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Original article

Annual biomass loss and potential value of urban tree waste in the United States

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ABSTRACT

Urban trees provide numerous benefits to society, but upon removal, this resource is underutilized and often considered a waste product to be discarded. However, urban trees have a potential to be utilized for various products, create jobs and an income stream for cities. The latest data on urban forests in the United States were used to estimate the potential annual value that could be derived from urban tree waste. Assuming a mortality rate of 2%, annual urban woody biomass loss in the U.S. equates to about 46 million tonnes of fresh-weight merchantable wood or 7.2 billion board feet of lumber or 16 million cords of firewood. The potential annual value from urban wood waste ranges between $89-786 million depending upon the product derived (e.g., wood chips to lumber). States with the greatest urban wood product potential are Florida ($6.6–57.6 million/year) and Georgia ($6.0–52.7 million/year). Along with woody biomass, annual leaf loss has a potential to produce value. The value of nutrients in annual leaf litter is estimated at $551 million per year. In addition to direct revenue from sales, other environmental benefits can be derived through tree waste utilization that reduces landfill waste, use of fertilizers and fossil fuel use in energy production. There are various reasons why this potential maximum value from urban tree waste is not and likely cannot be attained, but its current use and value can be increased. Creating markets and systems to utilize urban tree removals and leaves can help enhance income for urban forest management as well as create social and environmental goods.

1. Introduction

While healthy urban forests provide numerous benefits to society (e.g., Nowak and Dwyer, 2007; Nowak and Greenfield, 2018), debris from tree removals and leaf litter can create a significant disposal cost. However, these dead parts of a forest have the potential to be utilized to help reduce management costs and/or create income. Given the magnitude of the urban forest resource, the utilization of urban forest waste could produce significant value to society and enhance urban forest sustainability.

The total urban leaf area (one-sided) in the United States is estimated at 51.5 million hectares, with a dry-weight leaf biomass of 40.2 million tonnes (Nowak and Greenfield, 2018). These leaves provide numerous ecosystem services and values to humans, but also produce leaf litter that contains various nutrients that are essential for vegetation growth. In addition, the U.S. urban forest contain 834 million tonnes of carbon or 1.67 billion tonnes of dry-weight total tree biomass (Nowak and Greenfield, 2018). After death or removal, this urban wood can be used to produce products, rather than being a waste disposal cost.

Nationally, tree removals in urban areas account for approximately 14.0–34.5 million green tonnes per year (McKeever and Skog, 2003; Bratkovich et al., 2010). Dry weight biomass from dead and dying urban trees has also been estimated at 22.2 million tonnes per year (MacFarlane, 2009). In the past, much of the urban waste wood was dumped in landfills or burned. However, regulations and fees have made this approach impractical (Lough, 2012). Other popular uses of urban waste wood have included firewood and chips for mulch (Plumb et al., 1999). In a survey of urban landscape waste residue in the U.S. (Whittier et al., 1995), 67% of residue went to chips and 15% to unchipped logs. The most common residue disposal method was “give away” (42%), followed by landfill (17%).

In a study of municipalities in Georgia, North Carolina and Virginia, curbside pickup generated the highest percentage of urban wood waste for the public sector (32–44%), followed by tree pruning (23–31%) and tree removal (22–32%), while tree pruning (44–52%) and tree removal (34–43%) generated the greatest wood waste for the private sector (Stai et al., 2017). Logs were generally converted to firewood or lumber, while brush and chips were generally used for mulch and compost.

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Recently, there has been an increased awareness that desirable/useful products and services can be generated from urban waste wood. There is a growing movement to utilize urban wood as part of a commitment to sustainable urban forestry (e.g., Bratkovich et al., 2014; Michigan Urban Wood Network, 2019; Urban Wood Network, 2019; U.S. Forest Service, 2019d).

Creating products from urban tree waste can potentially help offset the cost of tree removal and maintenance, and provide for more secondary products that can be utilized to generate economic and environmental benefits to society. Urban waste wood can be used to produce commercial lumber, which can be further processed into secondary products (i.e. furniture, cabinetry, flooring, millwork, etc.). In addition, there are niche markets for irregular urban trees that may be special due to history, place of origin, personal value, or artistic value (e.g. unusual grain, figure, width, thickness, splits/crotches, etc.) (Sherrill, 2003; Sherrill and Bratkovich, 2018). Urban waste wood could also be used for biofuel (e.g. ethanol, butanol, pellets, etc.) and biochar production (e.g., Henkel et al., 2016; Muley et al., 2016). These markets, if available, can potentially create revenue that will offset some of the disposal costs and help bolster local small businesses (Cesa et al., 1994; Plumb et al., 1999). Incentives for urban wood utilization include reducing transportation costs and disposal fees, increasing environmental sustainability and production of additional revenue (Stai et al., 2017).

Waste wood utilization can also affect atmospheric carbon. Utilization of wood as an energy source can reduce use of and emissions from fossil-fuel based sources (e.g., Nowak et al., 2002b). In addition, upcycling of wood to more durable products (e.g., lumber, furniture) can lock carbon in the products for long periods, preventing the conversion of stored carbon back to atmospheric carbon via wood decomposition. Waste wood utilization is also viewed by many as an environmentally friendly approach to waste management because the waste wood is recycled and carbon is sequestered longer in the end-products (Solid Waste Association of North America, 2002).

Several limitations have prevented the utilization of urban wood in the past. These barriers include: lack of local processors and nearby markets, lack of space for stockpiling wood and/or equipment for processing wood, inconsistent wood supply, logistical difficulties in transporting wood, imbedded metal contaminants, and lack of planning (Bratkovich et al., 2008; Cesa et al., 1994; Stai et al., 2017). However, education, research, and improved technology and policies can lead to greater utilization of urban wood, which can provide many benefits to society (Bratkovich et al., 2008).

Utilizing tree and wood products can help recoup some of the costs associated with tree maintenance, both reducing costs and increasing benefits (e.g., jobs, products, reduced waste disposal). Various assessment of urban grass (e.g., Springer, 2012) and waste wood have been conducted in cities (e.g., Timilsina et al., 2014) and in states (e.g., MacFarlane, 2009; Joshi et al., 2015; Stai et al., 2017). However, national assessments of urban waste wood magnitude (MacFarlane, 2009; Bratkovich et al., 2010) and potential value are limited due to inadequate urban forest structural information. The objectives of this paper are to assess the annual potential values of urban tree waste by U.S. state based on more thorough and recent data on urban forest structure (Nowak and Greenfield, 2018) and to discuss the potential environmental and economic savings that can be realized through the utilization of urban tree waste. While various studies have focused on the total urban waste wood from cities (e.g., trees, buildings, etc.) (e.g., MacFarlane, 2009) or buildings (e.g., USDA Forest Service., 2019a), this paper only focuses on the urban tree resource.

2. Methods

Total urban tree leaf dry-weight biomass and carbon storage by U.S. states were derived from Nowak and Greenfield (2018). The definition of urban is primarily based on population density using the U.S. Census Bureau's (2017) definition: all territory, population, and housing units located within urbanized areas or urban clusters. To estimate leaf dry-weight biomass and carbon storage, state urban tree cover data from c. 2014 (Nowak and Greenfield, 2018) were combined with average structural attributes per acre of urban tree cover derived from field data collected in 28 U.S. cities and urban areas within 6 States from across the U.S. (Nowak et al., 2013a). These data were based on random samples of field plots in each city or state and analyzed using the i-Tree Eco model (www.itreetools.org; Nowak et al., 2008). The leaf biomass and carbon were estimated using measured tree data, allometric equations and leaf area to biomass conversion factors (Nowak, 1996; Nowak et al., 2008). The biomass and carbon estimates were converted to potential leaf nutrients and wood products, and associated values as follows.

