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Original article

Urban tree specific gravity and ash content: A case study from Baltimore, Maryland USA

James A. Westfall[a,*], Nancy F. Sonti[b], Michael C. Wiemann[c], Thomas L. Eberhardt[c], Chi-Leung So[d]

[a] U.S. Forest Service, Northern Research Station, 11 Campus Blvd., Newtown Square, PA, 19073, USA
[b] U.S. Forest Service, Northern Research Station, Baltimore Field Station, 5523 Research Park Drive, Baltimore, MD, 21228, USA
[c] U.S. Forest Service, Forest Products Laboratory, 1 Gifford Pinchot Drive, Madison, WI, 53726 USA
[d] Louisiana State University, School of Renewable Natural Resources, LSU Agricultural Center, Baton Rouge, LA, 70803, USA

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ABSTRACT

Interest in conducting urban tree inventories and quantifying the associated wood resource has accelerated at a pace faster than supporting research needs can be identified and accomplished. For example, it is common to apply allometric models and wood properties values developed from studies of rural forest-grown trees to urban trees, despite unknown degrees of inaccuracy that may exist. To examine potential differences in wood properties between trees grown in forest and urban settings, wood samples were collected from stumps of recently felled trees for nine native hardwood species in the city of Baltimore, MD USA. The samples were analyzed for basic specific gravity (SG) and ash content (AC). The results from urban trees were compared with published values from studies based on forest-grown trees. There was no general trend in the results for SG; however, urban *Acer rubrum* L., *Fraxinus spp.*, and *Quercus rubra* L. appeared to have higher SG, with *Quercus palustris* Münchh. having lower SG, than their forested counterparts. Based on these results, the use of existing forest-based SG data may produce weight estimates of urban woody biomass that are 5–10% too low. Conversely, most of the species studied exhibited higher AC than their forested counterparts, although some results were mixed depending on the basis of comparison. Further work is needed on a wider range of species and geographic locations to refine the results and better support the analysis of urban tree inventories, which are increasingly used for carbon accounting and assessing feedstocks for biofuel use.

1. Introduction

Urban trees are a tremendous asset to urban residents and municipalities. They provide a suite of ecosystem services – water purification, air filtration, shading and cooling, increased property values, and biodiversity that bestow significant economic, social, and environmental benefits (Ulmer et al., 2016; Livesley et al., 2016; Escobedo et al., 2015). The U.S. Forest Service conducts urban tree inventories via the Forest Inventory and Analysis (FIA) program (Nowak et al., 2016) and offers the i-Tree software suite (Nowak and Dwyer, 2007) to provide critical information to natural resource managers, policymakers, and the public-at-large on the quantity, health, composition, and benefits of urban trees.

While tools for inventorying urban trees and quantifying associated ecosystem services have become increasingly popular, there is still a lack of basic information on the degree to which the urban environment impacts tree growth and physiology across a range of urban site types. Many aspects of the urban environment may impact tree physiology, including warmer temperatures, higher levels of pollution, altered nutrient cycling, and increased impervious surfaces (Sonti, 2019). However, the effects of these factors are often omitted in assessments of urban tree resources due to the common practice of using existing models based on rural forest-grown trees. To determine whether models developed from forest-grown trees may be applicable, it is critical to examine key attributes of urban trees, such as wood specific gravity (SG), stem form, and crown architecture. Currently, there is no scientific consensus as to whether it is appropriate to apply forest-based allometric models to urban trees when estimating tree volume or biomass (McHale et al., 2009; Aguaron and McPherson, 2011; Yoon et al., 2013; Zhou et al., 2015).

* Corresponding author.
E-mail addresses: jameswestfall@fs.fed.us (J.A. Westfall), nancyfsonti@fs.fed.us (N.F. Sonti), michael.wiemann@usda.gov (M.C. Wiemann), thomas.l.eberhardt@usda.gov (T.L. Eberhardt), cso@agcenter.lsu.edu (C.-L. So).

