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Urban forest biomass estimates: is it important to use allometric relationships developed specifically for urban trees?

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Abstract Many studies have analyzed the benefits, costs, and carbon storage capacity associated with urban trees. These studies have been limited by a lack of research on urban tree biomass, such that estimates of carbon storage in urban systems have relied upon allometric relationships developed in traditional forests. As urbanization increases globally, it is becoming important to more accurately evaluate carbon dynamics in these systems. Our goal was to understand the variability and range of potential error associated with using allometric relationships developed outside of urban environments. We compared biomass predictions from allometric relationships developed for urban trees in Fort Collins, Colorado to predictions from allometric equations from traditional forests, at both the individual species level and entire communities. A few of the equations from the literature predicted similar biomass to the urban-based predictions, but the range in variability for individual trees was over 300%. This variability declined at increasingly coarse scales, reaching as low as 60% for a street tree community containing 11 tree species and 10, 551 trees. When comparing biomass estimates between cities that implement various allometric relationships, we found that differences could be a function of variability rather than urban forest structure and function. Standardizing the methodology and implementing averaged equations across cities could be one potential solution to reducing variability; however, more accurate quantification of biomass and carbon storage in urban forests may depend on development of allometric relationships specifically for urban trees.

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Introduction

Urbanization is a major contributor to global environmental change and can extensively alter regional carbon dynamics (Pataki et al. 2006). In North America, studies have shown a decline in existing ecosystem carbon storage pools following urbanization, however in semi-arid and arid environments, urbanization can increase ecosystem 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 changing 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 noteworthy carbon storage pool along the Front Range, and its importance tends to increase with urban forest maturity (Kaye et al. 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 volume and biomass (McPherson and Simpson 2001; Pataki et al. 2006). 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 volume 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 (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 in Virginia 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 tree growth, allocation, and phenology, indicating that allometric relationships developed using trees in traditional forest settings may misrepresent urban tree form. Also, the variables that influence urban tree growth can fluctuate from one city to another, so that urban based allometric relationships change as well. Our goals were to develop a method for estimating biomass and carbon storage capacity of urban forests in Colorado using estimates of urban tree volume from Fort Collins, and to evaluate how different our estimates of biomass would be if we implemented methods employed by other studies across the nation. We focus on an individual tree scale and on population and community scales, in attempt to answer the questions: 1) What is the variability associated with using different allometric relationships for calculating biomass and carbon, and 2) at what scale, if any, could this variability be important?

Pataki et al. (2006) argue that it is important to evaluate both the individual impacts of each city or metropolitan area on carbon cycling, and how cities compare to one another. This study can help us evaluate whether there is a need to standardize the methodology associated with urban biomass studies across cities, and whether developing urban-specific allometric relationships would be valuable.

Methods

Study area

Fort Collins (latitude: 40.6°N, longitude: 105.1°W) contains a large and diverse population of well-maintained street and park trees, most of which are not native to the surrounding the region. This system receives 38.5 cm of precipitation on average per year, and has a mean annual temperature of 8.9° C (100 year record at Colorado State University, CO, USA); however, the urban vegetation receives a large amount of additional water and nutrients (Kaye et al. 2005). Existing data from the Fort Collins municipal forest inventory were accessible (McHale, unpublished data), and McPherson et al. (2003) recently conducted a study in Fort Collins on the benefits of urban street trees, which allowed us to build on local urban forestry research.

Field measurements

The ideal method for measuring aboveground biomass and carbon is to destructively sample and physically weigh entire trees, however this method is time consuming (Ketterings et al. 2001), and impractical for acquiring data on a number of species in urban environments. It is particularly expensive to cut down urban trees; 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. The alternative to destructive sampling is to measure standing tree volume using an optical dendrometer, and convert volume to biomass using specific gravity values for individual tree species. Because of the challenges associated with destructive sampling in urban environments, we implemented a newly developed method to measure total tree volume using a terrestrial light detection and ranging system (LiDAR) (Lefsky and McHale 2008).