2.1. *Leaf biomass to nutrient value conversions*

To determine annual leaf litter produced, percent deciduous leaf area in urban areas needs to be estimated. This information is not known for urban areas at the state level, except for Indiana, Kansas, Nebraska, North and South Dakota, Tennessee and Wisconsin (Nowak et al., 2007, 2012a, 2012b, 2017). To estimate percent deciduous for the other states, percent tree cover classified as deciduous was determined for each county based on evergreen, deciduous and mixed forest land covers as classified by the National Land Cover Database (NLCD) for 2011 (U.S. Geologic Survey, 2016). The proportion of mixed forest cover that was deciduous was estimated as the proportion of deciduous to evergreen plus deciduous forest cover in each county. Using field data from 38 cities (Table 1), percent deciduous leaf area was compared with NLCD derived estimates from the county within which each city resides. This comparison revealed that the NLCD county estimates of deciduous cover tend to underestimate the percent deciduous cover in the cities by an average 12.4% (i.e., cities tend to have more deciduous cover than the county average). For states without percent deciduous urban tree cover estimates, the NLCD derived estimate of percent deciduous tree cover was adjusted upward by 12.4% for states with less than 85% deciduous tree cover. The 85% cutoff was established to prevent excessively high percent deciduous values due to the correction factor.

Total state leaf dry-weight was multiplied by estimated percent deciduous cover to estimate annual leaf litter produced in urban areas by state. To estimate nutrients within the annual deciduous leaf litter produced, the average nutrient composition of dry-weight leaves (Table 2) was applied to the leaf biomass estimate.

To estimate the value of the nutrients (nitrogen (N), phosphorus (P), potassium (K)) within the leaf litter, N,P,K fertilizer costs were used as a proxy. The proxy values are based on market price methods, which use the prices of goods and services that are bought and sold in commercial markets to determine the value of an ecosystem service (Carson and Bergstrom, 2003). For N, anhydrous ammonia is the most prevalent and lowest cost form of nitrogen (360 Yield Center, 2019). With 82% nitrogen and an average cost of $564/tonne (t) in August 2018 (Schnitkey, 2018), the nitrogen value converts to $688/tN. For P, a diammonium phosphate fertilizer cost of $538/t was used (Schnitkey, 2018). With 46% P (Noble Research Institute, 2019), this cost converts to $1,169/tP. For K, the cost of potash fertilizer of $390/t was used (Schnitkey, 2018). With 60% K (Noble Research Institute, 2008), this cost converts to $650/tK. These values were applied to the N,P,K amounts within annual leaf litter to estimate the potential value of the nutrients within the leaves.

2.2. *Tree carbon to wood product value conversions*

Total urban tree carbon storage was converted to total tree dry-weight biomass by multiplying by two (e.g., Chow and Rolfe, 1989). Total tree biomass was converted to above-ground biomass based on a root-shoot ratio of 0.26 (Cairns et al., 1997). Dry weight was converted to fresh-weight using an average moisture content of 48% for conifers and 56% for hardwoods (Nowak et al., 2002a) and a U.S. average of

Table 1
Percent deciduous leaf area from 38 U.S. cities where field data derived estimates of leaf area where available based on i-Tree Eco analyses of randomly sampled field plots (e.g., Nowak et al., 2013a).

City	% Deciduous
Adrian, MI	90.7
Albuquerque, NM	83.6
Arlington, TX	92.3
Atlanta, GA	82.3
Austin, TX	42.8
Baltimore, MD	89.4
Boise, ID	74.1
Boston, MA	90.7
Casper, WY	72.5
Chester PA	94.8
Chicago, IL	96.1
Freehold, NJ	89.6
Gainesville, FL	52.4
Golden, CO	85.2
Grand Rapids, MI	90.2
Hartford, CT	90.1
Houston, TX	67.4
Jersey City, NJ	96.2
Kansas City, KS/MO	96.5
Las Cruces, NM	29.2
Lincoln, NE	79.9
Los Angeles, CA	47.8
Milwaukee, WI	92.9
Minneapolis, MN	89.4
Moorestown, NJ	88.4
Morgantown, WV	93.5
New York, NY	97.3
Omaha, NE	87.1
Philadelphia, PA	90.7
Phoenix, AZ	52.6
Roanoke, VA	87.4
Sacramento, CA	68.6
San Francisco, CA	15.1
Seattle, WA	61.2
Scranton, PA	85.1
Syracuse, NY	83.0
Washington, DC	95.8
Woodbridge, NJ	94.8

Table 2
Average percent nutrient composition of dry-weight leaves derived from Daubenmire (1953); Ovington (1956), and Pardo et al. (2005).

Nutrient	Percent
Carbon	58.32
Nitrogen	1.82
Calcium	0.98
Potassium	0.79
Magnesium	0.20
Phosphorus	0.17
Manganese	0.15

70% hardwoods in urban areas (based on U.S. results of percent deciduous urban tree cover from above).

To estimate the annual wood product potential from urban tree above-ground biomass, a mortality rate for urban trees is needed. Average urban tree loss in Baltimore was estimated at 6.6% between 1999 and 2001 (Nowak et al., 2004) and 3.6% within residential areas (Nowak and Aevermann, 2019). In Syracuse, NY (Nowak et al., 2016) the residential tree annual mortality rate (1999–2009) was 3.8%. If the high density and multi-family residential lands are excluded, residential tree mortality drops to 2.2% in Baltimore and 3.3% in Syracuse (Nowak and Aevermann, 2019). From these limited studies, annual mortality ranges between 2 and 7%, with a likely average around 4%. As annual mortality rates for entire urban forest populations are limited, this paper assumes a conservative average annual mortality of 2%, which is consistent with past urban biomass estimates (MacFarlane, 2009). As annual mortality rates vary by diameter class (Nowak, 1994), the average mortality rate was distributed among diameter classes such that the total mortality rate would be 2% based on the average U.S. urban forest diameter class distribution (Nowak and Aevermann, 2019; Table 3).

Table 3
Estimated proportion of total population and total biomass within tree diameter classes, and average percent merchantable above-ground biomass and annual mortality by diameter class (assuming a population average mortality of 2%) for U.S. urban trees.

Diameter class (cm)	Population%[a]	Biomass%[b]	%Merchantable[c]	%Mortality[d]
0–7.6	34.6	0.7	0.0	2.3
7.7–15.2	23.6	3.6	32.2	1.8
15.3–30.5	22.1	14.0	59.5	1.7
30.6–45.7	10.2	20.5	64.4	1.7
45.8–61.0	4.9	21.3	66.5	2.3
61.1–76.2	2.5	19.2	67.7	2.4
> 76.2	2.0	20.7	68.3	4.4

[a] proportion of total tree population within diameter class.
[b] proportion of total population biomass within diameter class.
[c] average percent of above-ground biomass that is merchantable.
[d] average percent annual mortality.

