11 tree species and 10, 551 trees. In order to accurately quantify biomass and carbon storage in urban forests, it is important to develop allometric relationships specifically for urban trees.

Key words: biomass; carbon dioxide; allometric relationships; volume equations; urban forest

Introduction

Urbanization is a major contributor to global environmental change and can significantly alter regional carbon dynamics (Pataki et al. 2006). In North America, studies have shown a decline in existing carbon storage pools following urbanization, however in semi-arid and arid environments, urbanization can increase carbon storage capacity (Imhoff et al. 2004; Kaye et al. 2005; Golubiewski 2006). Humans supplement the amount of water and nutrients available to plants in these areas, increasing net primary productivity, and also change the species composition and structure from native systems to predominantly introduced horticultural species. Along the Colorado Front Range, one of the fastest growing metropolitan regions in the United States (US census 2000), urbanization represents a conversion of the native shortgrass steppe, a system dominated by grasses, to one composed of lawns and non-native herbaceous and woody vegetation.

Woody vegetation in particular can be a significant carbon storage pool along the Front Range, and its importance tends to increase with urban forest maturity (Kaye 2005; Golubiewski 2006). In urban areas, trees have been one of the most well studied organic carbon pools (Pataki et al. 2006) and studies have shown that generally urban forests store about half as much carbon as native forests (McPherson 1998). A potentially major issue with most of these analyses is that they lack direct measurement of urban tree allometry and biomass (Pataki et al, 2006; McPherson and Simpson 2001). In fact, most studies that quantify the benefits and costs associated with urban trees and their management use allometric equations to predict biomass that were developed for trees in traditional forests. Only one published study (Pillsbury et al. 1998) developed allometric equations for urban trees, and that was located in California.

There is reason to believe that the allometry associated with trees in traditional forests does not accurately represent urban trees. Low tree density is one important characteristic associated with urban environments, reducing potential competition for light and other resources with surrounding trees. In general, trees in traditional forests experience a change in growth and allocation with reduced competition. After thinning, trees tend to increase cambial activity and radial growth toward the base of a tree rather than the crown, producing a more tapered trunk (Kramer and Kozlowski 1979; Rhoades and Stipes 1999). There are changes in allometry as well as phenology associated with shady vs. open environments; e.g. Steingraeber et al. (1982) found that *Acer saccharum* (sugar maple) phenology changed drastically when a tree, or even a portion of a tree, was grown in an open environment.

In addition to growing in a more open environment, urban trees often receive additional nutrients and water. A study on Virginia Technological University campus reported that all urban trees, even those in locations that were considered stressful, experienced higher rates of trunk growth than published rates of those species in traditional forests; Rhoades and Stipes (1999) conclude that this could be a result of release from competition, turfgrass fertilization programs, and/or above average precipitation.

In some cases, stressful conditions exist in urban environments, which can negatively impact tree growth. Research comparing *Acer saccharum* planted in lawns along streets to the same species in a local forest stand reported that soil moisture, air temperature, leaf temperature, relative humidity, and vapor pressure deficit were less favorable for urban trees, resulting in slower growing, lower density root systems, significant terminal growth differences, and earlier leaf drop (Close et al. 1996a). Further, analysis by Close et al (1996b) showed that low soil moisture levels and high atmospheric demands associated with street tree sites were correlated with significantly lower predawn water potential, osmotic potential, and stomatal conductance than trees in forested sites. *Acer saccharum* has been identified as a potentially sensitive urban tree, however, and these results could be different for other species. Celestian and Martin (2005) found that some species were not significantly affected by growing in planting strips, while others experienced stressed symptoms.

Overall, research suggests that urban environments can impact urban tree growth, allocation, and phenology, therefore, studies on urban biomass that use allometric equations developed for traditional forest trees may be inaccurate. My goal was to compare biomass predictions based on allometric equations I developed in urban Fort Collins, Colorado to predictions from equations that have been used in past studies to estimate biomass of urban forests. In this analysis, I focus on the individual tree scale, as well as on a population and community scale, and attempt to answer two main questions: 1) Do predictions by equations available in the literature deviate from biomass values estimated using allometric equations developed for urban trees in the city?, and 2) Does it matter if literature versus urban based equations are used to predict biomass of an entire urban populations and communities of trees?

Methods

Study Area

Fort Collins is the most northern city along the Colorado Front Range (latitude: 40.6°N, longitude: 105.1°W). This area is semi-arid, receiving 38.5 cm of precipitation on average per year, with a mean annual temperature of 8.9° C (100 year record at Colorado State University, CO USA). Urbanization along the Front Range converts systems dominated by native drought tolerant grasses, to systems consisting of lawns, herbs, shrubs and trees that typically receive and depend on large nutrient and water inputs (Kaye et al. 2005, Golubiewski 2006). Fort Collins was an ideal location for this study because it contains a large and diverse population of well maintained street and park trees. There are existing data for the municipal forest inventory, and McPherson et al. (2003) recently conducted a study in Fort Collins on the benefits of urban street trees, which allowed me to build on local urban forestry research.

Field Measurements

I chose 11 dominant tree species in Fort Collins using a complete inventory of the municipal forest (Table 3.1) and therefore all of my sample trees are street trees (trees that are planted along roadways and sidewalks, and are owned and maintained by the municipality). The trees in this study were also popular urban trees in other localities, and had a wide range of diameter distributions within the city. For each species, the sample size ranged from 14-22 individual trees; the total sample (all species) was 184 trees (Table 3.1). All data were collected in the winter of 2002, to avoid visual interference from leaf cover. I measured diameter at breast height (DBH, 1.3 m) with a diameter tape, while all other tree metrics were calculated using a ground based light detection and ranging (LiDAR) system.

I used the Cyrax 2500 LiDAR system (Cyra Technologies), which has a 40 by 40 degree field of view, single point range accuracy within +/- 4 mm, a range of 50 m, and scanning dimensions of 1000 points per column and 2000 points per row. I scanned each tree with the Cyrax 2500 from two different locations, 90 degrees from one another. I used a constant resolution of 2.5 x 2.5 cm and the points clouds from both locations were later merged to create one single point cloud (Figure 3.1).

Tree Diameter Measurements using LiDAR vs. a Barr and Stroud Optical Dendrometer

To test if tree diameters could be measured accurately with a ground based LiDAR system, I compared LiDAR-based bole diameter measurements to measurements taken with a Barr and Stroud optical dendrometer. The Barr and Stroud was the standard instrument for bole diameter estimates for decades, but it is no longer commercially available (Clark et al. 2000). It can only be used to take measurements of branches that are completely vertical, but has been proven to take accurate measurement of bole diameters up to an inch (Clark et al. 2000). Diameter measurements from the LiDAR and the Barr and Stroud optical dendrometer correlated well for the two species analyzed (Figure 3.2).

LiDAR point cloud processing

To estimate total tree volume using LiDAR, we applied a cylinder fitting algorithm to each tree's point cloud (Lefsky and McHale, in prep). After cylinders were fit to main stems, the remaining points were analyzed using a probability matrix (Figure

3.3). Total volume was estimated as a function of both the volume of cylinders and the volume surrounding each point in space (see Lefsky and McHale, in prep, for the algorithm details).

Volume and Biomass Estimation

For each species I evaluated the relationship between total tree volume and diameter at breast height (DBH) (McHale et al. in prep, Chapter 2 of this dissertation). Due to increasing variance associated with increasing tree size, I transformed all data using the natural log function and analyzed the relationship. I then converted these allometric equations for volume (m^3) (Figure 4.1) to allometric biomass (kg) equations using average specific gravity (kg/ m^3) for each species. Average specific gravity values are published in *Hardwoods of North America* (Alden 1995) and have been used in past urban biomass studies.

No studies on urban based specific gravity appear in the literature, however, specific gravity has been shown to change with nutrient and water inputs (Nyakuengama et al. 2002). If urban trees grow faster due to nutrient and water inputs, it is likely that specific gravity values from the literature would overestimate wood density and specific gravity. However, average specific gravity values were developed for each species in a broad range of conditions and were an estimate for total tree specific gravity. Branches tend to have a higher specific gravity than bole wood (Clark et al. 1985), and if trees have more branches in urban settings, this would potentially balance out overestimates produced for faster growing trees.