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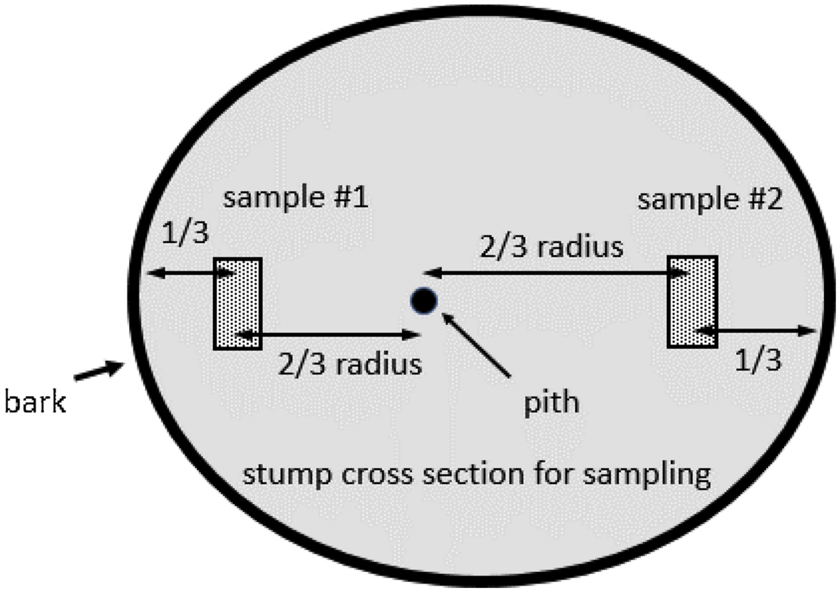

Fig. 1. Schematic of sampling protocol for obtaining two wood sections from each stump. Dimensions of samples taken at target locations are approximately 5 cm high x5 cm wide (tangentially) x2.5 cm wide (radially). Note that 1) the figure depicts irregularities of form and pith location that is often encountered, and 2) the orientation of the sampling axis in relation to stump shape was random and varied amongst sample trees.

A key component in tree biomass and carbon content is the SG of wood, which is the oven-dry weight of wood in a sample divided by the volume of the sample in the green (undried) condition, then divided by the density of water (= 1 g/ml). It is a measure of the amount of dry wood a tree species produces, representing a tradeoff between the rate of growth and wood strength (King et al., 2006; Swenson and Enquist, 2008; Williamson and Wiemann, 2010; Wiemann and Williamson, 2014). SG can vary greatly among tree species, with fast-growing, short-lived species producing stems with less structural material and more space filled with water or air. The wood of long-lived, slow-growing species is denser, resulting in greater stem support and longevity.

In recent decades, there has been increasing emphasis on estimating biomass and carbon storage of urban trees and the overall contribution of urban forests to the carbon cycle (Nowak and Crane, 2002; Pataki et al., 2006). The contributions of forest tree carbon sequestration to ameliorate CO_2 emissions has been well-documented (Domke et al., 2018). Similar assessments focusing on the role of urban trees will require scientifically-defensible methods for credibility, e.g., an understanding of key wood properties such as SG to examine potential biases resulting from applying forest-based models for urban tree biomass and carbon content prediction. Furthermore, differences between urban tree site types may also impact tree morphology (and thus SG) depending on available rooting space, impervious surfaces, crown light exposure, and other environmental factors. Yet, directly measured SG of urban trees (Persad et al., 2013) is rarely found in published studies.

Some cities have adopted practices for utilization of urban trees that create a revenue stream to offset costs associated with tree maintenance/removal activities. In a bioenergy utilization context, properties such as ash content (AC) of urban wood become of interest. Particularly, the AC is an important attribute due to the effects on furnace/boiler operational efficiency and maintenance requirements (Shao et al., 2012). Studies of AC by species for urban trees are unavailable. Some AC analyses have been done where the fuel is characterized as 'urban wood' (Miles et al., 1996), which likely contains a highly-variable blend of wood from urban trees, as well as forest-grown tree products such as pallets, construction wood waste, and other unknown components. As urban wood utilization becomes more mainstream, the potential use of urban wood as a source of bioenergy will need to be evaluated.

This study quantifies SG and AC across a range of native North American tree species and urban site types in Baltimore, Maryland. The SG information will help determine whether there is a need for a more intensive effort to develop urban-specific woody biomass estimates for use in urban tree resource assessments. Similarly, AC analyses will help inform bioenergy users concerning the use of urban wood in operational facilities. Specifically our research objectives are to: 1) estimate mean SG and AC values for common native tree species growing in urban areas, 2) assess the differences between SG and/or AC of trees in the urban environment compared to the same species in forest conditions, and 3) evaluate practical impacts of using SG and AC derived from urban studies in place of values obtained from forest-grown trees.