Because biomass increases with tree size, proportion of total tree population decreases with size, and varying mortality rates with tree size (Table 3), a 2% mortality rate does not mean that 2% of above-ground biomass will be removed. To determine an average percent biomass lost annually, the annual mortality by diameter class was weighted by the average proportion of biomass in the class. The proportion of total biomass in each diameter class was estimated by converting each 2.54 cm class to biomass using a sugar maple biomass equation (Wenger, 1984) and weighting this biomass by the proportion of total population in the diameter class based on the average U.S. diameter distribution (Nowak and Aevermann, 2019). Total biomass in the diameter class was divided by total biomass among all classes to determine the proportion of biomass in each class. Using this procedure, the annual biomass lost with a 2% mortality rate is 2.5%. This biomass mortality rate was then used to estimate annual above-ground dry and fresh-weight biomass removed in urban areas by state.

The fresh-weight above-ground biomass was converted to merchantable and non-merchantable biomass, which was consequently converted to four potential wood products: 1) lumber, 2) firewood, 3) pallets, and 4) wood chips. These products are mutually exclusive in that one unit of tree biomass can only go to one of the products. Thus the totals of these products are not additive for the same unit of biomass. Total tree biomass can be distributed among the products and added (e.g., 50% of the biomass used for lumber and 50% for wood chips). Also merchantable biomass and non-merchantable biomass products can be added regardless of the product.

2.2.1. *Merchantable vs. non-merchantable biomass*

The proportion of tree above-ground biomass that is merchantable (stem biomass from stump height 30 cm above ground to stem height with a 10.1 cm stem diameter) was calculated using formulas from Jenkins et al. (2004). Only trees with a minimum diameter at breast height (dbh) of 12.7 cm were considered to have merchantable biomass because of the 10.1 cm top definition. These formulas are based on tree diameter for hardwood and softwood trees. To estimate the average proportion of the urban forest that is merchantable, the percent merchantable for each 2.54 cm diameter class at or above 12.7 cm for hardwood and softwood was weighted based on a composition of 70% hardwood (based on U.S. results of percent deciduous urban tree cover from above), the average U.S. urban forest diameter distribution

(Nowak and Aevermann, 2019), and average percent biomass by diameter class (Table 3). This weighting produced an average proportion of 64% of above-ground urban tree biomass as merchantable.

2.2.2. Lumber estimates

Only trees with a minimum dbh of 22.9 cm (softwoods) and 27.9 cm (hardwoods) were considered for potential logs (Domke et al., 2013). Merchantable fresh-weight above-ground biomass for these trees was converted to board feet (BF) based on a ratio of 176 BF per tonne (Shelly, 2007). Two estimates of lumber value were made. Board feet was converted to monetary value using a cost of $105 per thousand BF (MBF) based on summer 2018 median cost for stumpage in New York Adirondack and Hudson/Mohawk regions using the International ¼ inch rule (New York State Department of Environmental Conservation (NY DEC), 2019). Tonnes of biomass were also converted to value based on 2018 stumpage prices from the Southern U.S. (Timber Update, 2019). These stumpage prices were reported based on pine and hardwood for small (< 23 cm) and large trees. Using the same weighting procedure as for merchantable biomass, the average stumpage value per tonne was $17.72.

2.2.3. Firewood estimates

Board feet of merchantable biomass was converted to cords of firewood using 500 BF / cord (New Hampshire Department of Revenue Administration (NH DRA), 2019). A price per cord of wood of $20.66 was used based on 25% of the price range of $16.53–$33.06 / tonne for firewood (Southern Maine Forestry Services, 2019). A minimum dbh for firewood was 12.7 cm based on the merchantable top definition (Jenkins et al., 2004).

2.2.4. Pallet estimates

Pallet price per MBF of $75 was used based on 25% of the price range of $50-$150 / MBF for pallet grade logs (Southern Maine Forestry Services, 2019). A minimum dbh for pallets was 12.7 cm based on the merchantable top definition (Jenkins et al., 2004).

2.2.5. Wood chip estimates

A price for wood chips of $1.25 / fresh-weight tonne was used for both merchantable and non-merchantable biomass based on 25% of the price range of $0.55–$3.31 / tonne for biomass fuel chips (Southern Maine Forestry Services, 2019).

3. Results

3.1. Urban tree leaf biomass, nutrient potential, and value

Total urban leaf biomass (dry-weight) in the United States is estimated at 40.2 million tonnes with 28 million tonnes of leaf litter produced annually. The amount of nutrients contained in leaf litter each year equates to about 16.4 million t of carbon, 511,000 t of nitrogen, 276,000 t of calcium, 221,000 t of potassium, 56,000 t of magnesium, 48,000 t of phosphorus and 41,000 t of manganese. The total nutrient value N, P, K in the leaf litter is estimated at $551 million per year. States with greatest annual leaf litter and value are Georgia ($35.5 million/yr), North Carolina ($34.9 million/yr), Pennsylvania ($34.7 million/yr), New York ($32.1 million/yr), and Ohio ($30.6 million/yr) (Table 4).

3.2. Urban tree waste wood potential and value

Total above-ground dry-weight biomass in the U.S. urban forest is estimated at 1.3 billion tonnes, with 33 million tonnes available annually assuming a 2% mortality rate. This annual woody biomass loss converts to a total of 46 million tonnes of fresh-weight merchantable wood or 7.2 billion board feet of lumber or 16 million cords of wood. This merchantable wood, if utilized, could produce between $57 million (based on wood chip values) to $753 million (based on board foot value) in value annually. In addition, chipping the non-merchantable wood could produce another $32 million dollars annually. States with the greatest urban wood product potential are Florida ($6.6–57.6 million/year), Georgia ($6.0–52.7 million/year), California ($5.5–48.7 million/year), North Carolina ($5.2–45.3 million/year) and Texas ($5.0–43.8 million/year) (Table 5).

4. Discussion

Nationally, tree removals in urban areas have been estimated at 14.0–34.5 million green tonnes per year (McKeever and Skog, 2003; Bratkovich et al., 2010). Data for our recent assessment reveal that current mortality and removals are on the order of 70 million green tonnes of above-ground biomass per year (33 million t/year dry-weight). The dry-weight removal estimate is comparable to a previous national estimate of 22.2 million tonnes per year, which was also based on a 2% mortality rate (MacFarlane, 2009). However, not all of this biomass is removed, as some of the urban trees that die each year will remain on site. The average annual waste wood yield per hectare of urban land is 1.2 t/ha, which is higher than 0.8 t/ha from MacFarlane (2009), but lower than estimates from 2.0 t/ha in Gainesville, Florida (Timilsina et al., 2014).

The potential annual biomass loss will increase through time as urban areas expand. Projections reveal that urban land in the conterminous United States is projected to increase from 3.6% (27.4 million ha) in 2010 to 8.6% (66.0 million ha) in 2060. This projected urban land increase over 50 years is 38.6 million ha, which is larger than the state of Montana (Nowak and Greenfield, 2018). This urban expansion could easily double the estimated product potential revealed from this current analysis.

The maximum potential value from the utilization of urban waste wood in the United States is $786 million per year based on lumber potential. This value will vary by year as mortality rates vary (e.g., storms, development, pest variations). It will also likely never be attained as not all of the trees that die within urban areas will be utilized for lumber due to limited access, log requirements, tree form, limited markets, tree decay, etc. The minimum national value if all above-ground biomass is converted to wood chips is $89 million dollars per year. This value is likely more attainable as trees often need to be chipped to be transported from the removal site. By converting the merchantable parts of trees to non-chip products (e.g., firewood, pallets, saw and veneer logs), the potential value of this wood increases.