Literature Based Equations

I chose to evaluate published allometric equations that were used for urban biomass studies from three main studies:

1. McPherson et al. (2005) analyzed the benefits and cost of municipal forests in five US cities;
2. Nowak et al. (2002) studied Brooklyn, New York's, urban forest; and
3. Golubiewski (2006) evaluated urbanization effects on grassland carbon storage pools in Boulder, Colorado.

Both McPherson and Nowak have published many other studies on urban forests in which they use the same literature based equations. These equations from the literature were derived from trees growing in traditional forests, in climates that differ from where the equations were applied, and sometimes developed for general hardwoods, or a completely different species than the species the equations were applied to (Table 4.1). This was a function of the availability of information on specific species. For example, no allometric information existed on *Gymnocladus dioicus* or *Acer platenoides* so past biomass studies implemented the use of general hardwood equations or equations for a species in a similar genus (Table 4.1). For species in which information on biomass is lacking, Nowak (2002) sometimes combined multiple equations to form a general equation. The methodology for development of these generalized equations was unavailable so I analyzed each individual equation he cited in his paper associated with the 11 species I studied in Fort Collins.

Biomass Comparisons on an Individual Tree Scale by Species

My goal was to compare biomass predicted on an individual tree scale by Fort Collins equations to biomass predicted for each tree by literature-based equations. To do this, I calculated biomass ratios as the amount of biomass predicted by my urban equation divided by the biomass predicted by literature equations. Therefore, if a literature equation has a biomass ratio of 2 at a specific DBH then that equation predicts two times as much biomass as the urban equation. Similarly if a biomass ratio is equal to 0.5 that equation predicts half as much biomass as the Fort Collins equation at that DBH.

Comparisons at the Population Scale for Each Species

Using a complete inventory of Fort Collins's street tree population, I again compared biomass estimates with allometric equations developed in Fort Collins to those in the literature, but this time for each population of species. This analysis took into account the characteristics of individual populations of species. For instance, *Fraxinus pennsylvanica* was the most abundant species in the urban street tree population, containing over 3,500 trees or 21% of the total street tree population, but was dominated by a large number of young trees in small diameter classes (Figure 4.2). In contrast, both *Ulmus americana* and *Posa sargentii* contain relatively fewer trees in their populations than *Fraxinus pennsylvanica*, 719 and 232 tree respectively, and a large percentage of those populations make up older and larger street trees (Figure 4.2).

In the second part of this analysis I evaluated the range in predicted biomass using the two equations from the literature that predicted the highest and lowest biomass values for each population. The exception was *Celtis occidentalis* because there was only one equation used in the past biomass studies on urban trees.

Comparisons at the Population Scale for 11 Urban Tree Species Combined

In the final analysis, my goal was to estimate total biomass for all of the trees in the 11 species together. I summed the "highest" literature estimates, and separately, the "lowest" literature estimtes, as an assessment of the possible range of total biomass for the community. These were then compared to biomass predictions based on the Fort Collins allometric equations for the entire community.

Results and Discussion

Biomass Comparisons on an Individual Tree Scale by Species

The biomass comparisons for each species varied by species, with four main trends. The first trend, exhibited by *Acer plantenoides* in particular, was that the equations used in the literature resembled predictions from urban equations when the trees were young and small, but most of the literature estimates over-predicted biomass by 1.5 to 3 times, such that potential errors increased with increasing DBH (Figure 4.3). The second trend, apparent in the results for *Ulmus americana* and *Ulmus pumilla*, showed similar estimates to the urban equations for medium sized trees (~ 40 to 80 cm DBH) falling within the 95% confidence limits for the urban tree sample, but the small and large diameter tree estimates were mostly outside of the confidence intervals. Third, for *Populus sargentii* and *Celtis occidentalis*, the estimates from literature equations under-predicted biomass for the smaller diameter trees, but the estimates were more similar to urban equations for larger diameter trees. Finally, while some of the literature predictions were similar to urban predictions for *Fraxinus pennsylvanica*, *Quercus macrocarpa*, and *Gleditsia triacanthos*, most of the literature predictions were lower than the urban equation predictions, regardless of tree diameter.

The maximum percent deviation of literature equations from urban based equation appeared in results for *Acer platenoides* and *Quercus macrocarpa*. An equation used to predict *Acer plantenoides* by Bickelhaupt (1973) deviated from the urban based equation by 205% at the largest diameters (Table 4.2); this equation was originally created for *Acer saccharum* (sugar maple). Bunce's (1968) allometric equation for general oak underestimated *Quercus macrocarpa* biomass by 95-97% (Table 4.2). However, one equation for *Quercus macrocarpa* by Brenneman et al. (1978) predicted biomass within 1-19% of the urban based biomass estimates. Similarly, *Gleditsia triacanthos, Tilia coradata, Populus sargentii, Celtis occidentalis,* and *Gymnocladus dioicus* all had at least one equation that predicted within 20% of the biomass estimated by the urban equations for certain specific DBH ranges, although at some point those equations also deviated from urban based estimations by over 40% (Table 4.2).

A study on urban trees in Oakland, California showed that rural tree biomass was typically 20% more than predicted by allometric equations developed for the same tree species in urban forests (Nowak, 1991). Due to a lack of research on this topic, a standard practice in this field of study is to reduce all traditional volume or biomass estimates by 20%. In my analysis, three equations for individual tree species predict 20-23% more biomass than the urban based estimates: 1) *Acer plantenoides* (Young et al. 1980), 2) *Gymnocladus dioicus* (Hahn 1984), 3) *Fraxinus pennsylvanica* (Pillsbury et al. 1998). In these limited cases, the standard 20% reduction might be appropriate; however, those same equations predict 63% less to 169% more biomass for other DBH values (Table 4.2, Figure 4.3). Furthermore, Pillsbury (1998) was the one study that actually developed allometric relationships for urban trees.

Overall, only three equations predicted within the 95% confidence intervals for the urban tree biomass equations across the range of DBH values (Figure 6): 1) *Fraxinus pennsylvanica* (Brenneman 1978), 2) *Quercus macrocarpa* (Brenneman 1978), and 3)

Gymnocladus dioicus (Hahn 1984). Ironically, Brenneman's equations were for different species (*Fraxinus americana* and *Quercus* rubra respectively) and Hahn's equation was developed for general hardwoods (Table 4.1).

These results indicate that it is difficult to know how well one equation will predict urban tree biomass for any number of urban forests around the country. Some authors have cut down a few sample trees and to test which equations fit best, however they developed a general equation for all urban species because of the time and monetary costs associated with testing species specific equations (McPherson and Simpson 2001). Importantly, studies on urban forests have used different sources and allometric equations, and comparing studies is confounded by this lack of congruence and high potential for error.

Comparisons at the Population Scale for Each Species

It was my objective to analyze if a wide range in biomass estimates was still apparent when equations from the literature were applied to populations of individual species. Overall, only 11 of the 31 literature equations predict biomass for a population of trees within about 20% of urban based estimates, ranging from 23% less to 11% more biomass; the rest of the equations predict ranges varying from 96% less to 109% more than urban estimates for the same population (Table 4.2). The maximum ranges of deviations from urban based equations were for *Acer plantenoides* and *Quercus macrocarpa*. For *Acer platenoides,* the equation by Bickelhaupt (1973) predicted a maximum percent difference of 205% for an individual tree, but this maximum percent deviation decreased for the population of *Acer platenoides* and only over-predicted by 109%. This difference in range is lower than for individual tree estimates only because the prediction associated with the population of *Acer plantenoides* was affected by its distribution (Table 4.2); there were a large number of young trees in this population, and most of the deviation from the urban based equation was for trees with larger DBHs.

Although population distributions did affect biomass estimates and for some species reduced the range of variation predicted, there were many equations where deviations did not change, or increased. The deviation from urban based estimates remained similar for the population of *Quercus macrocarpa* and predicted 96% less biomass (originally 95-97% less) for the population of this species relative to the urban equation. This occurred because this particular equation equally underestimated biomass throughout the entire DBH range, so population distribution did not have an effect on the results. Furthermore, Pillsbury's (1998) equation for *Fraxinus pennsylvanica* predicted 27% less to 29% more biomass over the DBH range for an individual tree, but when this equation was applied to the *Fraxinus* population his equation predicted 43% less than the urban equation. Like the *Acer platenoides* population, the *Fraxinus* population is dominated by a very large number of young trees, but Pillsbury's equation deviated from urban estimates more when the trees were small as opposed to when the trees were large.