2. Methods

2.1. Urban trees

2.1.1. Data

The urban tree wood samples used in this study were collected during 2017 in Baltimore, Maryland USA. Trees included in this study were in the public right of way or on other city-owned property such as parkland, and were removed prior to sampling by the City of Baltimore because they were structurally damaged or dead. Trees in the *Fraxinus* genus may have been removed as a precaution against emerald ash borer (*Agrilus planipennis* Fairmaire) infestation, even if they were still healthy and structurally sound. Specific site types where trees were located included the following: sidewalk cut out, sidewalk planting strip, front yard, maintained park, and natural area. Information regarding tree location, species, and size was provided by the Baltimore City Forestry Division, which was used to obtain wood samples from the top of tree stumps generally within a 2–8 week period after the tree had been removed. Although stumps are not the ideal collection location for wood samples, the logistical challenges of coordinating data collection efforts with tree removal contractors prevented us from collecting wood samples at other stem locations (e.g., at height of 1.3 m).

Wiemann and Williamson (2012) found that, for linear changes in SG across a tree diameter, a point at two-thirds of the distance from pith to bark gave a good approximation of mean SG across the whole stem at that height. Accordingly, two wood samples were obtained from each stump, centered at two-thirds the distance between the pith and outermost wood ring inside the bark (Fig. 1). The two samples were generally taken at 180 degrees of separation, with occasional minor deviations to avoid unsound wood or other anomalies. The selected trees were of sufficient maturity to avoid including juvenile wood in the samples. Measurements at the time of sample collection included stump diameter (inside and outside bark), stump height, direction/distance to

Table 1
Summary statistics for samples from nine tree species growing in an urban environment within Baltimore, MD, USA.

Species	n	Stump height (cm)			Stump diameter inside bark (cm)			Distance to nearest road (m)			Distance to nearest building (m)		
		Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.
Acer rubrum L.	17	3.8	14.8	43.2	15.0	39.4	74.4	0.4	0.9	2.3	2.6	8.2	21.8
Acer saccharinum L.	3	17.8	24.6	38.1	80.9	97.2	118.0	1.5	3.0	4.9	8.6	10.7	13.4
Acer saccharum Marsh.	5	15.7	29.6	38.1	30.5	67.8	97.3	0.9	7.4	31.5	3.7	9.8	12.9
Fraxinus spp.	25	5.1	19.4	45.7	17.8	50.3	121.9	0.4	3.8	17.2	2.8	12.7	27.8
Quercus alba L.	5	7.6	22.9	33.0	32.0	82.7	125.2	1.6	10.2	31.1	11.6	25.6	37.2
Quercus palustris Münchh.	7	22.9	31.9	48.3	49.4	83.4	103.0	0.9	1.4	2.0	8.4	9.8	11.2
Quercus rubra L.	9	12.7	24.8	45.7	39.9	71.3	125.1	1.2	8.7	37.3	5.3	19.2	43.4
Ulmus americana L.	2	10.2	19.1	27.9	54.4	67.5	80.6	1.2	2.6	3.9	9.2	20.2	31.3
Ulmus rubra Muhl.	2	22.9	22.9	22.9	57.4	62.6	67.8	3.8	3.8	3.8	34.3	34.3	34.3

nearest road and building, site type, and land use (Roman et al., 2017). Samples were obtained from the following genera/species: *Acer saccharum* Marsh., *Acer saccharinum* L., *Acer rubrum* L., *Fraxinus* spp., *Quercus alba* L., *Quercus palustris* Münchh., *Quercus rubra* L., *Ulmus americana* L., and *Ulmus rubra* Muhl. *Fraxinus pennsylvanica* Marsh. and *Fraxinus americana* L. are commonly found in the city of Baltimore; however, since differentiation of the two species was not possible from the wood alone, these trees are identified together as *Fraxinus spp*. Wood identifications conducted at the laboratory were done to verify the species of the wood samples prior to SG and AC determinations. Subsequent to wood specimen collection, the samples were stored in a cool, dry environment until laboratory work commenced. A summary of the sample collection data are provided in Table 1.

The basic specific gravity (SG) for each sample was determined on a dry mass and green (or water-saturated) volume basis (Williamson and Wiemann, 2010). Wood samples were submerged in water until they became water-saturated. The volume of each water-saturated wood sample was then determined by immersion in a beaker with water on an electronic balance; this process gave the weight of water displaced by the sample, which was readily converted to sample volume using the density of water. Wet samples were dried in a convection oven set at 103 ± 2 °C and weighed periodically until the cessation of weight loss. The final oven dry weight divided by the water-saturated volume gave the water-saturated density, converted to a unit-less value of SG upon dividing by the density of water (1 g/ml). The two sample values were averaged to obtain a single observation per tree.