From a complete street and park tree inventory, we chose 11 dominant tree species in Fort Collins. *Fraxinus pennsylvanica* and *Gleditsia triacanthos* were by far the dominant species, contributing to 22% and 10% of the total population, respectively (McPherson et al. 2003). The remaining 9 species ranged from 1–7% of the total population, equaling another 32% percent of the population combined (McHale, unpublished data). From the inventory of over 16,000 individual trees we randomly chose our sample trees, stratified according to diameter-at-breast height (DBH) ensuring our sample represented a wide range of tree sizes. We sampled a total of 184 trees, 14–22 trees per species, which was the largest sample size we could attain in a winter field season. All sample trees were growing along roadways and sidewalks, and were owned and maintained by the municipality. We used a terrestrial light detection and ranging (LiDAR) scanner to collect three-dimensional point cloud data of trees in the winter of 2002. The Cyrax 2500 LiDAR system (Cyra Technologies) 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.

We tested whether tree diameters could be measured accurately with a ground based LiDAR system by comparing LiDAR-based bole diameter measurements 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 it has been proven to take accurate measurement of vertical bole diameters up to an inch (Clark et al. 2000). Results showed that the diameter measurements correlated well (R^2 values were 0.96 and 0.98) for the two species analyzed (Lefsky and McHale 2008).

Laser scanners produce three dimensional point clouds, where each point sits on the surface of an object and is associated with a specific location (has an x, y, and z value). We applied a cylinder fitting algorithm for a tree's main stems while analyzing point density for smaller branches (Fig. 1) (Lefsky and McHale 2008). Since point resolution was constant, we assumed that each point in space was surrounded by an average volume of 2.65 cm^3 (Lefsky and McHale 2008). Total volume was a function of both the volume of cylinders and the volume surrounding each point in space.

Volume and biomass estimation

For each species, we evaluated the relationship between our estimates of total tree volume and diameter at breast height (DBH). Because variance increased with tree size, data were transformed using the natural log function and using linear regression, and analyzed

$$1n(tvol) = a + b * 1n(DBH) \qquad (1)$$

where ln = the natural log function, (tvol) = total tree volume (m^3), DBH = diameter at breast height (cm), and a and b are parameters in the model. We ran all regressions 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 this method may underestimate tree volume (van Laar and Akca 1997; Parresol 1999). Some studies have attempted to correct for potential

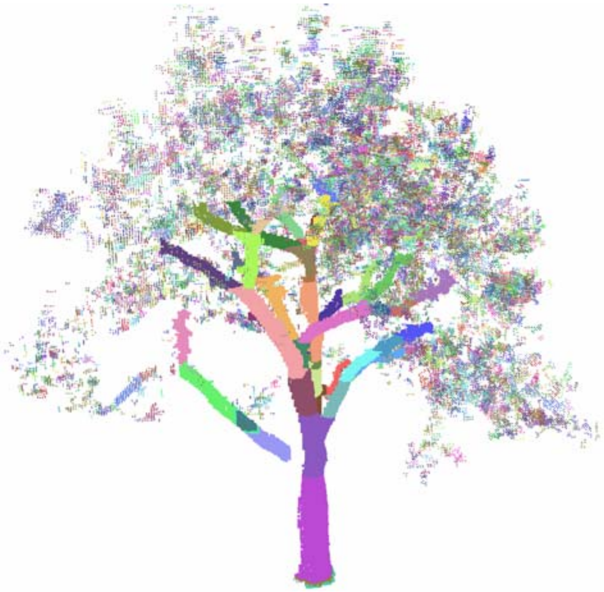


Fig. 1 LiDAR Processing. Using LiDAR point clouds total volume was calculated as the volume contained in cylinders created with an automated algorithm and the volume associated with each point determined by a set resolution (Lefsky and McHale 2008)

underestimations, but other studies show that corrections may over-compensate for underestimation (Madgwick and Satoo 1975; Hepp and Brister 1982; Parresol 1999). Some researchers have recently chosen to use a weighted least squares regression; we chose linear over weighted nonlinear regression for several reasons. First, overall, both regressions predicted very similar results across the entire diameter ranges for all species. Second, when we 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. Third, the weighted regressions corrected for some of the increasing variance with increased tree size for most species, however transforming the data corrected the heteroschedasticity associated with all species. Finally, 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.

The logarithmic linear regressions for volume vs. DBH were highly significant ($p<$ 0.001) and explained 82–99% of the variability for each species (Table 1). *Gymnocladus dioicis* and *Ulmus pumila* displayed the lowest coefficient of variation (R^2) values, as well as the highest RMSE values (Table 1). The 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 1).