Four main trends appear when comparing the maximum and minimum literature based predictions for these populations (Figure 4.4):

1. The maximum literature equation predicts more biomass than the urban equation, but the minimum literature equation predicts a similar biomass to the urban equation (e.g. *Ulmus Americana* and *Ulmus pumilla*).

2. The minimum literature equation predicts less biomass than the urban equations, but the maximum literature equation predicts a similar biomass to the urban equation (e.g. *Fraxinus pennsylvanica* and *Populus sargentii*).
3. The urban equation predicts more biomass than both the maximum and minimum literature equation (e.g. *Gleditsia triacanthos* and *Celtis occidentalis*).
4. The urban equation predicts less biomass than both the maximum and minium literature equation (e.g. *Acer platenoides*).

Again, these results were a function of how different predictions were for individual trees, as well as the distribution of each population. For instance, *Ulmus americana, Ulmus pumilla*, and *Populus sargentii* only represented 4.4%, 3%, and 1.4% of the total street tree population respectively, yet the biomass predicted for these populations is generally higher than populations of *Gleditsia triacanthos, Tilia coradata, Quercus macrocarpa,* and *Celtis occidentalis* which all had a higher number of total trees in the street tree population (10%, 7%, 7%, and 6% respectively). Although there were fewer total trees in *Ulmus* and *Populus* populations there were a higher number of trees in the larger diameter classes (Figure 4.2). Overall, the range in biomass values predicted from the literature was still large and could lead to highly erroneous estimates of biomass, depending on the equation used and the population distribution.

Comparisons at the Community Scale for 11 Urban Tree Species Combined

My objective in the last analysis was to total the population estimates for each species and acquire predicted biomass ranges for all 10,551 trees that represent 11 species in the Fort Collins street tree community. The literature “highest biomass” equations estimated over 1,500,000 kg or 18% more biomass for the Fort Collins tree community, while the literature "lowest biomass" equations estimated 3,400,000 kg or 40% less biomass than urban based estimates (Figure 4.5). Again the distribution of sizes within each species population was a factor: the equations associated with *Ulmus americana, Fraxinus pennsylvanica, Ulmus pumilla, Populus sargentii, Gleditsia triacanthos,* and *Celtis occidentalis* affected these results more than *Tilia cordata, Quercus macrocarpa, Acer saccharinum,* and *Gymnocladus dioicus*, because the former species have a higher number of trees in the smaller DBH classes (Figure 4.2).

This range of predictions for the entire community is a great deal lower than the ranges associated with individual trees, or populations of species (-40% to 18% rather than -95% to 205% and -95% to 109% respectively). This shows that potential errors associated with biomass estimates are diluted when a diversity of species are included as part of the analysis. However, the potential range in error as large as 60% is substantial suggesting that investigators comparing across sites should exercise extreme care when choosing allometric equations and interpreting results. Furthermore, characteristics associated with urban tree populations affect the results, and potential errors could increase.

General discussion

Similar issues regarding allometric relationshipshave been identified in traditional forest biomass analyses, especially in tropical forests. The accuracy of using allometric equations in predicting stand biomass has been practically untested (Clark et al. 2001). A study by Araujo et al. (1999) compared actual fresh biomass harvested in an Amazonian forest to predictions using 14 allometric equations developed elsewhere in the forest.

They showed that some equations predicted biomass well, while others produced errors up to 318% higher than actual biomass. This could be a result of the heterogeneity that exists in tropical forests or a product of the difficulty associated with developing allometric equations for tropical trees that have buttresses.

There could be many potential causes for literature based equations to deviate from the equations I developed for Fort Collins. If heterogeneity within one forest type could affect allometric relationships, there is also reason to believe that equations developed for trees in traditional forest settings, often grown in completely different climates, may not represent urban trees well. Furthermore, the equations from the literature were sometimes for a different species, or were developed for a large group of species.

I did not compare direct biomass measurements from an urban environment to literature based allometric equations in this analysis, so differences in methodology could also have played a role in deviations from urban based equations. For developing volume equations I tested the accuracy of the LiDAR method for measuring tree diameters, I had a large amount of information for each individual tree because I used a high scanning resolution, and I had a large sample size associated with each species (17-22 trees per species) (McHale and Lefsky, in prep; McHale et al., in prep). For this analysis, however, I converted volume to biomass using average specific gravity for each species, and there has not yet been research on whether or not specific gravity values are different for urban trees.

Preliminary results comparing predictions from available allometric equations to biomass for a small sample of urban trees that were actually cut down and weighed also showed a large range in potential variation that is dependent on species. For certain species allometric equations overestimated biomass by 35-45%, while other predictions underestimated biomass by 5-50% (Jo and McPherson 1995). These results support my findings that variation associated with literature based equations developed for trees in traditional forests, can be large and is dependent on the species being evaluated.

Conclusion

I found that some of the equations published in the literature produce similar estimates of biomass to urban based allometric equations; however, depending on scale and species or population and community characteristics, potential errors ranged from 60-300%. This means we can not be confident in the accuracy of urban biomass studies at this time, and can not compare biomass estimates from two studies that utilize different allometric equations from the literature. There are a host of potential reasons for these differences in biomass predictions, but more research on urban tree biomass, allometry, and ecophysiology is needed.

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Tables

Table 4.1

Sources for allometric equations used in urban biomass studies. For some species there is a limited amount of information, so general equations or equations for different species were used.

Species	Equation	Source Species	DBH Range (cm)	Source
Bur Oak, *Quercus macrocarpa*	QU1	Red Oak	13-129	Brenneman et al. 1978, Ter-Mikaelian and Korzukhin 1997
	QU2	Bur Oak	3-40	Perala and Alban 1994
	QU3	Oak	14-163	Bunce 1968
Silver Maple, *Acer saccharinum*	ACS1	Sugar Maple	6-168	Young et al. 1980, Ter-Mikaelian and Korzukhin 1997
	ACS2	London Plane	15-74	Pillsbury et al. 1998
	ACS3	Silver Maple	5-46	Alemdag 1984
Green Ash, *Fraxinus pennsylvanica*	FR1	White Ash	13-129	Brenneman et al. 1978, Ter-Mikaelian and Korzukhin 1997
	FR2	Green Ash	15-84	Pillsbury et al. 1998
	FR3	Green Ash	3-79	Schlaegel 1984
	FR4	Ash	9-104	Bunce 1968
Honeylocust, *Gleditsia triacanthos*	GL1	General	10-85	Harris et al. 1973, Jenkins et al. 2004
	GL2	General	>94	Hahn 1984
	GL3	Green Ash	15-84	Pillsbury et al. 1998
Little Leaf Linden, *Tilia cordata*	TI1	American Basswood	13-129	Brenneman et al. 1978, Ter-Mikaelian and Korzukhin 1997
	TI2	American Basswood	5-56	Alemdag 1984
Populus sargentii	PO1	Cottonwood	6-32	Standish et al. 1985
	PO2	Cottonwood	>94	Hahn 1984
American Elm, *Ulmus americana*	ULA1	American Elm	5-30	Perala and Alban 1993, Ter-Mikaelian and Korzukhin 1997
	ULA2	General	10-85	Harris et al. 1973,

				Jenkins et al. 2004
	ULA3	Elm	>94	Hahn 1984
	ULA4	American Elm	5-56	Alemdag 1984
Hackberry, *Celtis occidentalis*	CE1	Hackberry	>94	Hahn 1984
Siberian Elm, *Ulmus pumilla*	ULP1	General	10-85	Harris et al. 1973, Jenkins et al. 2004
	ULP2	Sawleaf Zelkova	6-34	Pillsbury et al. 1998
	ULP3	American Elm	5-30	Perala and Alban 1993, Ter-Mikaelian and Korzukhin 1997
	ULP4	Elm	>94	Hahn 1984
	ULP5	American Elm	5-56	Alemdag 1984
Kentucky Coffee Tree, *Gymnocladus dioicus*	GY1	General	10-85	Harris et al. 1973, Jenkins et al. 2004
	GY2	General	>94	Hahn 1984
Norway Maple, *Acer platenoides*	ACP1	Sugar Maple	6-168	Young et al. 1980, Ter-Mikaelian and Korzukhin 1997
	ACP2	Sugar Maple	3-66	Bickelhaupt et al. 1973, Tritton and Hornbeck 1982

Table 4.2

Percent deviation of literature equations from urban based equations. Equation numbers 1-5 correspond to equation numbers for each species in Table 2. Species code is the first two letters of the genus and species names combined. Maximum and minimum figures represent percent deviation of the literature equations for individual trees across the entire range of DBH values. Population values are the percent deviations from urban based equations when both the urban and literature equations were applied to an entire population of one species. Negative values mean that the literature equation predicted less biomass than the urban equation.