The potential maximum values of the wood products assume that there is a local market available for these products, which may not be the case. In addition, local costs associated with transporting, stockpiling, sorting, and producing products will lead to a lower net value for the products. Creating markets and cost-effective systems to utilize urban tree wood can help enhance income for urban forest management as well as create local jobs.

In addition, utilizing wood to produce more long-term products (e.g., lumber, furniture) could reduce waste in landfills and will delay the release of carbon back to the atmosphere (e.g., via burning or decomposition) for longer periods. This longer term storage should reduce near-term carbon emissions depending upon how much carbon is used to produce the long-term products. This paper only assessed potential wood values related to logs, pallets, firewood and wood chips, but numerous other alternative wood products could developed.

4.1. Logs

Saw logs from urban trees offer the greatest potential for value ($753 million/year) as they can be used for manufactured wood products (e.g., furniture, cabinetry, millwork and flooring) and lumber (Bratkovich et al., 2010). Sherrill (2003) estimated that approximately 3–4 billion board feet of potential urban lumber are thrown away

Table 4
Dry-weight leaf biomass (LB) and nutrient composition and values of annual leaf litter from deciduous urban trees by U.S. state.

State	Total LB		Dec. LB[a]		Nutrients in annual leaf litter (t x 10^3)							Annual value ($ x 10^3)			
	(t x 10^3)	SE	%	(t x 10^3)	C	N	P	K	Ca	Mg	Mn	N	P	K	Total
Alabama	898.0	182.3	66.8	600.1	350.0	10.9	1.0	4.7	5.9	1.2	0.9	7,524	1,189	3,079	11,792
Arizona	546.8	111.0	15.1	82.5	48.1	1.5	0.1	0.7	0.8	0.2	0.1	1,034	163	423	1,620
Arkansas	486.7	98.8	82.6	401.9	234.4	7.3	0.7	3.2	4.0	0.8	0.6	5,039	797	2,062	7,897
California	2,488.4	505.2	18.3	455.8	265.8	8.3	0.8	3.6	4.5	0.9	0.7	5,714	903	2,338	8,955
Colorado	257.5	52.3	31.9	82.2	47.9	1.5	0.1	0.6	0.8	0.2	0.1	1,031	163	422	1,615
Connecticut	1,079.4	219.1	93.9	1,014.1	591.4	18.5	1.7	8.0	10.0	2.0	1.5	12,713	2,010	5,203	19,925
Delaware	137.0	27.8	92.3	126.5	73.8	2.3	0.2	1.0	1.2	0.3	0.2	1,586	251	649	2,485
Florida	2,947.5	598.4	14.0	411.9	240.2	7.5	0.7	3.2	4.0	0.8	0.6	5,163	816	2,113	8,093
Georgia	2,695.7	547.2	67.0	1,805.0	1,052.7	32.9	3.1	14.2	17.7	3.6	2.7	22,628	3,577	9,260	35,465
Idaho	62.8	12.8	18.4	11.6	6.7	0.2	0.0	0.1	0.1	0.0	0.0	145	23	59	227
Illinois	1,188.3	241.2	99.8	1,185.8	691.6	21.6	2.0	9.4	11.7	2.4	1.7	14,866	2,350	6,084	23,300
Indiana	760.4	154.4	94.3	717.0	418.2	13.1	1.2	5.7	7.0	1.4	1.1	8,989	1,421	3,679	14,089
Iowa	248.6	50.5	99.0	246.1	143.5	4.5	0.4	1.9	2.4	0.5	0.4	3,085	488	1,263	4,836
Kansas	324.5	65.9	91.2	296.0	172.6	5.4	0.5	2.3	2.9	0.6	0.4	3,710	587	1,518	5,815
Kentucky	482.8	98.0	94.8	457.5	266.8	8.3	0.8	3.6	4.5	0.9	0.7	5,735	907	2,347	8,989
Louisiana	843.3	171.2	44.1	371.8	216.8	6.8	0.6	2.9	3.7	0.7	0.5	4,661	737	1,907	7,305
Maine	201.4	40.9	54.7	110.2	64.3	2.0	0.2	0.9	1.1	0.2	0.2	1,381	218	565	2,165
Maryland	1,004.6	203.9	90.4	908.0	529.6	16.5	1.5	7.2	8.9	1.8	1.3	11,383	1,800	4,658	17,841
Massachusetts	1,625.9	330.1	81.5	1,325.4	773.0	24.1	2.2	10.5	13.0	2.6	2.0	16,616	2,627	6,800	26,043
Michigan	1,472.4	298.9	93.9	1,381.9	806.0	25.2	2.3	10.9	13.6	2.7	2.0	17,324	2,739	7,090	27,153
Minnesota	765.4	155.4	87.8	672.2	392.1	12.2	1.1	5.3	6.6	1.3	1.0	8,427	1,332	3,449	13,208
Mississippi	485.0	98.5	56.4	273.5	159.5	5.0	0.5	2.2	2.7	0.5	0.4	3,428	542	1,403	5,373
Missouri	771.0	156.5	97.2	749.7	437.3	13.7	1.3	5.9	7.4	1.5	1.1	9,399	1,486	3,846	14,731
Montana	61.1	12.4	14.5	8.9	5.2	0.2	0.0	0.1	0.1	0.0	0.0	111	18	46	175
Nebraska	102.8	20.9	84.0	86.4	50.4	1.6	0.1	0.7	0.8	0.2	0.1	1,083	171	443	1,697
Nevada	95.0	19.3	13.1	12.4	7.2	0.2	0.0	0.1	0.1	0.0	0.0	156	25	64	244
New Hampshire	347.6	70.6	68.6	238.3	139.0	4.3	0.4	1.9	2.3	0.5	0.4	2,987	472	1,223	4,682
New Jersey	1,295.0	262.9	94.8	1,227.2	715.7	22.4	2.1	9.7	12.1	2.4	1.8	15,384	2,432	6,296	24,112
New Mexico	133.5	27.1	14.0	18.7	10.9	0.3	0.0	0.1	0.2	0.0	0.0	235	37	96	368
New York	1,918.5	389.5	85.1	1,633.4	952.6	29.8	2.8	12.9	16.1	3.2	2.4	20,477	3,237	8,380	32,094
North Carolina	2,317.8	470.5	76.7	1,777.6	1,036.8	32.4	3.0	14.0	17.5	3.5	2.6	22,285	3,523	9,120	34,928
North Dakota	17.9	3.6	76.7	13.7	8.0	0.3	0.0	0.1	0.1	0.0	0.0	172	27	71	270
Ohio	1,594.4	323.7	97.8	1,559.1	909.3	28.4	2.6	12.3	15.3	3.1	2.3	19,546	3,090	7,999	30,635
Oklahoma	305.3	62.0	94.8	289.4	168.8	5.3	0.5	2.3	2.8	0.6	0.4	3,628	573	1,485	5,686
Oregon	327.0	66.4	15.6	51.0	29.8	0.9	0.1	0.4	0.5	0.1	0.1	640	101	262	1,003
Pennsylvania	1,844.1	374.4	95.8	1,766.7	1,030.4	32.2	3.0	13.9	17.4	3.5	2.6	22,148	3,501	9,064	34,713
Rhode Island	194.3	39.5	89.3	173.6	101.3	3.2	0.3	1.4	1.7	0.3	0.3	2,177	344	891	3,412
South Carolina	1,136.1	230.6	57.6	654.6	381.8	11.9	1.1	5.2	6.4	1.3	1.0	8,206	1,297	3,358	12,861
South Dakota	40.3	8.2	78.4	31.6	18.4	0.6	0.1	0.2	0.3	0.1	0.0	396	63	162	621
Tennessee	1,146.0	232.6	85.3	977.5	570.1	17.8	1.7	7.7	9.6	1.9	1.4	12,255	1,937	5,015	19,207
Texas	2,241.0	454.9	61.8	1,384.1	807.2	25.2	2.3	10.9	13.6	2.7	2.0	17,351	2,743	7,101	27,195
Utah	130.3	26.4	68.9	89.7	52.3	1.6	0.2	0.7	0.9	0.2	0.1	1,125	178	460	1,763
Vermont	73.7	15.0	88.4	65.1	38.0	1.2	0.1	0.5	0.6	0.1	0.1	816	129	334	1,280
Virginia	1,157.9	235.1	89.4	1,035.6	604.0	18.9	1.8	8.2	10.2	2.1	1.5	12,983	2,052	5,313	20,348
Washington	801.4	162.7	20.4	163.1	95.1	3.0	0.3	1.3	1.6	0.3	0.2	2,045	323	837	3,205
West Virginia	305.9	62.1	96.4	294.9	172.0	5.4	0.5	2.3	2.9	0.6	0.4	3,697	584	1,513	5,794
Wisconsin	500.3	101.6	81.6	408.2	238.1	7.4	0.7	3.2	4.0	0.8	0.6	5,118	809	2,094	8,021
Wyoming	22.3	4.5	17.7	3.9	2.3	0.1	0.0	0.0	0.0	0.0	0.0	49	8	20	77
US48[b]	39,916	8,100	69.8	27,868	16,254	507.7	47.2	219.9	273.9	55.3	41.1	349,369	55,232	142,975	547,577
Alaska	118.2	24.0	69.8	82.5	48.1	1.5	0.1	0.7	0.8	0.2	0.1	1,035	164	423	1,622
Hawaii	156.4	31.8	69.8	109.2	63.7	2.0	0.2	0.9	1.1	0.2	0.2	1,369	216	560	2,146
US50[c]	40,174	8,152	69.8	28,048	16,359	511.0	47.5	221.3	275.7	55.7	41.4	351,626	55,589	143,899	551,114