Subsequently, the wood samples from each tree were cut into thin strips (ca. 5 mm by 5 mm) with a band saw and further processed in grinding mills to afford wood meals passing through a 4 mm sieve. To ensure sufficient material for all AC determinations, the wood strips from the two separate samples were combined before grinding. Aliquots (3 g) of the wood meals were transferred to ceramic crucibles and combusted at 575 °C in a muffle furnace for 5 h following a standard protocol (Sluiter et al., 2008). The weight of the resultant gray ash was then used to calculate the ash content as percentage of the dry weight of wood meal placed in the crucible. Samples were analyzed in triplicate, resulting in three AC observations per tree. These values were averaged to determine a single AC value for each tree.

It is worthwhile to note that the trees chosen for sampling were not selected under an *a priori* probability-based sampling design. Thus, not all tree species and tree size combinations were available for sampling; nor were all possible site conditions (e.g., private vs. public ownership, street vs. yard trees, etc.) included in the sample. These limitations to collecting wood material in urban environments exemplify challenges that deserve further deliberation and resolution. Despite the lack of conformity to sampling principles necessary for unequivocal validity of the estimations and inferences made here, the analysis was conducted as though these issues were not present. The purpose for doing so was twofold: 1) to present an analytical framework applicable to other studies using a similar within-tree sampling protocol, and 2) to provide a basis for discussion of potential differences between urban and forest trees, as well as the inherent difficulties of conducting such assessments (including sampling issues).

2.1.2. Analysis

The primary statistics of interest from the urban tree data were the mean, standard error of the mean, and 95 % confidence intervals for both SG and AC. These values were considered to be from a simple random sample with statistics being calculated from the following formulae:

$$\bar{y} = \frac{\sum_{i=1}^{n} y_i}{n} \tag{1}$$

$$v(\bar{y}) = \frac{\sum_{i=1}^{n} (y_i - \bar{y})^2}{n(n-1)} \tag{2}$$

where y_i is the observation from tree i, $\bar{y}$ is the sample mean, n is the number of trees, and $v(\bar{y})$ is the estimated variance of the mean. The standard error of sample mean, $SE_{\bar{y}}$, is then obtained from:

$$SE_{\bar{y}} = \sqrt{v(\bar{y})} \tag{3}$$

2.2. Comparison with forest-grown trees

2.2.1. Data

A key question for urban trees is whether their SG and AC properties differ from trees found in forested areas. For SG, one source of forest tree data was the Wood Handbook (Forest Products Laboratory, 2010), which provides summarized information across available studies for each species. We used the single published values (denoted SG_{WH} hereafter) from this publication for comparative purposes (Table 2). A

Table 2
Species-level summary of specific gravity (SG) information from the Wood Handbook (FPL 2010; WH), and stump-height disk data from legacy-treedata.org (Legacy); with ash content (AC %) values from Koch (1985); Pettersen (1984), and unpublished Michigan data (MI). All reported values are from forest-grown trees.

Species	Specific gravity		Ash content (%)		
	WH	Legacy	Koch	Pettersen	MI
Acer rubrum L.	0.49	0.52	0.50	0.40	0.36
Acer saccharinum L.	0.44	0.52	–	0.29[b]	–
Acer saccharum Marsh.	0.56	0.64	–	0.20	0.48
Fraxinus spp.[a]	0.54	0.48	0.67	–	–
Quercus alba L.	0.60	0.66	0.68	0.40	0.66
Quercus palustris Münchh.	0.58	0.63	–	–	–
Quercus rubra L.	0.56	0.59	0.43	0.40	0.35
Ulmus americana L.	0.46	0.55	0.94	0.40	–
Ulmus rubra Muhl.	0.48	–	–	–	–

[a] Average of *Fraxinus pennsylvanica* Marsh. and *Fraxinus americana* L.
[b] Published data from Geyer et al. (2008).

listing of forest tree SG values was also found in the compilation of Miles and Smith (2009); however the published values for species in this study were obtained from the Wood Handbook (Forest Products Laboratory, 2010). The SG_{WH} data likely arise from data samples taken at breast-height or throughout the stem. Thus, these values may not be directly comparable to data from stump-height; nonetheless, there is some value in making such comparisons, particularly in the context of assessing the magnitude of differences and providing evidence for further research needs.