Spp. Code		**Percent Deviation from Urban Based Equations for Equations:**				
		1	**2**	**3**	**4**	**5**
QUMA	Max	-19	-45	-97	NA	NA
	Min	1	-26	-95	NA	NA
	Population	-10	-35	-96	NA	NA
ACSA	Max	25	-58	-53	NA	NA
	Min	37	-8	-25	NA	NA
		33	-26	-35	NA	NA
FRPE	Max	-29	-63	-44	-96	NA
	Min	27	-23	-31	-94	NA
	Population	2	-43	-37	-95	NA
GLTR	Max	-44	-67	-72	NA	NA
	Min	-14	-52	-22	NA	NA
	Population	-23	-60	-41	NA	NA
TICO	Max	-33	-72	NA	NA	NA
	Min	58	-8	NA	NA	NA
	Population	7	-46	NA	NA	NA
POSA	Max	-64	-70	NA	NA	NA
	Min	-16	21	NA	NA	NA
	Population	-31	7	NA	NA	NA
ULAM	Max	-44	-34	-57	-38	NA
	Min	74	73	2	16	NA
	Population	48	45	-11	-2	NA
CEOC	Max	-65	NA	NA	NA	NA
	Min	-8	NA	NA	NA	NA
	Population	-32	NA	NA	NA	NA
ULPU	Max	-56	-76	-63	-71	69

	Min	116	75	120	26	-50
	Population	60	21	58	-4	11
GYDI	Max	2	-21	NA	NA	NA
	Min	53	57	NA	NA	NA
	Population	34	-7	NA	NA	NA
ACPL	Max	-21	-10	NA	NA	NA
	Min	169	205	NA	NA	NA
	Population	83	109	NA	NA	NA

Figures

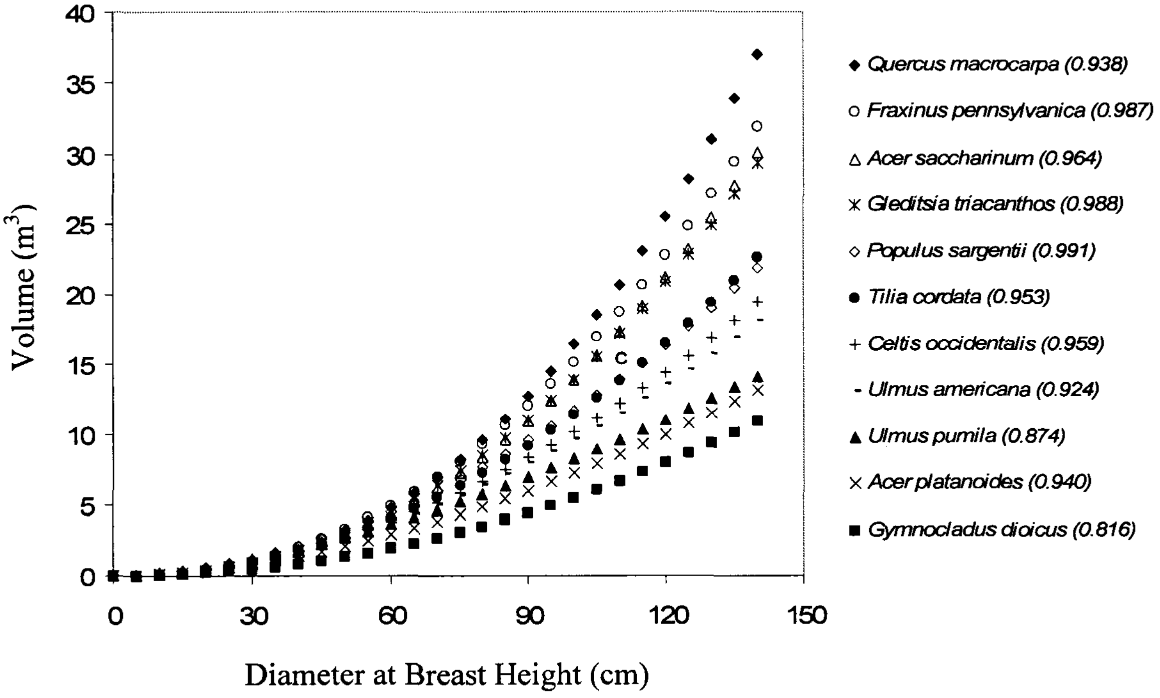

Figure 4.1

Volume Equations for 11 dominant urban tree species in Fort Collins, Colorado, derived from LiDAR estimates (McHale et al. Chapter 2). The numbers in parentheses represent R^2 values.

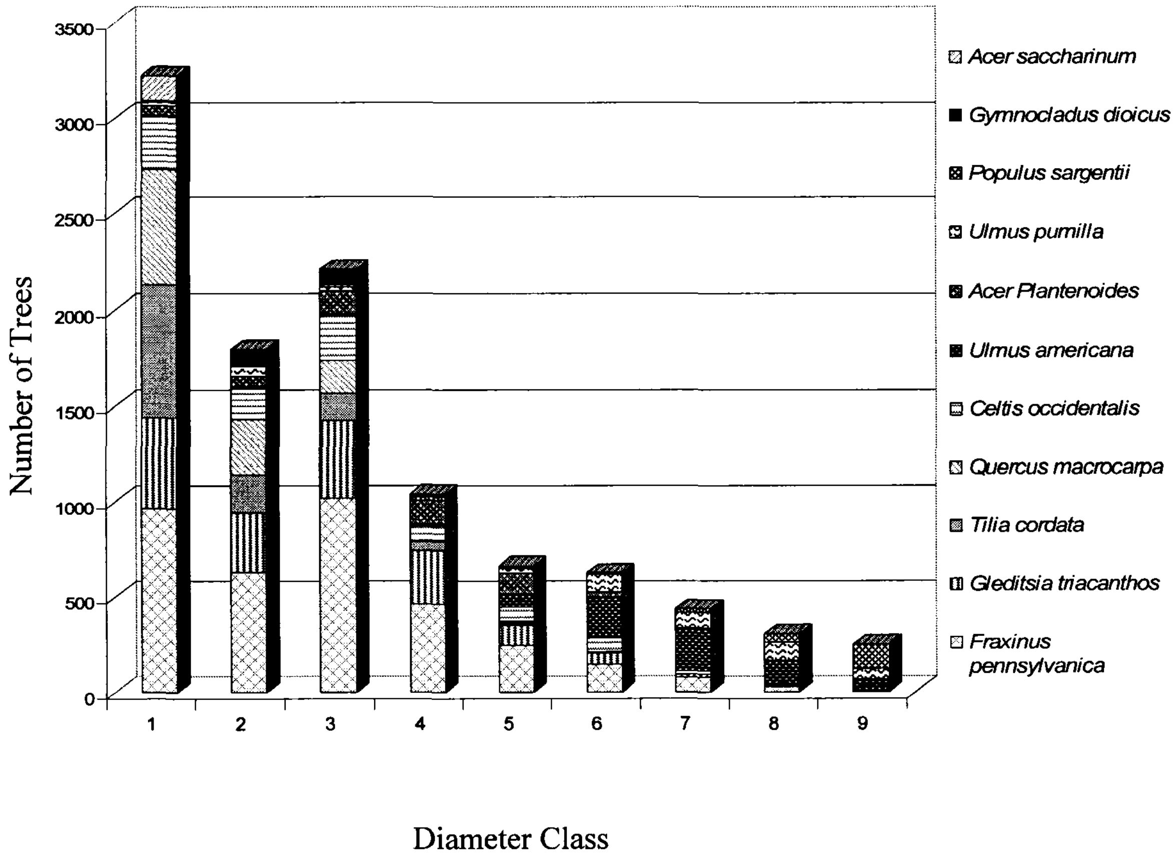

Figure 4.2

Diameter class distribution for the urban street tree community in Fort Collins, Colorado. *Fraxinus pennsylvanica* is the most abundant tree in the community, but its population is composed of a large number of younger trees. As opposed to *Ulmus americana* and *Populus sargentii*, which have much fewer trees in the population, have a larger number of those trees are in larger diameter classes.