SE – standard error (t x 10^3).

[a] deciduous leaf biomass.

[b] conterminous 48 states.

[c] all 50 states.

annually. This analysis reveals that the annual maximum log potential is around 7 billion board feet. However, given the issues of required log dimensions and likely rot or inadequate forms (cull) in urban trees, this maximum potential is likely unattainable. Thus, the 3–4 billion board feet of potential urban lumber is likely a reasonable estimate. This value is not insignificant considering that an estimated 37.3 billion board feet of lumber (softwoods plus hardwoods) was produced in the United States in 2013 (Howard and Jones, 2016).

Traditional and portable band sawmills can be used to create lumber once an urban tree is harvested (Brashaw et al., 2012). However, tree size can be a limitation as saw logs are considered to be at least 2.4 m long (plus 15.2 to 20.3 cm trim) and have a small end diameter inside bark of at least 15.2 cm for softwoods and 20.3 cm for hardwoods (USDA Forest Service, 2004). Urban trees often have a more open-grown form than trees within traditionally forested stands, which creates a wider canopy and a relatively high number of large branches from the main bole. This form can decrease the value of grade lumber from urban trees. In addition, metal contamination and bark defects (both of which can cause discoloration in the sapwood) can be a concern.

Table 5

Total above-ground dry-weight biomass (AGB) and potential biomass products and values from urban waste wood by U.S. state assuming a 2% mortality rate. All values are in millions (x 10^6).