We converted these volume equations (m^3) to allometric biomass (kg) equations using average specific gravity (kg/ m^3) for each species (Fig. 2). 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.

Table 1 Parameter estimates for allometric equations relating volume (m^3) and diameter breast height (DBH, cm)

Tree species (Spp. Code)	a	b	R2	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 pumila (ULPU)	4.9 E-03	1.613	0.874	0.461
Populus sargentii (POSA)	2.1 E-03	1.873	0.991	0.181
Gymnocladus 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

Parameter values are given for each individual species. The equation form is Volume = $a(\text{DBH})^b$

2002). If urban trees grow faster due to nutrient and water inputs, it is likely that specific gravity values from the literature could 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. Also, 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.

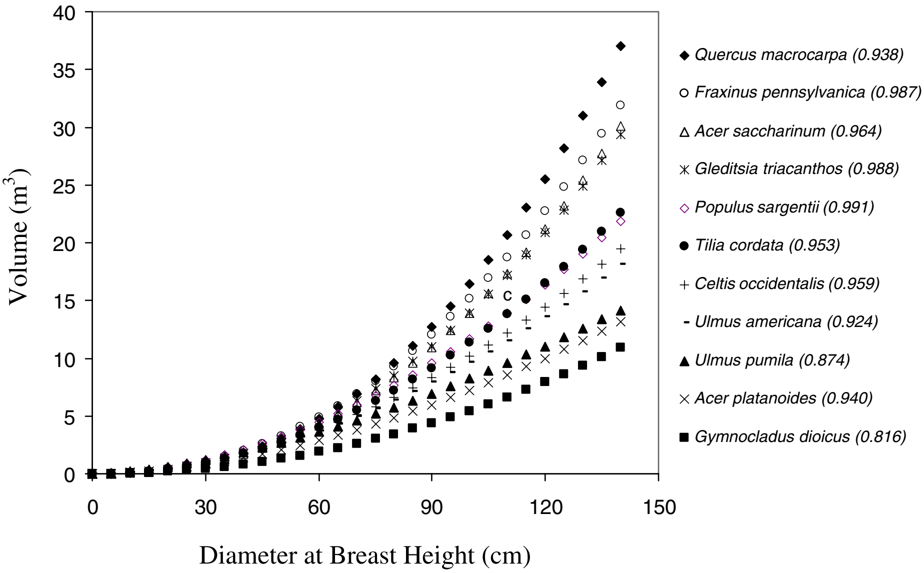


Fig. 2 Volume Equations for 11 dominant urban tree species in Fort Collins, Colorado, derived from LiDAR estimates. The numbers in parentheses represent R^2 values

Literature-based equations

We chose to evaluate published allometric equations that were used for urban biomass studies from three main sources. The first group is the Center for Urban Forest Research (USDA Forest Service, Pacific Southwest Research Station) (McPherson 1998; McPherson et al. 2005), which has developed the STRATUM model for resource managers to quantify the benefits and costs associated with urban trees and their management (http://www.fs.fed.us/psw/programs/cufr/). The second group is the Urban Forest, Human Health, and Environmental Quality Unit (USDA Forest Service, Northern Research Station) (Nowak and Crane 2000; Nowak et al. 2002). Their UFORE (Urban FORest Effects) model has been used to evaluate the benefits of urban trees in many cities across the nation including Baltimore (MA), Jersey City (NJ), Minneapolis (MN), Brooklyn (NY), Syracuse (NY), New York City (NY), Philadelphia (PA), and San Francisco (CA) (http://www.fs.fed.us/ne/syracuse/).

The literature on carbon storage and sequestration of urban trees has been dominated by these two groups and although there have been other studies on biogeochemical cycling in urban systems they tend to incorporate one of the models developed for urban forests. For example, Baker et al. (2007) studied household choices on fluxes of carbon, nitrogen and phosphorus, and used the UFORE model to estimate carbon dynamics associated with trees. One recent study on urban carbon dynamics that did not use an urban forest model was by Golubiewski (2006) and she evaluated urbanization effects on carbon storage pools in Boulder, Colorado. This was the third equation source we used because, not only was this study in close proximity to Fort Collins, CO, but Golubiewski (2006) also incorporated a list of allometric equations for estimating urban tree biomass.