Another source of forest tree SG values was the data compilation from numerous published and unpublished studies available at www.legacytreedata.org. For these data, SG information was available from disks taken at or below 0.3 m – which are directly comparable to our stump samples. There were six sources of data that contained at least one of the species found in this study (Clark and Schroeder, 1985; Mroz et al., 1985; Perala and Alban, 1993; Whittaker et al., 1974; Njiti, 1982, Schlaegel – unpublished data (no date)). From these legacy data (denoted SG_L hereafter), a single value of SG for each tree species was obtained as the mean SG from all trees having SG measures available from the tree section at or below 0.3 m (Table 2).

Two published compilations of species-level AC information from forested trees were used for comparison with the urban data. Published values of AC were largely from Pettersen (1984; hereafter referred to as AC_P) and Koch (1985; hereafter AC_K). AC data for *Acer saccharinum* L. were from Geyer et al. (2008). A small amount of additional unpublished AC data from an ongoing study of forest-grown trees in Michigan, USA was also obtained and the mean values (AC_{MI}) for 4 species were used for comparison (Table 2). Other published studies of tree AC were not used in this analysis primarily due to a lack of information on the moisture content used as the basis for AC determination.

3. Results and discussion

$\bar{SG}_U$ across the species studied varied from 0.484 for *Acer saccharinum* L. to 0.637 for *Quercus alba* L. (Table 3). $\bar{AC}_U$ across species was more variable, ranging from 0.415 % for *Quercus rubra* L. to 1.096 % for *Acer saccharum* Marsh. Due to the high relative frequency of occurrence and tree removal for *Acer rubrum* L. and *Fraxinus* spp., sample sizes were the largest for these species; while sample sizes for remaining species were fewer than 10 trees. The primary effect of the sample size is evident in the width of the 95 % confidence intervals, thus indicating the reliability of the estimated mean. It should also be noted that the standard errors may also be poorly estimated from small sample sizes. As with the estimated mean, the standard error estimate may be either too high or too low in comparison to the true population value.

A primary objective of the study was to determine differences in wood SG and AC between urban and forest-grown trees. Due to the lack of a probabilistic sampling design and the small sample sizes, the statistics shown in Table 3 are primarily intended to provide a summary of the data. However, it is worthwhile to proceed with comparisons in the interest of evaluating potential differences that may suggest further research of the topic is warranted. For $\bar{SG}_U$, comparisons with SG_{WH} showed that all species except *Quercus palustris* Münchh. had larger $\bar{SG}_U$ ranging from 0.037 to 0.119 (Table 4); whereas *Quercus palustris* Münchh. exhibited $\bar{SG}_U$ nearly 0.019 smaller. The analysis using the SG_L data (lacking data for *Ulmus rubra* Muhl.) produced differing results in two ways: 1) the magnitude off differences were generally smaller than those found in the SG_{WH} comparison, and 2) larger $\bar{SG}_U$ was found for *Acer rubrum* L., *Fraxinus* spp., and *Quercus rubra* L., while the remaining species had smaller $\bar{SG}_U$. The fact that SG_L values came from samples below 0.3 m may make them more comparable to the $\bar{SG}_U$ values in this study, although the absolute difference was larger for *Fraxinus* spp. and *Quercus palustris* Münchh.

Table 4
Comparisons of mean specific gravity between urban trees ($\bar{SG}_U$) and 1) the published Wood Handbook data (SG_{WH}), and 2) the SG_L information from stump-height disks available at legacytreedata.org. Positively-valued mean differences indicate $\bar{SG}_U$ is comparatively larger.

Species	$\overline{SG}_U - SG_{WH}$ Mean difference	$\overline{SG}_U - SG_L$ Mean difference
Acer rubrum L.	0.069	0.036
Acer saccharinum L.	0.044	−0.033
Acer saccharum Marsh.	0.064	−0.012
Fraxinus spp.	0.044	0.103
Quercus alba L.	0.037	−0.020
Quercus palustris Münchh.	−0.019	−0.066
Quercus rubra L.	0.041	0.011
Ulmus americana L.	0.064	−0.030
Ulmus rubra Muhl.	0.119	–

The comparative SG results are mixed, in that some species appear to have larger SG for urban environments than forest, while *Quercus palustris* Münchh. is consistently smaller and a few species have contrasting positive/negative values. There also exists much inconsistency in the literature. For example, Nowak (1994) found urban tree biomass to be roughly 20 % less than that predicted for forest-grown trees of the same size. However, Gardi et al. (2016) indicated biomass predictions for forest-grown trees were highly accurate when applied to urban trees. Further, Zhou et al. (2011) observed 6–16% higher biomass in boles of open-grown agroforestry trees than forest-grown counterparts; the result being attributed to lower SG in forest-grown trees. McHale et al. (2009) proposed urban trees are faster growing than those in forested environments, which may result in lower stem SG values, although there may be some offsetting effects from relatively higher tree branch SG and branch proportion of total biomass (Clark et al., 1985). Other tree characteristics, such as stem form, crown architecture, and mechanical load distribution may produce differences in SG between urban and forest trees.