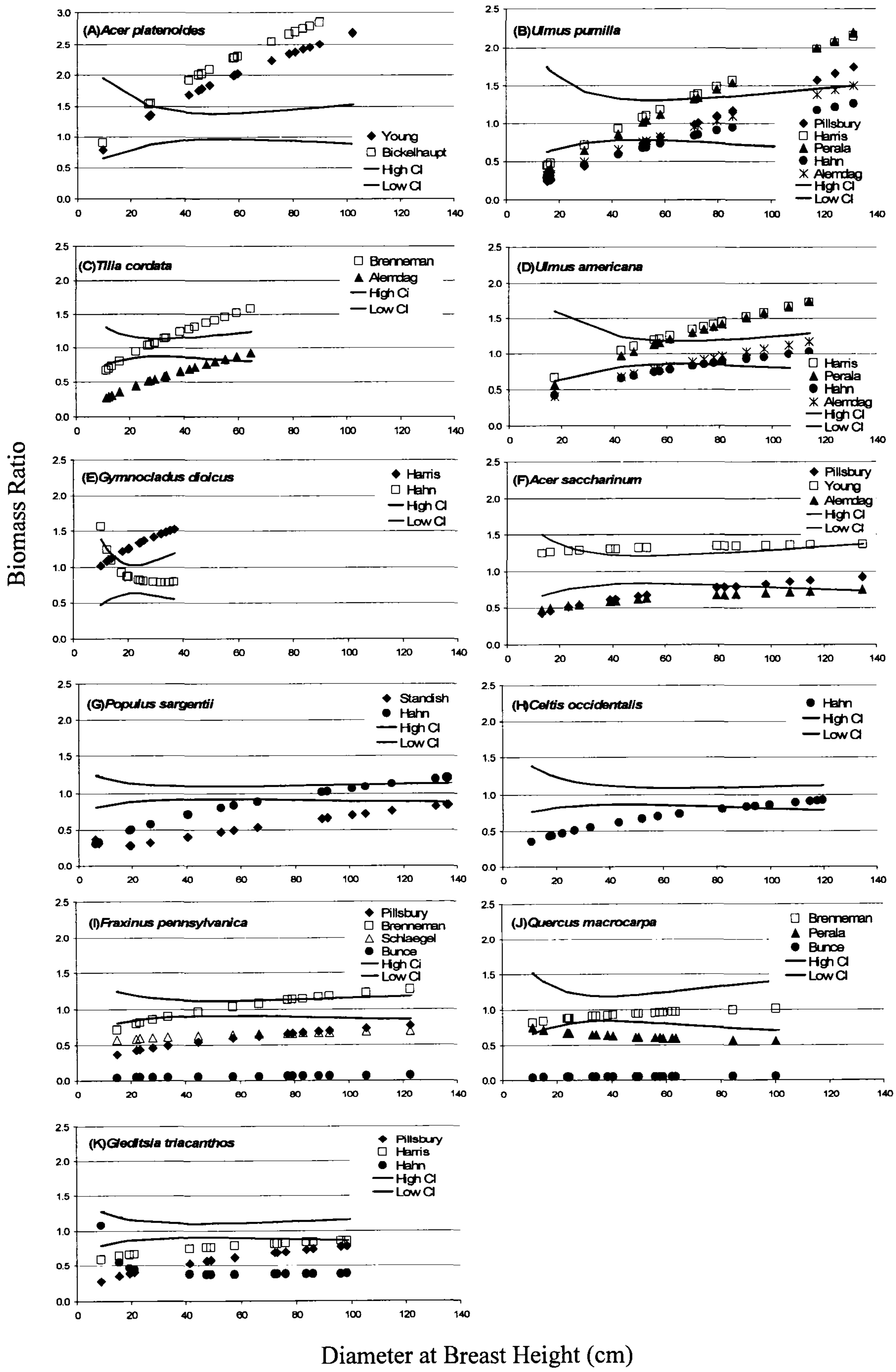
Biomass Ratio
(A) Acer platenoides
Young
Bickelhaupt
High CI
Low CI
(B) Ulmus pumilla
Pillsbury
Harris
Perala
Hahn
Alemdag
High CI
Low CI
(C) Tilia cordata
Brenneman
Alemdag
High CI
Low CI
(D) Ulmus americana
Harris
Perala
Hahn
Alemdag
High CI
Low CI
(E) Gymnocladus dioicus
Harris
Hahn
High CI
Low CI
(F) Acer saccharinum
Pillsbury
Young
Alemdag
High CI
Low CI
(G) Populus sargentii
Standish
Hahn
High CI
Low CI
(H) Celtis occidentalis
Hahn
High CI
Low CI
(I) Fraxinus pennsylvanica
Pillsbury
Brenneman
Schlaegel
Bunce
High CI
Low CI
(J) Quercus macrocarpa
Brenneman
Perala
Bunce
High CI
Low CI
(K) Gleditsia triacanthos
Pillsbury
Harris
Hahn
High CI
Low CI
0.0
0.5
1.0
1.5
2.0
2.5
3.0
0
20
40
60
80
100
120
140
Diameter at Breast Height (cm)

Figure 4.3

Biomass ratios for available equations from the literature. The ratio is the biomass predicted from a literature based equation divided by the biomass estimated using urban based equations; therefore the reference value is equal to one for urban based equations. The CI lines represent 95% confidence intervals associated with the urban tree sample for each species.

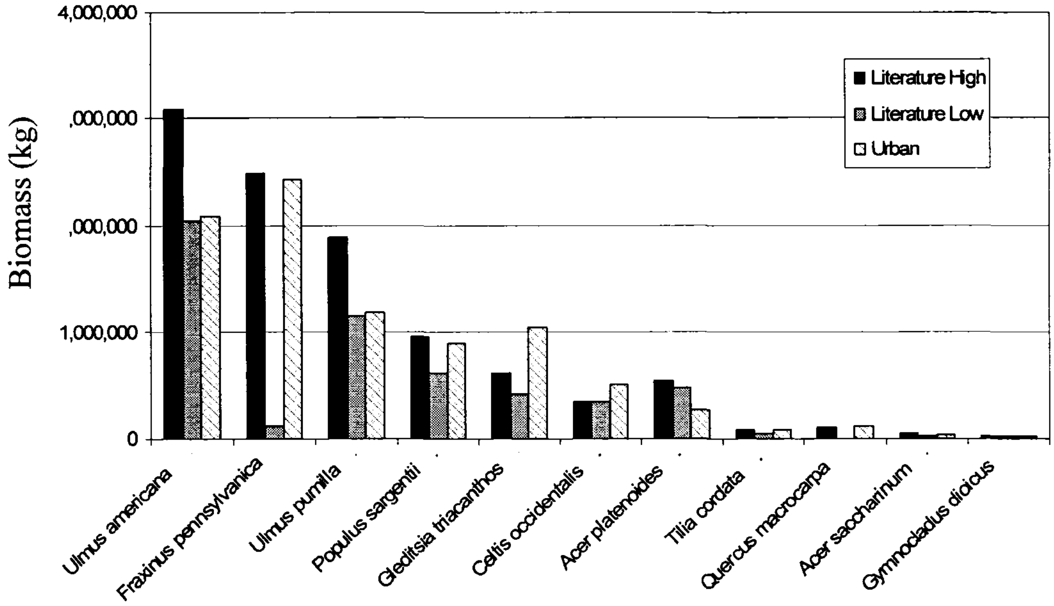

Figure 4.4

Comparison of biomass estimates for individual species populations. Highest and lowest predictions of literature based equations were analyzed for each population and compared to biomass estimates using urban based equations.