Both McPherson (1998) and Nowak et al. (2002) include lists of allometric equations used for biomass estimation. Through personal communication with Paula Peper (Center for Urban Forest Research 2005) we also acquired a spreadsheet with the equations that group incorporated into their model, STRATUM. STRATUM implements different equations depending on region, so here we analyzed the equations that the model specifically uses when analyzing a city in the Northern Mountain and Prairie Region where Fort Collins is located. We also searched for all of the original sources for the equations listed in Nowak et al. (2002) and Golubiewski (2006) associated with our 11 species.

The literature trail became confounding because some of the citations were reviews and compilations of other biomass literature. For instance, both Nowak et al. (2002) and Golubiewski (2006) cited Tritton and Hornbeck (1982) and Golubiewski (2006) cited Ter-Miklaelian and Kozukhin (1997); these publications listed a large number of equations from various other studies and incorporate equations for predicting biomass of many different tree components (branch, leaf, stump, etc.). Any number of equations could have been used from these reviews, but we only chose equations that represented a measure of total aboveground biomass without leaves and that covered a large enough diameter range to be useful for comparison purposes. As an example, Williams and McClenahen (1984) was cited by Golubiewski (2006), but was not useful for our comparisons because the equations were only for seedlings and sprouts. There were also situations where an equation was referenced for a particular species, but did not actually exist and even if there was an equation it produced unreasonable results (to low to actually be physically possible) and had to be excluded from our analysis.

Most of 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 2). This was a function of the availability of information on specific species. For example, no allometric information existed on *Gymnocladus dioicus* or *Acer platanoides*, so past biomass studies implemented the use of general hardwood equations or equations for a species in a similar genus (Table 2). The

Table 2 Sources for allometric equations used in urban biomass studies

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 1994, 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 pumila*	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 1994, 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 platanoides*	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

For some species there is a limited amount of information, so general equations or equations for different species were used. If there are two references listed for one equation it is because we cited both the original author(s) and the following reviews that incorporate that equation as well

STRATUM model incorporated one study by Pillsbury et al. (1998) that developed volume equations for trees in urban environments in California. Average specific gravity was used to transform those values into biomass estimates as well.

Nowak et al. (2002) cites complex criteria on how the equations were used. The exact methodology implemented in that study was difficult to follow, so we analyzed the individual equations he cited in his paper that were associated with the 11 species we studied in Fort Collins. For instance, Nowak et al. (2002) report that using multiple equations can create disjointed predictions, so equation results were combined to produce one predictive equation for a wide range of diameters. They also found that results with this formula produced very similar results to the original estimates of total carbon storage. In their publication three equations were listed for *Ulmus americana* (Alemdag 1984, Hahn 1984, Perala and Alban 1994) and we analyzed all three of those equations separately.

Biomass comparisons on an individual tree scale by species

Our goal was to compare biomass predicted on an individual tree basis from our own Fort Collins equations ("urban equations") to biomass predicted for each tree from literature-based equations ("literature equations"). To do this, we calculated biomass ratios as the amount of biomass predicted by the 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, we again compared biomass estimates with allometric equations developed in Fort Collins to those in the literature, but this time for each population of each 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 (Fig. 3). In contrast, both *Ulmus americana* and *Posa sargentii* contain relatively fewer trees in their populations than *Fraxinus pennsylvanica*, 719 and 232 trees respectively, and a large percentage of those populations make up older and larger street trees (Fig. 3).

In the second part of this analysis, we 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 community scale for 11 urban tree species combined

In the final analysis, our goal was to estimate total biomass for all of the trees in the 11 species together. We summed the "highest" literature estimates, and separately, the "lowest" literature estimates, 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.