State	AGB Standing[a]		AGB Rem[b]	Merchantable AGB			Merchantable Value ($)[c]					N-M Value ($)[d]	Total Value ($)	
	t	SE	t	t[e]	BF[f]	Cords	Logs[g]	Logs[h]	Pallets	Firewood	Chips	Chips	Min[i]	Max[j]
Alabama	29.6	5.2	0.7	1.0	160.4	0.4	16.2	16.8	13.5	7.4	1.3	0.7	2.0	17.6
Arizona	18.0	3.2	0.5	0.6	97.7	0.2	9.8	10.3	8.2	4.5	0.8	0.4	1.2	10.7
Arkansas	16.0	2.8	0.4	0.6	86.9	0.2	8.8	9.1	7.3	4.0	0.7	0.4	1.1	9.5
California	82.0	14.5	2.1	2.8	444.5	1.0	44.8	46.7	37.4	20.6	3.5	2.0	5.5	48.7
Colorado	8.5	1.5	0.2	0.3	46.0	0.1	4.6	4.8	3.9	2.1	0.4	0.2	0.6	5.0
Connecticut	35.6	6.3	0.9	1.2	192.8	0.4	19.4	20.2	16.2	8.9	1.5	0.9	2.4	21.1
Delaware	4.5	0.8	0.1	0.2	24.5	0.1	2.5	2.6	2.1	1.1	0.2	0.1	0.3	2.7
Florida	97.1	17.1	2.4	3.4	526.5	1.2	53.0	55.3	44.3	24.4	4.2	2.4	6.6	57.6
Georgia	88.8	15.7	2.2	3.1	481.5	1.1	48.5	50.6	40.5	22.3	3.8	2.2	6.0	52.7
Idaho	2.1	0.4	0.1	0.1	11.2	0.0	1.1	1.2	0.9	0.5	0.1	0.1	0.1	1.2
Illinois	39.2	6.9	1.0	1.4	212.3	0.5	21.4	22.3	17.9	9.8	1.7	1.0	2.6	23.2
Indiana	25.1	4.4	0.6	0.9	135.8	0.3	13.7	14.3	11.4	6.3	1.1	0.6	1.7	14.9
Iowa	8.2	1.4	0.2	0.3	44.4	0.1	4.5	4.7	3.7	2.1	0.4	0.2	0.6	4.9
Kansas	10.7	1.9	0.3	0.4	58.0	0.1	5.8	6.1	4.9	2.7	0.5	0.3	0.7	6.3
Kentucky	15.9	2.8	0.4	0.5	86.2	0.2	8.7	9.1	7.3	4.0	0.7	0.4	1.1	9.4
Louisiana	27.8	4.9	0.7	1.0	150.6	0.3	15.2	15.8	12.7	7.0	1.2	0.7	1.9	16.5
Maine	6.6	1.2	0.2	0.2	36.0	0.1	3.6	3.8	3.0	1.7	0.3	0.2	0.4	3.9
Maryland	33.1	5.8	0.8	1.1	179.5	0.4	18.1	18.8	15.1	8.3	1.4	0.8	2.2	19.6
Massachusetts	53.6	9.4	1.3	1.9	290.4	0.7	29.2	30.5	24.4	13.5	2.3	1.3	3.6	31.8
Michigan	48.5	8.6	1.2	1.7	263.0	0.6	26.5	27.6	22.1	12.2	2.1	1.2	3.3	28.8
Minnesota	25.2	4.4	0.6	0.9	136.7	0.3	13.8	14.4	11.5	6.3	1.1	0.6	1.7	15.0
Mississippi	16.0	2.8	0.4	0.6	86.6	0.2	8.7	9.1	7.3	4.0	0.7	0.4	1.1	9.5
Missouri	25.4	4.5	0.6	0.9	137.7	0.3	13.9	14.5	11.6	6.4	1.1	0.6	1.7	15.1
Montana	2.0	0.4	0.1	0.1	10.9	0.0	1.1	1.1	0.9	0.5	0.1	0.0	0.1	1.2
Nebraska	3.4	0.6	0.1	0.1	18.4	0.0	1.8	1.9	1.5	0.9	0.1	0.1	0.2	2.0
Nevada	3.1	0.6	0.1	0.1	17.0	0.0	1.7	1.8	1.4	0.8	0.1	0.1	0.2	1.9
New Hampshire	11.5	2.0	0.3	0.4	62.1	0.1	6.3	6.5	5.2	2.9	0.5	0.3	0.8	6.8
New Jersey	42.7	7.5	1.1	1.5	231.3	0.5	23.3	24.3	19.5	10.7	1.8	1.0	2.9	25.3
New Mexico	4.4	0.8	0.1	0.2	23.8	0.1	2.4	2.5	2.0	1.1	0.2	0.1	0.3	2.6
New York	63.2	11.1	1.6	2.2	342.7	0.8	34.5	36.0	28.8	15.9	2.7	1.5	4.3	37.5
North Carolina	76.4	13.5	1.9	2.6	414.0	0.9	41.7	43.5	34.8	19.2	3.3	1.9	5.2	45.3
North Dakota	0.6	0.1	0.0	0.0	3.2	0.0	0.3	0.3	0.3	0.1	0.0	0.0	0.0	0.4
Ohio	52.5	9.3	1.3	1.8	284.8	0.6	28.7	29.9	24.0	13.2	2.3	1.3	3.5	31.2
Oklahoma	10.1	1.8	0.3	0.3	54.5	0.1	5.5	5.7	4.6	2.5	0.4	0.2	0.7	6.0
Oregon	10.8	1.9	0.3	0.4	58.4	0.1	5.9	6.1	4.9	2.7	0.5	0.3	0.7	6.4
Pennsylvania	60.8	10.7	1.5	2.1	329.4	0.7	33.2	34.6	27.7	15.3	2.6	1.5	4.1	36.1
Rhode Island	6.4	1.1	0.2	0.2	34.7	0.1	3.5	3.6	2.9	1.6	0.3	0.2	0.4	3.8
South Carolina	37.4	6.6	0.9	1.3	202.9	0.5	20.4	21.3	17.1	9.4	1.6	0.9	2.5	22.2
South Dakota	1.3	0.2	0.0	0.0	7.2	0.0	0.7	0.8	0.6	0.3	0.1	0.0	0.1	0.8
Tennessee	37.8	6.7	0.9	1.3	204.7	0.5	20.6	21.5	17.2	9.5	1.6	0.9	2.5	22.4
Texas	73.9	13.0	1.8	2.6	400.3	0.9	40.3	42.0	33.7	18.6	3.2	1.8	5.0	43.8
Utah	4.3	0.8	0.1	0.1	23.3	0.1	2.3	2.4	2.0	1.1	0.2	0.1	0.3	2.5
Vermont	2.4	0.4	0.1	0.1	13.2	0.0	1.3	1.4	1.1	0.6	0.1	0.1	0.2	1.4
Virginia	38.2	6.7	1.0	1.3	206.8	0.5	20.8	21.7	17.4	9.6	1.6	0.9	2.6	22.6
Washington	26.4	4.7	0.7	0.9	143.2	0.3	14.4	15.0	12.0	6.6	1.1	0.6	1.8	15.7
West Virginia	10.1	1.8	0.3	0.3	54.6	0.1	5.5	5.7	4.6	2.5	0.4	0.2	0.7	6.0
Wisconsin	16.5	2.9	0.4	0.6	89.4	0.2	9.0	9.4	7.5	4.1	0.7	0.4	1.1	9.8
Wyoming	0.7	0.1	0.0	0.0	4.0	0.0	0.4	0.4	0.3	0.2	0.0	0.0	0.0	0.4
US48[k]	1,315	231.9	32.9	45.5	7,130	16.0	717.9	748.7	600.1	330.6	56.8	32.0	88.8	780.7
Alaska	3.9	0.7	0.1	0.1	21.1	0.0	2.1	2.2	1.8	1.0	0.2	0.1	0.3	2.3
Hawaii	5.2	0.9	0.1	0.2	27.9	0.1	2.8	2.9	2.4	1.3	0.2	0.1	0.3	3.1
US50[l]	1,324	233.5	33.1	45.8	7,176	16.1	722.5	753.5	604.0	332.8	57.2	32.2	89.4	785.7

[a] standing above-ground dry-weight biomass prior to removal.

[b] removed above ground biomass assuming a 2% annual mortality (removal) rate.

[c] values are mutually exclusive.

[d] non-merchantable value (based on chip value).

[e] fresh-weight merchantable tonnes; minimum dbh of 12.7 cm.

[f] board feet based on minimum dbh of 22.9 cm (softwood) and 27.9 cm (hardwoods).

[g] log value based on average cost per tonne.

[h] log value based on average cost per board foot.

[i] minimum of total combined value of merchantable and non-merchantable wood; all wood converted to chips.

[j] maximum of total combined value of merchantable and non-merchantable wood; all merchantable wood converted to logs and non-merchantable converted to chips.

[k] conterminous 48 states.

[l] all 50 states.

Smaller urban logs can also be used for wood pulp, which is the basic raw material used to make paper, insulation board, and hardboard products (Widmann, 1991). Oftentimes, trees with multiple large branches or other major defects are used for pulpwood because they are not desirable for use as saw timber. Pulpwood trees usually generate less revenue than sawtimber trees, depending on the local markets.

4.2. Pallets

Pallets from urban trees have a potential annual value of $604 million. Generally, the raw material used to produce pallets consists of lower grade hardwood and softwood logs. This includes the interior portion of higher grade saw logs (heartwood), low-valued species, and low-quality roundwood (Brashaw et al., 2012).

4.3. Firewood

Firewood production has long been a popular use for urban trees and has the third highest potential value at $333 million per year. Though not as valuable as other potential products (e.g. flooring, furniture, etc.), it is a good market for large amounts of low-grade wood (Brashaw et al., 2012). The production of firewood from urban trees can be small scale, where only chainsaws and wood splitters are needed or large scale, where turn-key, automated systems are used to cut and split the wood. Firewood is generally cut and sold locally, thus a wide variety of species are utilized. Dense hardwoods are preferred because of their superior burning qualities (e.g. oak, maple, hickory, ash, elm, etc.).

Utilization of firewood for heating buildings can reduce carbon emissions from fossil-fuel based energy sources. One cord of seasoned firewood generates 15.3 million Btus (British thermal unit = 1055 joules), which is equivalent to about 0.53 tonnes of coal, 500 liters of #2 fuel oil, or 815 liters of propane (USDA Forest Service, 2019b). Thus, the national urban forest annual fuel potential is equivalent to 246 million MBtu (million Btu), 8.6 million tonnes of coal, 8.1 billion liters of fuel oil or 13.2 billion liters of propane. The urban waste wood Btu value is equivalent to about ¼% of total U.S. primary energy consumption in 2017 (97.7 billion MBtu; U.S. Energy Information Administration, 2019).