It is beyond the scope of the current study to delve deeply into biomechanics of tree growth and the pertinent influences of

Table 3
Summary of specific gravity (SG) and ash content (AC) statistics from samples of 9 tree species in Baltimore, MD, USA. The information shown are sample size (n), mean SG and AC ($\bar{SG}_U$ and $\bar{AC}_U$, respectively) standard error of the $\bar{SG}_U$ and $\bar{AC}_U$ ($SE_{\bar{SG}_U}$ and $SE_{\bar{AC}_U}$, respectively), and 95 % confidence intervals for $\bar{SG}_U$ and $\bar{AC}_U$. Note: some samples were not analyzed for $\bar{AC}_U$.

Species	n	$\overline{SG}_U$	$SE_{\overline{SG}_U}$	95 % Conf. Int.			n	AC_U	$SE_{\overline{SG}_U}$	95 % Conf. Int.		
Acer rubrum L.	17	0.559	0.014	0.531	–	0.588	17	0.908	0.101	0.694	–	1.121
Acer saccharinum L.	3	0.484	0.014	0.426	–	0.542	2	0.571	0.106	−0.770	–	1.912
Acer saccharum Marsh.	5	0.624	0.007	0.604	–	0.645	5	1.096	0.143	0.700	–	1.492
Fraxinus spp.	25	0.584	0.012	0.559	–	0.608	21	0.536	0.043	0.447	–	0.626
Quercus alba L.	5	0.637	0.029	0.556	–	0.717	5	0.761	0.325	−0.141	–	1.662
Quercus palustris Münchh.	7	0.561	0.017	0.519	–	0.602	7	0.973	0.099	0.731	–	1.216
Quercus rubra L.	9	0.601	0.013	0.572	–	0.630	9	0.415	0.055	0.289	–	0.541
Ulmus americana L.	2	0.524	0.048	−0.086	–	1.135	1	0.756	–	–	–	–
Ulmus rubra Muhl.	2	0.599	0.019	0.364	–	0.835	2	0.587	0.006	0.510	–	0.665

environmental conditions that prevail in urban and forested settings; however, it should be acknowledged that differences in wood SG between urban and forested environments would correlate with differences in tree architecture. In open grown conditions, MacFarlane and Kane (2017) found lower light competition will result in larger crowns and shorter tree heights. Also, increased tree taper where there is greater wind exposure (Loehle, 2016) further illustrates the plasticity of tree architecture. Among tree species with either relatively low or high wood SG, Iida et al. (2012) showed thicker stems coinciding with lower wood SG and a lower cost to the tree in terms of biomass allocation. Intuitively, since wood SG is correlated with wood mechanical properties, the necessary mechanical support provided both by the stem and branches imposes a significant constraint on tree growth and architecture. Fournier et al. (2013) theorized that trees should have the capacity to adapt to environmental conditions by manipulating wood properties, even down to the anatomical features of the wood cell wall. Thus, if the biomechanics of tree growth can be affected within a forested environment alone, said biomechanics can certainly be influenced by the stark differences between forested and urban conditions.

Comparisons of AC between urban and forested trees indicated $\bar{AC}_U$ was higher for most comparisons. Exceptions included the single comparison for *Fraxinus spp*. which had lower $\bar{AC}_U$ than AC_K and mixed results for *Quercus rubra* L. and *Ulmus americana* L. The mixed outcomes clearly arise from differences in AC values among AC_K, AC_P, and AC_{MI} – most notably for *Ulmus americana* L. with a difference of 0.54 % between AC_P and AC_K. It has been suggested that the AC content of most forest-grown hardwood species ranges from 0.3 – 0.6 % (Hytönen and Nurmi, 2015). However, this seems to be a generalization as Koch (1985) shows an average AC of 0.75 % across 22 species; with some species having AC greater than 1.0 %. In our study, 5 of the 9 $\bar{AC}_U$ values exceed 0.6 % (Table 3) and were comparatively high when assessed against AC_P and AC_{MI}, but seem to have better agreement with AC_K.