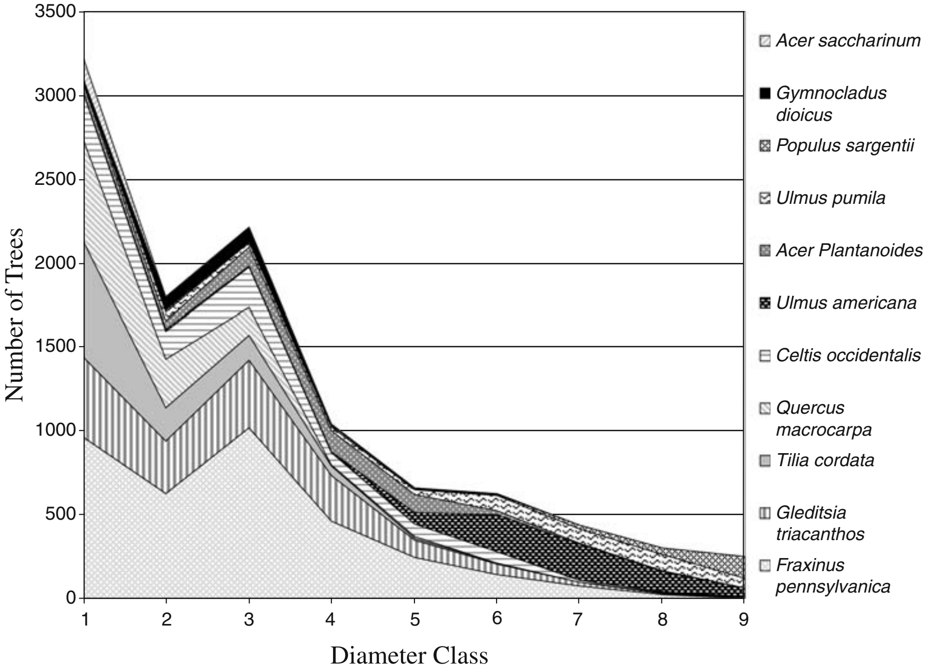


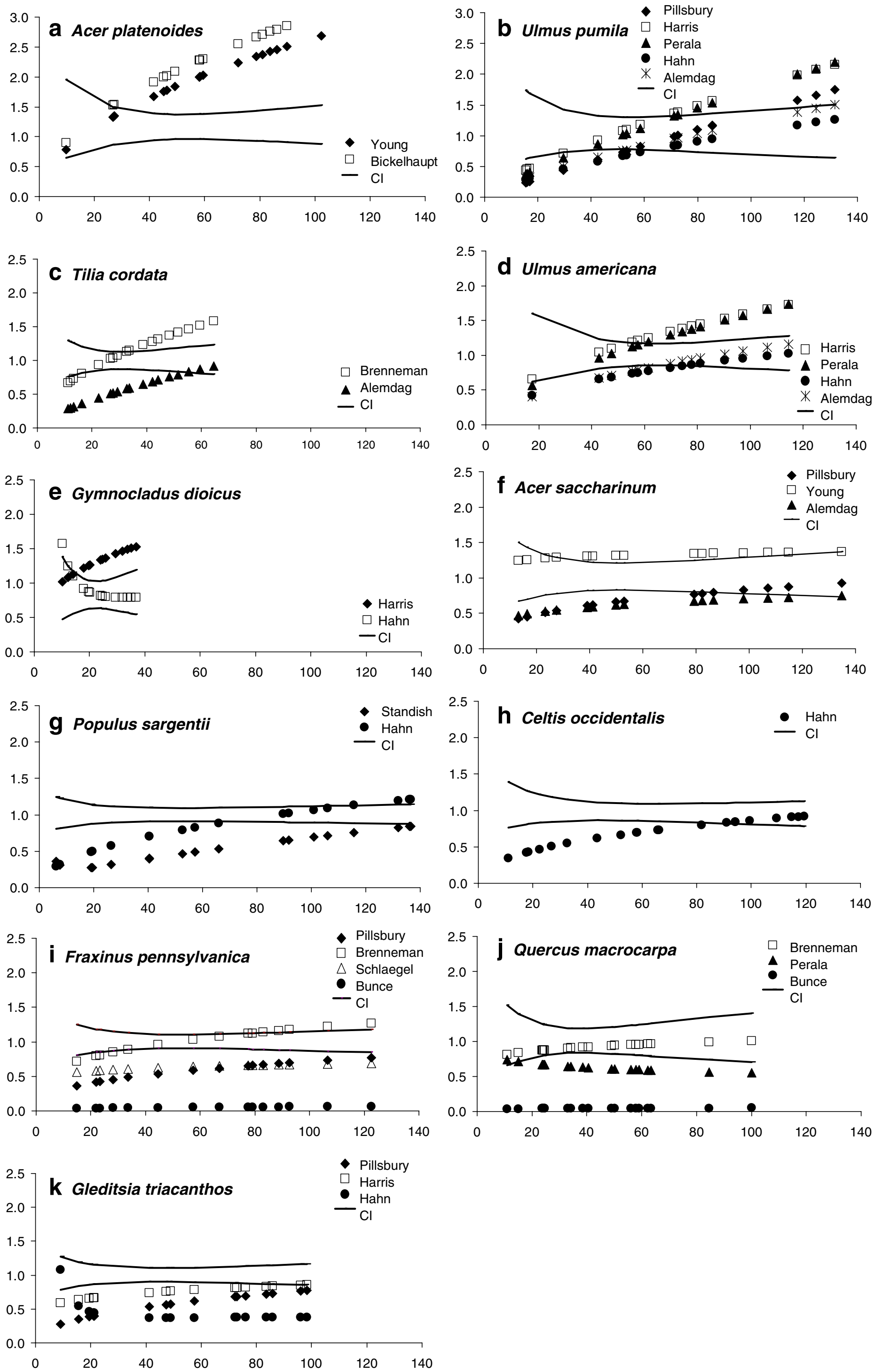
Fig. 3 Diameter class distribution for the urban street tree community in Fort Collins, Colorado. *Fraxinus pennsylvanica* is the most abundant tree in the community, but its population is composed of a large number of younger trees. As opposed to *Ulmus americana* and *Populus sargentii*, which have much fewer trees in the population, have a larger number of those trees are in larger diameter classes