4.4. Wood chips

Wood chips produce the lowest value of the analyzed potential products at $89 million per year. Wood chips can be used for a variety of purposes such as wood pulp, mulch and fuel. Chips for wood pulp need to be uniform sized and de-barked (“clean chips”) (Peterson, 2019). Chips for mulch or fuel can be non-uniformed shaped and barked. Mulch sold for flower beds and other aesthetic purposes need to be a uniform size and shape, however, mulch that is being used as a potting medium at a nursery can be non-uniform (Bratkovich et al., 2010). Institutional and state/city/town departments use chips/mulch in parks, schools, and vacant lots (Lough, 2012).

Biomass is being used increasingly around the U.S. and other countries as a fuel source in combined heat and power (CHP) plants. CHP is defined as “the simultaneous production of electrical or mechanical energy (power) and useful thermal energy from a single energy source” (ASHRAE, 2008). Dried urban wood chips can be turned into a gas and burned to generate heat. This heat is used to heat water, but also routed via heat exchangers into an external combustion engine (or gas turbine) where the heat is used to generate electricity. The electricity and thermal energy (i.e. hot water) produced are used to feed the entire process and the excess energy is stored/sold and used to heat and power other places (U.S. Environmental Protection Agency, 2007).

An example of a CHP use from urban wood comes from St. Paul, Minnesota, where District Energy utilizes approximately 270,000 tonnes of waste wood each year, primarily from urban tree removals. The plant simultaneously produces 65 MW of thermal energy for District Energy and 33 MW of electricity for Xcel Energy (Bratkovich et al., 2010). The company estimates that “the collection, processing and transportation of local wood residuals for the CHP plant contributes more than $10 million annually to the local economy” (District Energy, 2013).

Various biofuel and other products can also be developed from CHP plants by converting these plants into biorefineries. These products include fuel pellets, pulp and paper, reconstitutes (e.g. fiberboard, etc.), and cellulose nanocrystals, as well as acetic acid, formic acid, methanol, furfural, butanol, acetone, ethanol, and lactic acid (Amidon et al., 2008). Based on this biorefinery process, a tonne of urban waste wood (dry chips) could produce about 700 kg of premium wood fiber for the production of fuel pellets, pulp and paper, etc. It could also produce about 9 kg of furfural, 127 kg of sugars, 16 kg of acetic acid, 5 kg of methanol, 25 kg of lignin, and 2 kg of formic acid (T. Amidon, pers. comm., 2013). This production is in addition to the heat and power production. Biofuel production can help reduce fossil-fuel use and associated greenhouse gas emissions.

Wood chips can also be used to create bio-char (e.g., Henkel et al., 2016), which is a charcoal produced by burning organic matter under low oxygen conditions. Biochar can be used a soil amendment to potentially improve soil fertility and help mitigate climate change (e.g., Lehmann et al., 2011). By producing and utilizing biochar in soils, tree carbon could be stored for long periods of time and urban tree productivity and performance potentially increased. Significant potential exists for the production of bioenergy/biofuel and biochar from wood waste (cellulose, hemicellulos and lignin).

4.5. Specialty and other products

Specialty wood-working products can also be produced from urban trees as these trees can contain natural variation in wood color, knots, burls, insect damage (e.g. larvae galleries/holes) and mineral stains that create unique wood characteristics that can increase its value. These products include picture frames, bowls, small jewelry boxes, gunstocks, lamp bases, clocks, coasters, cribbage boards, cutting boards, custom table tops, and tool handles (Brashaw et al., 2012). Small business and craft shop owners prefer these types of wood because of the special/unique effects they give their finished products. Taylor Guitars, a leading guitar manufacturer, is currently exploring utilizing urban wood for guitars and believes that there is a sufficient quantity of music quality tonewood within the urban wood waste stream to use as a future component on a line of its mass produced guitars (S. Paul, pers. comm., 2019). Urban trees also have the potential to produce numerous other products such as shipping containers, landscape ties, railroad ties, poles and piling, bolts and billets, mine timbers, and fence posts.

4.6. Leaf biomass utilization

In addition to potential products from waste wood, annual urban leaf litter could be utilized to add nutrients to the soil. The potential value from these leaves in terms of N, P, and K is $551 million per year. The estimated leaf biomass of 28 million tonnes is less than the 40 million tonnes (Nowak and Greenfield, 2018) due to updated state level estimates of percent deciduous cover.

How these urban leaves are distributed and disposed of in urban areas will influence carbon and nutrient cycling, water quality and the use of fertilizers to provide essential nutrients for urban forests. There are various options related to disposing of leaf litter. Some options facilitate recycling of these nutrients, others dispose of the leaves. Recycling options include using mowers to mulch and distribute the leaves on site and mulching/composting the leaves either on- or off-site. Mulch can be used around plants to suppress weeds, retain moisture, insulate the soil, reduce erosion and provide nutrients to the soil. Compost can be added to soils to enrich soil, help retain moisture, suppress plant diseases and pests, and reduce the need for chemical fertilizers (U.S. Environmental Protection Agency, 2019).

Leaves that are moved off-site are either composted or become part of the waste stream. A previous study (U.S. Environmental Protection

Agency, 2013) that investigated the amount of yard waste generated in the United States found that as of 2011, 22 states—representing about 40% of the nation's population—have legislation affecting disposal of yard trimmings. In addition, some local and regional jurisdictions regulate disposal of yard trimmings. Of the 30.6 million tonnes of yard trimmings in the United States, 57.3% or 17.5 million tonnes were recovered by off-site composting or wood waste mulching in 2011. Yard waste contributed 13.5% of the total annual weight of municipal solid waste in 2011 (U.S. Environmental Protection Agency, 2013). It is estimated that the average composition of yard trimmings by weight is about 50% grass, 25% brush, and 25% leaves. Utilizing urban leaves and leaf nutrients can help reduce landfill waste and also add thousands of tonnes of essential nutrients back to the soil.

While leaves contain nutrients, they could also contain heavy metals and other pollutants that may be retained on the leaf surface through the interception of particulate pollution (Smith, 1990; Nowak et al., 2013b). These pollutants could be concentrated in soils where numerous leaves are aggregated to develop mulch/compost. In addition, leaf molds, which can be beneficial to soils, could also create allergic reactions in humans (Rackemann et al., 1938; Vinje, 2019)

4.7. Limitations

The estimates of biomass loss provided in this paper are based on the best available data related to urban forest structure and mortality rates. The cumulative uncertainty of these estimates and the associated monetary values is unknown. The relative standard error of the estimate of above-ground biomass is 18%, but uncertainty increases as conversions of biomass to potential waste value are calculated. These conversions include above-ground dry-weight biomass to fresh-weight merchantable biomass (low uncertainty), mortality rates (high uncertainty), conversion of merchantable biomass to products (low to moderate uncertainty), and valuing of products (low to moderate uncertainty). The largest potential uncertainty arises from mortality rates, which are likely between 2 to 7% annually. Changes in mortality rates can have substantial effects with 7% mortality more than tripling the values. Monetary values will also fluctuate through time as market values change.

These estimates can be improved with more comprehensive urban forest structural data and long-term monitoring. Urban forest monitoring (mortality) information will improve in the future based on the U.S. Forest Service Forest Inventory and Analysis' urban forest inventory program. This program measures urban forest data annually to assess urban forest structure, ecosystem services and values, and changes in structure, services and values through time. Thirty five cities were monitored in 2018 with new cities to be added to the monitoring program annually (USDA Forest Service, 2019c).