Higher AC may make urban wood less appealing for use as a bioenergy source. However, Table 5 suggests that *Fraxinus spp*., *Quercus alba* L., and *Quercus rubra* L. and may have $\bar{AC}_U$ values similar to or lower than those of forested trees and could be targeted in the urban wood procurement process. It should also be noted that woody biomass in general tends to have lower AC than other forms of biomass such as herbaceous/agricultural biomass or industrial biomass wastes (Vassilev et al., 2017). This study sampled tree species commonly found in urban areas, but there remain a number of other species found in urban settings for which AC information is lacking – additional investigation to cover the range of urban tree species composition is warranted. Beyond the scope of this study, but still important and in need of further research are elemental composition differences in wood ashes between urban and forest trees (Vassilev et al., 2010).

The differences shown above need to be considered for practical implications. Differences in SG between urban and forest environments could produce substantial biases in estimates of urban woody biomass resources. To broadly assess the implications for our species composition, tree frequency information from a 2014 urban tree sample in Baltimore (Nowak, 2018) was used to calculate an overall weighted average. This analysis suggests using $\bar{SG}_U$ instead of SG_{WH} would increase the estimated weight of urban wood biomass by 9.1 % (Table 6) under standard FIA tree biomass calculations (Woodall et al., 2011). The most notable increases would be found in *Acer spp*. and *Ulmus spp*. If $\bar{SG}_U$ was substituted for SG_L, urban biomass estimates would increase by 3.5 %; however, in this case, *Fraxinus* spp. would be the primary contributors to the increase, while a considerable decrease in biomass of *Quercus palustris* Münchh. would occur. Based on these results, the ad-hoc method of using existing forest-based SG to estimate the biomass of urban trees (McPherson et al., 2016) is not recommended (Tanhuanpää et al., 2017). The practice may produce estimates of urban woody biomass that are roughly 5–10% too low, which would cause systematic underestimation of urban carbon sequestration contributions and possibly other issues related to assessments of urban woody biomass availability.

Differences between urban and forest wood AC would be important to bioenergy-based operations, as fuel selection and associated efficiency may be altered. Overall, the results suggest $\bar{AC}_U$ may be substantially higher than that for wood obtained from forests, depending on the species mix and source of forest tree AC information (Table 6). For individual species, the increases were moderately consistent for *Acer rubrum* L., *Acer saccharum* Marsh., and *Quercus alba* L.; but otherwise results were inconsistent in some manner. The analyses based on AC_P and AC_{MI} provide evidence that AC may be 30–40% higher for urban-grown trees; however, the negative values and relatively large weights for *Fraxinus spp*. and *Ulmus americana* L. in the AC_K analysis indicate the overall difference may be small (Table 6). If the former result were to reflect the general trend, the additional AC of urban wood could have a substantial impact on operations and maintenance strategies for bioenergy uses. Thus, an important knowledge gap of urban-tree AC remains to be fully resolved; yet should be of high interest for those who may use urban wood for bioenergy purposes. The differences amongst the published studies for AC suggest further research may also be needed to better quantify species-specific values for forest-sourced trees. It may also be that AC values for common forest-grown trees is well-established proprietary information within certain forest industries, but is not available to the general public.

There are several factors related to the sample design and wood specimen collection that deserve further attention. First, urban wood

Table 5
Comparisons of mean ash content (%) between urban trees ($\bar{AC}_U$) and 1) the published values from Koch (1985; AC_K), 2) the published values from Pettersen (1984; AC_P), and 3) the unpublished Michigan data (AC_{MI}). Positively-valued mean differences indicate $\bar{AC}_U$ is comparatively higher. No data were available for *Quercus palustris* Münchh. and *Ulmus rubra* Muhl.

Species	$\overline{AC}_U - AC_K$ Mean difference	$\overline{AC}_U - AC_P$ Mean difference	$\overline{AC}_U - AC_{MI}$ Mean difference
Acer rubrum L.	0.41	0.51	0.55
Acer saccharinum L.[a]	–	0.28	–
Acer saccharum Marsh.	–	0.90	0.62
Fraxinus spp.	−0.13	–	–
Quercus alba L.	0.08	0.36	0.10
Quercus rubra L.	−0.02	0.01	0.06
Ulmus americana L.	−0.18	0.36	–

[a] Published data from Geyer et al. (2008).