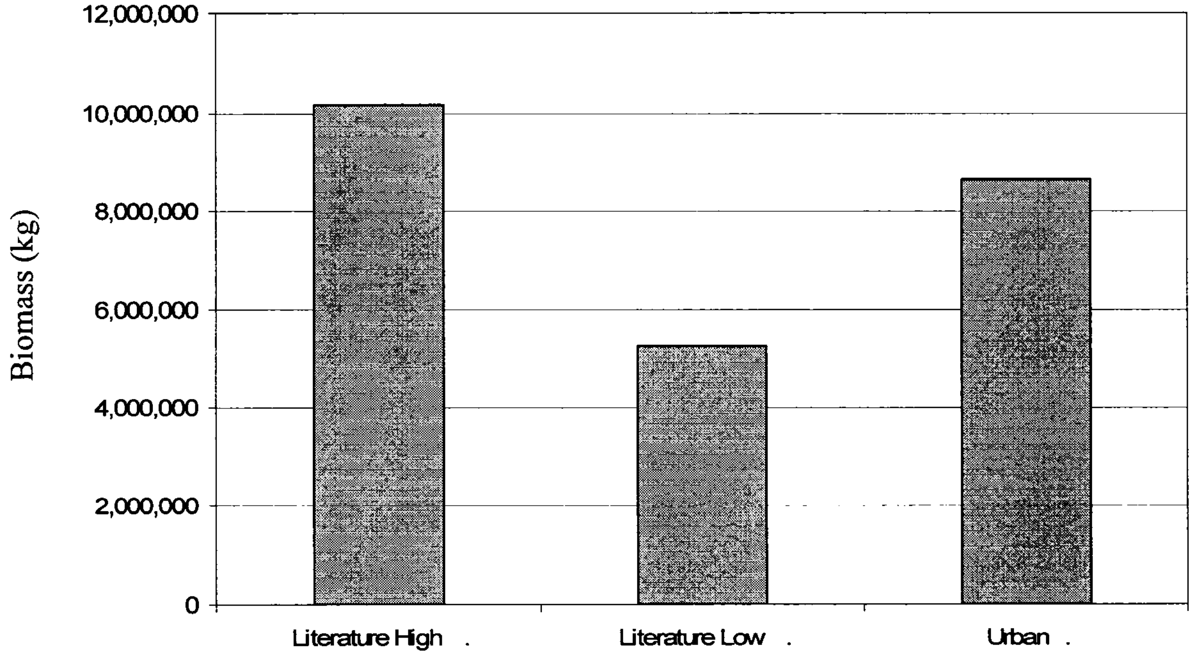

Figure 4.5

Literature high and low biomass estimates vs. urban based estimates for the entire community of 11 street tree species. High estimates resulted in an over-prediction of 18%, and low estimates under-predicted by 40%, in comparison to the urban based equations.

Chapter 5: POTENTIAL CARBON STORAGE CAPACITY OF URBAN FORESTS ALONG THE COLORADO FRONT RANGE

Abstract

Urbanization is increasing steadily on a global scale and can have a significant effect on nutrient cycling and carbon dynamics. Urban land areas may be associated with a decrease in potential carbon storage pools in many systems, however in arid and semi-arid systems some carbon pools may increase with urbanization because of anthropogenic water and nutrient inputs. The Colorado Front Range is interesting as a set of semi-arid ecosystems that represent one of the most rapidly growing regions in the US. Previous research in this area has shown enhanced carbon cycling rates and increased surface soil carbon in urbanized areas relative to the surrounding short grass steppe and agricultural systems. These studies focused on suburban lawns, without real consideration of the major increases in non-native tree biomass, a potentially large carbon reservoir. We modeled potential carbon storage in aboveground woody biomass using allometric equations developed for urban trees in the city of Fort Collins, Colorado. In my model, potential carbon storage depends on species composition, tree density, and age distribution. My results suggest that mature urban forests with a density of 121 trees/ha can store up to 11,000 gC/m^2 in their aboveground biomass; this aboveground carbon pool is similar to that of most productive forests in Colorado.

Key Words: Urban trees; biomass; carbon dioxide; carbon budget; Front Range of Colorado

Introduction

Urban forest management is considered to be a good option for reducing atmospheric carbon dioxide (CO_2) (Sejo 1989, Houghton et al.1990, Freedman et al. 1982, Trexler and Haugen 1995, Freedman et al. 1996). Recent research on urban greenspace and urban forests shows that the vegetation usually offsets a very small portion of the CO_2 emitted from urban areas (Nowak 1994, Jo 2002, McPherson), however urban greenspace and planning could be one of the more time and cost effective options for reducing atmospheric CO_2 concentrations (Jo 2002). Urban trees not only assimilate carbon (C), but they can also reduce energy related CO_2 emissions by shading or blocking winds (McPherson 1984, Huang et al. 1987, Nowak 1993, Simpson 1998, Akbari 2002). Furthermore, urban forests provide a multitude of other benefits for communities; trees can negate many of the negative effects associated with impervious surfaces and contribute to higher water and air quality (Nowak et al. 2002, McPherson et al. 2003, McPherson et al. 2005).

Research on urban forests globally has shown that C storage in urban trees ranges from 355-9500 gC/m^2 with the US national average estimated at 2510 gC/m^2 (Table 5.1). The average urban forest contains about half as much C as a natural forest on a per area basis partly because tree density in natural forests is often much higher than in urban forests (McPherson 1998). However, analyses on C storage per tree suggest that individual urban trees may store up to 4 times more than their counterparts in natural forests because age structure is weighted by large trees in urban environments, and faster growth rates are associated with lower density (Nowak 1994). Moreover, recent studies suggest that in arid and semi-arid systems, urban C storage pools in both vegetation and soils may increase due to stimulation of net primary productivity by water and nutrient inputs (Imhoff et al. 2004, Kaye et al. 2005, Golubiewski 2006). Finally enhanced C storage pools have also been shown to occur with introduction of non native vegetation. For instance, along the Front Range, woody vegetation is almost absent in the native semi-arid shortgrass steppe, however with time since urbanization woody vegetation has become an increasingly significant C pool (Kaye et al. 2005, Golubiewski 2006)

Previous research on urban forests has proven valuable on many fronts including increasing our understanding of urban forests' role in the global carbon cycle; however, most of the estimations of biomass and carbon have relied heavily on information derived from trees in natural forest settings. Because of the lack of research on urban tree growth and allometry, researchers are forced to use allometric relationships developed for natural trees. McHale et al. (in prep, Chapter 4 of this dissertation) found that potentially large errors (up to 200%) were associated with using allometric equations developed for natural forests when predicting the amount of volume, biomass or carbon stored in urban trees. Allometries developed for urban trees are necessary for accurate assessment.

Past research on urban forests has focused on the average C storage of these forests in their current condition while indicating that much potential exists for increases in tree cover. It is also valuable to assess the carbon storage potential because urban areas could, with management and planning, play a larger role in regional carbon cycles than they do presently. My goals were: 1) To use allometric relationships developed specifically in Fort Collins, Colorado (McHale et al, in prep, Chapter 3 of this dissertation) to analyze the potential carbon storage capacity of an urban forest along the Colorado Front Range, one of the most rapidly expanding urban areas in the nation; 2) To analyze the effects of tree density (trees/ha) and urban forest age (young, middle aged and mature forests) on carbon storage capacity for this region; 3) To compare these estimates to previous estimates for carbon storage in urban forests, as well as for natural forests in Colorado.

Methods

Study area

Fort Collins is the most northern city along the Colorado Front Range (latitude: 40.6N, longitude: 105.1W). The city lies within a semi-arid region, receiving 38.5 cm of precipitation on average per year, with an average temperature of 8.9^{O} C (100 year record at Colorado State University, CO USA). Urbanization along the Front Range converts ecosystems dominated by native drought tolerant grasses to systems consisting of lawns, herbs, shrubs and trees that typically receive and depend on large nutrient and water inputs (Kaye et al. 2005, Golubiewski 2006). Fort Collins was an ideal location for this study because it contains a large and diverse population of well-maintained street and park trees.

The urban forest model

To evaluate potential carbon storage capacity, I developed a set of equations that allowed me to analyze the relative effects of two main variables, tree density and stand age or maturity. Tree density has previously been shown to be one of the main variables influencing carbon storage in urban forests (Rowntree and Nowak 1991). The average urban forest in the Unites States has been estimated to have about 21 trees/ha and 28% cover (Rowntree and Nowak 1991, Nowak 1994, Nowak and Crane 2002). However, tree density varies greatly depending on region and it can often decline as cover increases with time due to large trees (Table 5.1). Studies in the United States thus far indicate that urban trees can reach a density of 121 trees/ha (Nowak 1994), although for suburban areas and urban areas outside of the country, higher densities have been recorded (Table 5.1). For the purposes of this analysis, I modeled tree densities from 21 to 121 trees/ha.

The maturity or age of a forest also has a large influence on carbon storage because older trees are larger and store more carbon. McPherson and Rowntree (1986) established the distribution of trees by diameter classes (diameter breast height or DBH size) in young, middle-aged, and mature forest or what they refer to as Type I, II, and III forests respectively (Table 5.2). At each tree density, I modeled all three forest types.