Results and discussion

Biomass comparisons on an individual tree scale by species

The biomass comparisons for individual trees varied by species and presented four main trends. The first trend, exhibited by *Acer plantanoides* 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 (Fig. 4). The second trend, apparent in the results for *Ulmus americana* and *Ulmus pumila*, showed similar estimates to the urban equations for medium sized trees (~ 40 to 80 cm DBH) falling within the 95% confidence limits (PROC REG, SAS, V9.1, Cary, NC) 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

Fig. 4 Biomass ratios for available equations from the literature. The y axis represents the ratio of 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 ▶


a Acer platenoides
Young
Bickelhaupt
CI
b Ulmus pumila
Pillsbury
Harris
Perala
Hahn
Alemdag
CI
c Tilia cordata
Brenneman
Alemdag
CI
d Ulmus americana
Harris
Perala
Hahn
Alemdag
CI
e Gymnocladus dioicus
Harris
Hahn
CI
f Acer saccharinum
Pillsbury
Young
Alemdag
CI
g Populus sargentii
Standish
Hahn
CI
h Celtis occidentalis
Hahn
CI
i Fraxinus pennsylvanica
Pillsbury
Brenneman
Schlaegel
Bunce
CI
j Quercus macrocarpa
Brenneman
Perala
Bunce
CI
k Gleditsia triacanthos
Pillsbury
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Hahn
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0.0
0.5
1.0
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0
20
40
60
80
100
120
140

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 equations appeared in results for *Acer platanoides* and *Quercus macrocarpa*. An equation used to predict *Acer plantanoides* by Bickelhaupt et al. (1973) deviated from the urban based equation by 205% at the largest diameters (Table 3); however, the maximum diameters

Table 3 Percent deviation of literature equations from urban based equations

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
	Population	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

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 were also out of the recommended range for this equation. Bunce's (1968) allometric equation for general oak underestimated *Quercus macrocarpa* biomass in Fort Collins by 95–97% (Table 3). Yet, 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 3).

A study on urban trees in Oak Park, IL showed that open grown trees had on average 20% less biomass than allometric equations predicted for traditional forest trees (Nowak 1994). Due to a lack of research on this topic, a standard practice in this field of study is to multiple biomass predictions for forest trees by 0.8 when estimating open-grown tree biomass. In our analysis, three equations for individual tree species predict 20–23% more biomass than the urban-based estimates: 1) *Acer platanoides* (Young et al. 1980), 2) *Gymnocladus dioicus* (Hahn 1984), and 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 3, Fig. 4). Moreover, Hahn's (1984) equation was actually developed for trees larger than the *Gymnocladus dioicus* in our study and Pillsbury et al. (1998) actually developed allometric relationships for predicting volume of urban trees and his equation was specifically for *Fraxinus velutina*.

Overall, only three equations predicted within the 95% confidence intervals for the urban tree biomass equations across the entire range of DBH values (Fig. 4): 1) *Fraxinus pennsylvanica* (Brenneman et al. 1978), 2) *Quercus macrocarpa* (Brenneman et al. 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 2).