Table 6
Percentage differences between urban and forest tree specific gravity (SG) and ash content (AC %) by study source. The overall mean is weighted by species frequency found in Baltimore during 2014 (Nowak, 2018). Positively-valued differences indicate the urban values are comparatively higher than those found in the forested studies.

		Specific gravity (SG)		Ash content (AC %)		
Species	n	SG_{WH}	SG_L	AC_K	AC_P	AC_{MI}
Acer rubrum L.	49	12.4 %	6.5 %	44.9 %	55.9 %	60.3 %
Acer saccharinum L.	18	9.1 %	−6.8%	–	49.2 %[a]	–
Acer saccharum Marsh.	14	10.3 %	−1.9%	–	81.7 %	56.2 %
Fraxinus spp.	91	7.5 %	17.7 %	−24.9%	–	–
Quercus alba L.	50	5.7 %	−3.1%	10.6 %	47.4 %	13.2 %
Quercus palustris Münchh.	11	−3.5%	−11.7%	–	–	–
Quercus rubra L.	55	6.8 %	1.9 %	−3.7%	3.5 %	15.6 %
Ulmus americana L.	63	12.3 %	−5.6%	−24.4%	47.1 %	–
Ulmus rubra Muhl.	19	19.9 %	–	–	–	–
Weighted mean		9.1 %	3.5 %	−4.2%	41.4 %	31.3 %

[a] Published data from Geyer et al. (2008).

data collection is more challenging than in forested settings; primarily because trees available for wood specimens are largely restricted to those on public lands being removed due to mortality, construction, pest or pathogen outbreaks, and other hazardous conditions. Thus, imposition of a typical statistical design such as a simple random sample is infeasible as the range of species and tree sizes across all urban lands is not accessible (Frank et al., 2019). At present, opportunistic samples are likely the most realistic and practical solution; however as urban research information needs become more vital, researchers and city officials need to work together to develop more rigorous approaches that help ensure the samples are representative of the population. For example, implementation of municipal tree inventories will enable better sampling of city-owned trees. Coordination with private arborists may facilitate sample collection on private property but presents logistical challenges to researchers.

A key issue in this study was the collection of wood samples from stump height, which does not conform to most forested studies that obtain samples at breast height (1.3 m; corresponding with diameter measurements) or at numerous locations along the bole length. Thus, with the exception of the SG_L comparison, the differences in within-tree sampling locations may produce systematic deviations between studies. The extent to which this circumstance affected our study results is unknown and may be species- and/or geospatially-specific. These knowledge gaps will continue to exist until studies are implemented to closely examine variation in wood properties, from both within- and between-tree perspectives. Further studies would also benefit from having a sampling paradigm that covers the range species and growing conditions existing across the population(s) of interest (Calfapietra et al., 2015).

There is evidence from other studies that some differences in SG and AC may be attributed to site conditions and associated environmental characteristics. For SG, trends related to soils (Nyakuengama et al., 2002; Muller-Landau, 2004), precipitation (Wiemann and Williamson, 2002), temperature (Wiemann and Williamson, 2002; Slik et al., 2010), and stand density (Filipescue et al., 2014) have been reported. Environmental effects on AC have received little examination; however, correlations with land-use type (Montes et al., 2012), tree age (Senelwa and Sims, 1999; Kumar et al., 2011), and soil moisture (Hosner and Leaf, 1962) were found in some studies. Greater pollution in urban environments relative to that in rural environments may also be a factor; in a study on English oak trees (*Quercus robur* L.), sapwood from trees sampled near a foundry and a heat and power plant showed higher ash content compared to trees from a forest district (Krutul et al., 2014). These studies may be of some value, but it is often difficult to synthesize localized effects for extrapolation to larger areas.

4. Conclusion

The results of this study suggest there may be important differences in SG and AC between trees grown in urban areas within Baltimore and trees found in rural forested environments across North America, with the magnitude and direction of differences seeming to be species dependent. The research presented here is an initial foray into examination of urban tree wood properties to further understanding of differences that might be encountered compared to forest-grown counterparts. Additional investigation is warranted to address 1) species inclusion – the species sampled should fully represent the urban tree population, 2) spatial coverage – similar studies are needed in other urban areas, 3) sample sizes – the number of observations per species should be sufficient to reliably estimate attribute means and variances, and 4) alternative within-tree sampling locations, e.g., at breast height. Thus, the urban values reported here should be used with caution until more studies are completed. A complicating factor remains that sometimes large variation in results occurs among published results from forest trees, which makes comparisons more difficult and suggests that independent studies of urban trees may be similarly afflicted.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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