A third important variable for carbon storage is species composition; some species grow to be a larger size when they are mature and therefore store more carbon. For this analysis I held species composition constant. I assumed that the species composition of the entire model urban forest was similar to that of the street tree population in Fort Collins, Colorado, because I had a detailed tree inventory for the city's street trees. I used volume equations developed for the 11 dominant tree species in Fort Collins (McHale et al., in prep, Chapter 3 of this dissertation) to calculate biomass and carbon. The 11 species studied were 64% of the total street tree population, while most of the remaining species each made up much less than 1 percent of the population. I limited this analysis to use of these equations because natural forest based allometric equations may be inaccurate when applied to urban trees (McHale et al., in prep, Chapter 4 of this dissertation), and equations developed for an urban forests in California were significantly different from equations developed specifically for trees in Fort Collins (McHale et al., in prep, Chapter 3 of this dissertation).

Species that were in the same genus, or were functionally similar to one of the 11 species, were grouped together. This was easily accomplished since most of the remaining species were categorized by their genera only (*e.g. Quercus* spp.). There were some species, however, that did not fit well into 1 of the 11 species groups. For instance, *Malus* and *Pyrus* spp. are considered to be small stature trees at maturity where the smallest tree analyzed in the volume study was *Gymocladus dioicus*, a small to medium stature tree. I developed a 12th group that had half the biomass and carbon storage of *Gymocladus dioicus* at all diameters to represent these smaller species (Table 5.3).

Results and Discussion

My results show that under maximum density and maturity potential carbon storage could reach almost 11,000 gC/m2 along the Front Range (Figure 5.1). Previous research shows urban forests in the United States store 300-4700 gC/m2 with the national average estimated as 2000 gC/m2 (Table 5.1, Nowak and Crane 2002); these results fall within the lower range of carbon storage predicted by my model. In contrast, results from urban forest studies in other nations signify noteworthy differences in existing urban tree carbon storage compared to the United States. A study in Nova Scotia, Canada indicated that their urban forests are very dense and mature and can store up to 9500 gC/m^2; these mature forests with 158 trees/ha fall within the range of results predicted as possible for the Colorado Front Range. On the other end of the spectrum are urban forests in Korea that store less than the typical urban forest in the United States (470-1300 gC/m^2).

Prior researchers estimated that urban forest storage is about half that of natural forests, which on average store 5500 g/m^2 (Birdsey 1992, McPherson 1998); however, my results show that along the Front Range, potential carbon storage could well exceed that value (Figure 5.1). Furthermore, urban forests could store as much or more than the most productive forests in Colorado; ponderosa and lodgepole pine forests store 4000-9000 gC/m^2 (Ryan and Waring 1992, Hall et al. 2005). This means that not only are urban forests the most influential forests, but they are also a potentially large carbon storage pool that could affect the global carbon cycle.

Additionally carbon storage potential of urban areas is high with a relatively low tree density. In this analysis I included 121 trees/ha as the maximum density because that is the highest density recorded for urban areas in the US thus far; however this density is still quite low, especially compared to natural forests that have hundreds to thousands of trees/ha. This phenomenon of high carbon storage associated with a relatively low tree density has been noticed in the past; Nowak and Crane (2002) concluded that natural forests can have half the carbon density of urban forests per area of tree cover because urban forests tend to have a greater number of large trees.

The Colorado Front Range has been one of the fastest growing metropolitan centers in the United States. At least 24 of the major cities along the Front Range have population densities over 1000 persons/ha, the defining number for urban area classification in the US Census (US Census 2000). These cities approximately cover an area of 245,000 ha; a young urban forest covering this area with an average tree density of 21 trees/ha would store over 1 million tonnes of C (Table 5.4). These results are comparable to a study conducted by American Forests (2001) that showed a smaller portion of the Front Range could store over a million tonnes of C with an increase in tree cover around the Denver Metro Area.

Urban systems along the Front Range were originally part of the native shortgrass steppe ecosystem. Golubiewski (2006) estimated that the native shortgrass steppe stores a little over 3000 gC/m2; therefore, the shortgrass steppe covering the same area would only store 800 tonnes of carbon. Furthermore, my results suggest a mature urban forest along the Colorado Front Range could potentially store over 26 million tonnes of carbon (Table 5.4). In comparison to the shortgrass steppe this carbon storage pool is exceptionally high; however, when compared to the amount of emissions from the population residing along the Front Range, the size of this pool seems less significant. I used average per capita emissions estimates (Energy Information Administration 2004) and calculated that the population associated with the major cities I analyzed, emits over 48 million tonnes of CO_2 a year. That means that this urban population emits almost as much CO_2 in two years as a mature and dense urban forest would offset in C storage over its entire maturation period (about 30-50 years). Interestingly, the area I included in this analysis covers less than 1% of the total land area of Colorado, while 55% of Colorado's total population resides there; urban forests may only be able to offset a relatively small amount of emissions but they also cover a very small proportion of the land area.

Future directions

In this model I only account for aboveground carbon storage making my estimates of urban forest carbon storage pools conservative. There is little information available on urban tree roots, and past studies have calculated belowground biomass by multiplying aboveground biomass by 0.25, which is the average amount of belowground biomass found in natural forests (Jo and McPherson 1995). This may under-predict belowground biomass since plants in well lit environments have been shown to have more roots

(Maggs 1960, Whittaker 1962, Jo and McPherson 1995). On the other hand this could be an over-prediction if irrigation and fertilization cause a decrease in root biomass (Bray 1863, Jo and McPherson 1995). Future research on below ground carbon storage in urban areas will greatly improve estimates on total carbon storage capacity in these areas.

Additionally, trees in urban areas affect energy usage through shading and serving as windbreaks. Previous estimates of energy effects on CO_2 emissions vary to a great extent and a better understanding of these effects is much needed. Akabari et al. (1989) estimated that on average nationally urban trees reduce 15 times more carbon through energy savings than through the process of assimilation, while Nowak (1994) predicted that carbon reduced through energy savings is about 4 times that of assimilation. The ratio of energy related carbon reduction to carbon assimilation has been very low in a few cases as well. For instance, in Chicago and Sacramento ratios were found to be 1:28 and 1:3 respectively (Nowak 1994, Simpson 1998). Low ratios were a function of cleaner energy supplies like hydroelectric, nuclear, wind, and solar, or less than ideal tree placement (Nowak 1994). In Colorado it is likely that the ratio would be low, even though coal is the main energy source, because shading buildings during winter can cause heating costs to increase rather than decrease (McPherson and Simpson 2001, McHale et al. 2007, Chapter 2 of this dissertation).

Urban trees tend to need regular maintenance like pruning and watering and these activities can lead to CO_2 emissions. When carbon released from maintenance activities is accounted for urban forests over time could become a net CO_2 emitter. However energy conservation can be used to set off those emissions or decomposition can be limited by dedicating dead trees to long-term C storage pools (Nowak et al. 2002b).

Future analyses on decomposition and potential contribution of longer term C pools, will assist in determining the length of time C assimilated by trees remains in storage.

Furthermore, urban areas are generally highly maintained environments receiving large inputs of water and nutrients. A study of residential greenspace in Chicago revealed that 60 percent of the CO_2 sequestered each year was returned to the atmosphere through maintenance activities (Jo and McPherson 1995). To date, this is the only study I can find in the literature that attempts to create a fully detailed carbon budget for an urban area. In order to improve projections of 21st century carbon budgets, more information is needed on urbanization: we need comprehensive analyses on total urban ecosystem carbon balance for multiple regions (Pataki et al. 2006).

Conclusion

Since a relatively small area is occupied by urban areas carbon storage capacity of these systems has often been overlooked. This research suggests that not only do carbon storage pools increase with urbanization, but urban forests themselves can be very large carbon storage pools. With rapid urban expansion along the Colorado Front Range this potential pool could be significant on the continental scale. Although urbanization of semi-arid environments may increase net primary productivity and enhance carbon storage capacity, there is at least one significant tradeoff and that is the limited amount of water resources. Furthermore, urban areas are highly maintained and this could lead to large quantities of CO_2 emitted. The best way to understand the true role urban areas play in the global carbon cycle in the future is to begin to develop large scale carbon budgets that incorporate all human related emissions as well as information on carbon storage pools. Developing a large scale carbon budget is a difficult endeavor, but my research implies it is a worthy one.