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 destructively sampled a few trees 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 our 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 ~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 3). The maximum ranges of deviations from urban-based equations were for *Acer plantanoides* and *Quercus macrocarpa*. For *Acer platanoides,* the equation by Bickelhaupt et al. (1973) predicted a maximum percent difference of 205% for an individual tree, but this maximum percent deviation decreased for the population of *Acer platanoides* 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 plantanoides* was affected by its distribution (Table 3); 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 in which 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 et al. (1998) equation for *Fraxinus velutina* 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 Fort Collins based urban equation. Like the *Acer platanoides* 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.

Similarly to the results for individual trees, four main trends appear when comparing the maximum and minimum literature-based predictions for these populations (Fig. 5):

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 pumila*).
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*).

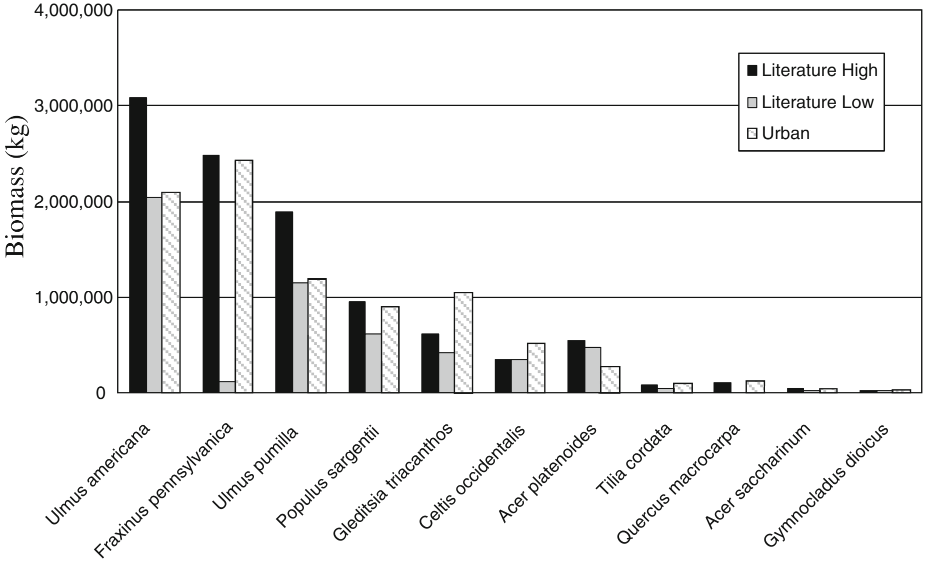

Fig. 5 Comparison of biomass estimates for individual species populations. Highest and lowest predictions of literature based equations were analyzed for each population and compared to biomass estimates using urban based equations

4 The urban equation predicts less biomass than both the maximum and minimum literature equation (e.g. *Acer platanoides*).

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 pumila*, 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 (Fig. 3). 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, the range in predictions associated with the *Ulmus americana* population being a good example of large potential error (Fig. 5).

Comparisons at the community scale for 11 urban tree species combined

Our 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 10,000,000 kg dry biomass, or 18% more biomass for the Fort Collins tree community, while the literature “lowest biomass” equations estimated 5,300,000 kg dry biomass, or 40% less biomass than urban-based estimates (Fig. 6). Again the distribution of sizes within each species population was a factor: the equations associated with *Ulmus americana, Fraxinus pennsylvanica, Ulmus pumila, 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 (Fig. 3).

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, a variability range as large as 60% is still substantial, suggesting that investigators comparing across sites should exercise extreme care when