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Tables

Table 5.1

Carbon Storage in Urban Forests

Place	Carbon Storage (g/m2)	Trees/ha	Percent cover	Source
National Average	2510	21	28%	Nowak and Crane 2002, Rowntree and Nowak 1991, Nowak 1994
Chicago, IL	1410	68	Overall 19.4%	Nowak 1994
DuPage County, Chicago, IL	1770	173	Overall 19.4%	Nowak 1994
Suburban Cook County, Chicago, IL	1700	169	Overall 19.4%	Nowak 1994
Oakland, CA	1250	121		Nowak 1993, Nowak 1994
Shorewood, WI	2280		39%	(Nowak 1993), Dorney et. al. 1985
Halifax, Nova Scotia (Oldest Res. Neighborbhood)	6550	145	82.6%	Freedman et al. 1996
Halifax, Nova Scotia, Mature Natural Area/Urban Parks	7160			Freedman et al. 1996
Halifax, Nova Scotia, (Young Res. Neighborhood)	8500	241	13.9%	Freedman et al. 1996
Halifax, Nova Scotia, (Young-Middle Aged Res. Neighborhood)	9500	158	31.9%	Freedman et al. 1996
Halifax, Nova Scotia, (Sparsley Treed Institutional areas)	1060			Freedman et al. 1996
Sacramento, CA	4690	73	13%	Nowak and Crane 2002
Jersey City, NJ	500			
Boulder, CO	2070	18-3048		Golubiewski 2006

Sacramento County, CA	846		McPherson 1998
Sacramento, CA (City)	4695		McPherson 1998
Sacramento, CA (Suburban Developments)	1119		McPherson 1998
Sacramento, CA (Rural)	355	10	McPherson 1998
Yongin, Korea	1310	130	Jo and Tae-Won 2000
Chuncheon, Korea	470	150	Jo 2002
Kangleung, Korea	630	150	Jo 2002
Kangnam, Seoul, Korea	660	330	Jo 2002
Junglang, Seoul, Korea	720	310	Jo 2002

Table 5.2

Tree distribution associated with each urban forest type as documented by McPherson and Rowntree (1986).

Forest Type	Percent of trees in each DBH class					
	0-15 cm	16-30 cm	31-45 cm	46-60 cm	61-80 cm	80+ cm
Type I: Young	42	27	14	10	6	1
Type II: Midde-aged	21	29	26	8	8	8
Type III: Mature	23	15	20	16	18	8

Table 5.3

Percentage of trees in the 12 species groups that were used to represent a model urban forest.

Species or Species Group	Original Percentage of the Street Tree Population	Percentage used for Modeling Purposes
Fraxinus pennsylvanica	22	26
Quercus macrocarpa	7	12
Gleditsia triancanthos	10	12
Tilia cordata	7	12
Acer platenoides	3	7
Celtis occidentalis	6	7
Ulmus pumila	3	5
Ulmus americana	4	4
Populus sargentii	1	3
Acer saccharinum	1	2
Gymnocladus dioicus	1	3
½ *Gymnocladus* (small stature trees)	8	8

Table 5.4

Potential C storage capacity (tonnes) for large* cities along the Colorado Front Range

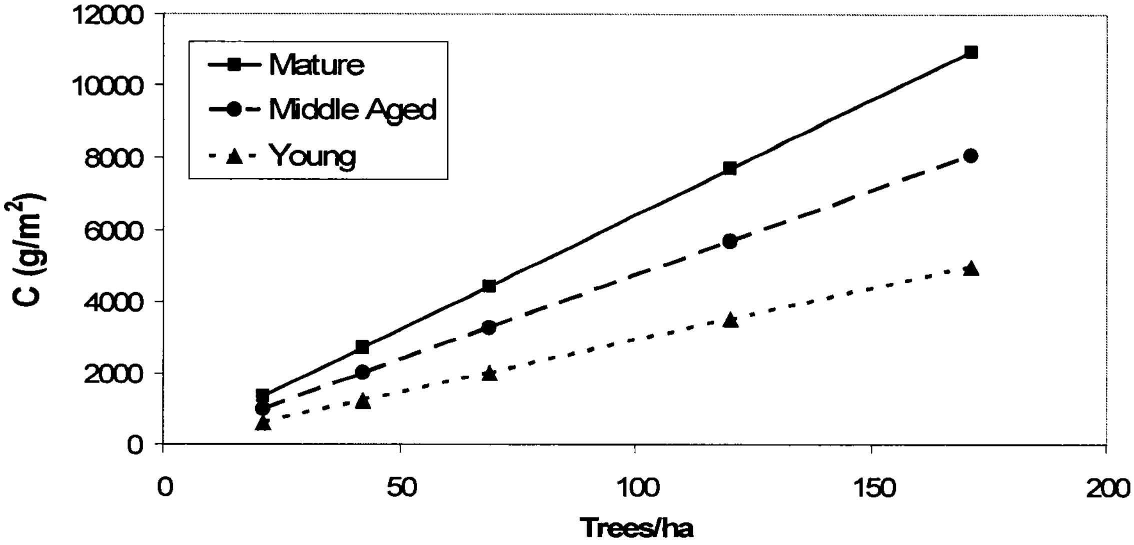
Tree Density	Mature Urban Forest	Young Urban Forest
21	3,209,008	1,499,232
171	26,863,354	12,208,031

*Includes Arvada, Aurora, Boulder, Brighton, Broomfield, Castle Rock, Colorado Springs, Denver, Highlands Ranch, Englewood, Evans, Greeley, Lakewood, Littleton, Longmont, Louisville, Loveland, Parker, Superior, Thornton, Westminster, Wheatridge, Windsor, Northglenn.

Figures

Figure 5.1

Modeling results for potential carbon storage capacity of urban forests along the Colorado Front Range.



Chapter 6: CONCLUSION TO THE DISSERTATION

In this dissertation, I addressed the potential cost effectiveness of tree planting projects in carbon credit markets, developed allometric equations for urban trees, analyzed the variability associated with using traditional forest allometric equations to estimate urban forest biomass, and estimated the potential carbon storage capacity of urban forests along the Front Range. I aimed to fill in some gaps associated with these issues within the urban forestry research field.

The sensitivity analysis indicated that certain urban forestry projects may be cost effective solutions for mitigating atmospheric CO_2 concentrations, however, indirect effects of reductions on energy related emissions contributed significantly to the total amount of CO_2 reduced. The model I used to analyze the variables that influence cost effectiveness showed that rate of carbon assimilation was the prominent variable affecting cost effectiveness. Carbon assimilation in the model was based on three general tree growth zones, and total biomass in those growth zones was a function of three tree sizes (i.e. trees of large, medium, and small stature at maturity). Although for the purposes of the cost effectiveness study this simplification was justifiable in the fact that I was studying effects on a general scale, but for tree planting project to be included in carbon credit markets we would have to more accurately quantify urban carbon storage.

Allometric relationships are needed to quantify carbon storage in urban tree biomass and to date only one study on urban tree allometry has been published. I implemented a new method for estimating total tree volume, and developed allometric relationships for urban trees that should be of use along the Colorado Front Range. These equations are useful both because the Front Range is one of the fastest growing metropolitan regions, and it is important to understand how carbon dynamics change with urbanization in semi-arid systems. Prior research has attempted to quantify the role of urban trees in these environments; although they have indicated there is potential for urban trees to be a significant carbon sink, we have no idea how well this pool has been estimated since the studies published have used allometric relationships developed for traditional forest trees. My research further suggests that equations developed for trees growing in urban areas in California would not accurately estimate tree volume in Fort Collins, and more research is needed on allometric relationships for urban trees in regional climate zones.

I further analyzed the potential errors associated with using allometric equations from traditional forests to estimate biomass stored in urban forests. Large variances were associated with equations that have been applied to urban forests but were developed in traditional forests. The large differences indicate that it is important to use allometric relationships developed for urban systems for more accurate quantification of urban forest biomass. Future research should focus on why urban allometric relationships are important, as well as on developing accurate estimates of carbon storage in urban trees.

Finally, I estimated the potential carbon storage capacity of urban forests growing in major cities along the Colorado Front Range. I found that this potential carbon storage pool could be quite large and far exceeds the storage capacity associated with the native shortgrass steppe ecosystem. A mature forest, however, could only offset the amount of carbon that is emitted in the atmosphere as CO_2 by the large population residing along the Front Range for a little more than two years. Even though urbanization is resulting in increased carbon storage capacity along the Front Range, in order to reduce the CO_2 emissions from that population will take more than planting trees. To better understand regional carbon dynamics complete carbon budgets are needed in the future.