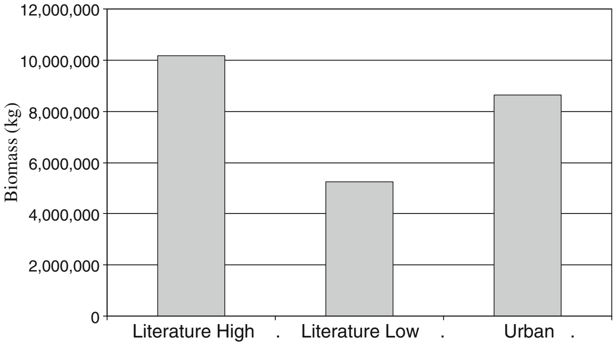

Fig. 6 Literature high and low biomass estimates vs. urban based estimates for the entire community of 11 street tree species. High estimates resulted in an over-prediction of 18%, and low estimates under-predicted by 40%, in comparison to the urban based equations

choosing allometric equations and interpreting results. Furthermore, characteristics associated with urban tree populations can affect the results, and variability could increase. It is noteworthy that the chances one would choose all of the equations that provide the most extreme results are low, and using many equations reduces the odds of reaching maximum variability. In this case, if the extreme results from the literature were averaged the variability is within 10% of the urban-based estimates, which is a relatively similar estimation.

Substitution of allometric equations from native environments

The accuracy of using allometric equations in predicting stand biomass has been recognized as a potential issue in tropical forests (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 the relatively high variation shown in this analysis. First, the equations from the literature that we tested were sometimes for a different species, or were developed for a large group of species. Also, 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, would be very different from one another, especially the urban-based equations. We actually 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.

In this study, we had a large amount of information for each individual tree because we used a high scanning resolution with the LiDAR, and we had a large sample size associated with each species (17–22 trees per species) (Lefsky and McHale 2008). For this analysis, however, we 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. We also used some of the literature-based equations outside of the DBH range for which they were developed.

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 2001). These results support our 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.

Our results show that variation could be quite high depending on the equations applied in urban biomass studies and the scale at which biomass is evaluated. Urban biomass analyses are commonly conducted at coarse scales that incorporate entire cities or metropolitan regions, and often do not focus on individual tree biomass. Mostly this is because one urban tree can do very little on its own to offset CO_2 emissions, and the results are more interesting in the framework of cities as ecosystems. With this in mind, it is interesting that when the highest and lowest literature-based predictions at the community scale were averaged, our estimates of biomass fall within 10% of the literature-based mean (Fig. 6**).** This shows that one potential remedy for reducing variation associated with using different allometric relationships among cities may be to average a group of equations for each species. Similarly, Pastor et al. (1984) suggested developing a single equation from data predicted by multiple equations when faced with the issue of choosing equations without adequate site information and found that the generalized regression predicted values mostly within the range of error associated with the original regressions. Standardizing regressions is valuable for comparisons of total biomass and production among various sites, because it is important to know that differences aren't only due to the application of regression equations (Pastor et al. 1984).

The uncertainty associated with the application of regression equations is also an issue that Jenkins et al. (2003) address while developing equations suitable for large-scale biomass estimation in traditional forests across the US. They conclude that the variability in carbon allocation from site to site and among studies makes it difficult to estimate biomass accurately even when site-specific regressions are implemented. Although variability is high, at this time it would be extraordinarily difficult to execute the continental scale measurement campaign needed to develop a broad-scale equations with known accuracy and the broad-scale equations developed from available data sets within the literature seem to be in general agreement (Jenkins et al. 2003). These results, combined with ours, suggest that generalized regressions may be the best method available for dealing with high variability in both urban and forested environments.

Nonetheless, if a 20% reduction in biomass (Nowak 1994) was applied to the averaged results, the average biomass would be 30% less than the urban-based predictions. Although at this time we are unable to determine which estimates are actually more accurate, this result could indicate that the standard 20% reduction applied in urban biomass studies may lead to conservative estimates of urban biomass and carbon storage.

Conclusion

We found that some of the allometric equations published in the literature produce similar estimates of biomass to urban-based allometric equations developed for an individual location; however, depending on scale and species or population and community characteristics, variability ranged from 60–300%. In sum, we can not be confident in the accuracy of urban biomass studies at this time, and cannot compare biomass estimates from studies that utilize different allometric equations from the literature. Data on urban tree biomass, allometry, and ecophysiology are needed to produce more accurate estimates of urban carbon storage, especially when predictions are needed for individual trees or populations consisting of low species diversity. Until we can be more confident in the accuracy of allometric relationships for urban trees, one solution is to standardize the methodology used to predict urban tree biomass and apply averaged equations that could reduce variability in biomass estimates. In fact, our results show when a variety of equations are applied to an entire urban forest community, variability can be as low as 10%. Furthermore, our findings indicate that the practice of reducing biomass by 20% for open grown trees should be re-evaluated.

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