The current estimates are likely conservative relative to total annual percent mortality, thus the values given are likely conservative maximum potential values. However, most of this potential is not being realized, so the actual value that is utilized from urban tree waste is substantially lower than the potential maximum. There are various reasons why this potential maximum is not realized, including: a) not all trees that die are removed as many trees remain on site and decompose (e.g., forest stands), b) not all of the wood can be utilized for products due to defects, c) log estimates are liberal as they are based on merchantable biomass to a 10.1 cm top (saw logs typically go to a 15.2 cm (softwoods) and 20.3 cm (hardwood) top diameter) (USDA Forest Service, 2004) and d) many areas do not have markets to sell these potential products. Other limitations include: a) log length and quality of logs (e.g., defects, knots) are not considered in the log calculation, b) valuation will vary through time as market values fluctuate, and c) nutrient values maybe overestimated based on market prices as the nutrients from the leaves may not be as effective in supplying nutrients as commercial fertilizers.

While several cities are creating revenue by utilizing urban waste wood to produce mulch, chips, logs or fuel for CHP plants (e.g., Bratkovich, 2001; Bratkovich et al., 2010; Lough, 2012), much of this potential resource value is lost through underutilization of these potential products. To aid in aligning urban waste wood with potential buyers or markets, i-Tree and the USDA Forest Service Forest Product Lab have developed i-Tree Wood Marketplace. This free tool (wood.itreetools.org/market/map) is designed to connect people who remove urban trees with potential buyers. The actual value utilized can increase if cities or regions make the effort to produce products from waste wood and help establish markets. These efforts could include policies, regulations, coordination among supplies and markets, and funding to create a robust system for utilizing urban tree waste. Improved forest recycling and use of waste can reduce costs and help create more sustainable urban forests. Increasing the number of cities utilizing urban wood and leaf waste could potentially equate to over a billion dollars in annual value nationally.

5. Conclusion

Urban tree wood waste could reasonably produce between $100 million to $1 billion dollars in annual value nationally if utilized. The value will vary by state and the type of product produced (e.g., saw logs vs. wood chips). Though some cities utilize urban waste wood, the potential nationally is largely untapped. Some of the value produced by utilizing urban tree waste will be lost through the cost of production, but many of these trees are already being removed (harvested) (e.g., Sherrill and Bratkovich, 2018) and the potential products and revenue underutilized. In addition to direct revenue from sales, other environmental benefits can be derived through tree waste utilization that reduces use of fertilizers and fossil fuels in energy production. Improved utilization of urban tree waste can also lead to reduced wood waste in landfills, increased urban jobs, and reduced need for harvesting rural forests. As urbanization expands, so will the potential value of urban tree waste. Creating markets and systems to utilize urban tree removals and leaves can help improve income for urban forest management, as well as create social and environmental goods.

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References

360 Yield Center, 2019. Sponsored: know nitrogen forms to understand what's at risk. Successful Farming. https://www.agriculture.com/crops/corn/know-nitrogen-fms-to-underst-whats-at_136-ar52601 (March 2019).

Amidon, T.E., Wood, C.D., Shupe, A.M., Wang, Y., Graves, M., Liu, S., 2008. Biorefinery: conversion of woody biomass to chemicals, energy and materials. J. Biobased Mater. Bioenergy 2 (2), 100–120.

ASHRAE, 2008. ASHRAE Handbook: Systems and Equipment. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA 888 p.

Brashaw, B.K., Ross, R.J., Wang, X., Wiemann, M.C., 2012. Wood Utilization Options for Urban Trees Infested by Invasive Species. University of Minnesota 96 p.

Bratkovich, S., 2001. Utilizing Municipal Trees: Ideas From Across the Country. United States Department of Agriculture Forest Service, Northeastern Area State and Private Forestry, NA-TP-06-01, St. Paul, MN 91 p.

Bratkovich, S., Bowyer, J., Fernholz, K., Lindburg, A., 2008. Urban Tree Utilization and Why It Matters. Dovetail Partners, Inc. http://www.dovetailinc.org/reports/Urban%20Tree%20Utilization%20and%20Why%20It%20Matters_n323?prefix=%2Freports (April 2019).

Bratkovich, S., Bowyer, J., Fernholz, K., 2010. Urban Wood Utilization and Industrial Clusters: A Twin Cities Case Study. Dovetail Partners, Inc. http://www.dovetailinc.org/reports/Urban%20Wood%20Utilization%20and%20Industrial%20Clusters_n284?prefix=%2Freports (April 2019).

Bratkovich, S., Fernholz, K., Howe, J., Frank, M., Pepke, E., Bowyer, J., 2014. Urban Forests and Urban Tree Use: Opportunities on Local, State, National and International Scales. Dovetail Partners, Inc. http://www.dovetailinc.org/report_pdfs/2014/dovetailurbanforests112014.pdf (May 2019).

Cairns, M.A., Brown, S., Helmer, E.H., Baumgardner, G.A., 1997. Root biomass allocation in the world's upland forests. Oecologia. 111, 1–11.

Carson, R.M., Bergstrom, J.C., 2003. A Review of Ecosystem Valuation Techniques FS 03-03. Department of Agricultural & Applied Economics College of Agricultural &

Environmental Sciences, The University of Georgia 24 p.

Cesa, E.T., Lempicki, E.A., Knotts, J.H., 1994. Recycling Municipal Trees: a Guide for Marketing Sawlogs From Street Tree Removals in Municipalities. NA-TP-02-94. USDA Forest Service, Northeastern Area, State and Private Forestry, Morgantown, WV 49p.

Chow, P., Rolfe, G.L., 1989. Carbon and hydrogen contents of short-rotation biomass of five hardwood species. Wood and Fiber Science 21 (1), 30–36.

Daubenmire, R., 1953. Nutrient content of leaf litter of trees in the Northern Rocky Mountains. Ecology. 34 (4), 786–793.

District Energy, 2013. Combined Heat and Power. St. Paul, MN. http://www.districtenergy.com/technologies/combined-heat-and-power/ (April 2013).

Domke, G.M., Oswalt, C.M., Woodall, C.W., Turner, J.A., 2013. Estimation of merchantable bole volume and biomass above sawlog top in the National Forest Inventory of the United States. J. For. 111 (6), 383–387.

Henkel, C., Muley, P.D., Abdollahi, K.K., Marculescu, C., Boldor, D., 2016. Pyrolysis of energy cane bagasse and invasive Chinese tallow tree (Triadica sebifera L.) biomass in an inductively heated reactor. Energy Convers. Manage. 109, 175–183.

Howard, J.L., Jones, K.C., 2016. U.S. Timber Production, Trade, Consumption, and Price Statistics, 1965–2013.Research Paper FPL-RP-679. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI 91 p.

Jenkins, J.C., Chojnacky, D.C., Heath, L.S., Birdsey, R.A., 2004. Comprehensive Database of Diameter-based Biomass Regressions for North American Tree Species. United States Department of Agriculture Forest Service, Northeastern Research Station, General Technical Report NE-319, Newtown Square, PA 45 p.

Joshi, O., Grebner, D.L., Khanal, P.N., 2015. Status of urban wood-waste and their potential use for sustainable bioenergy in Mississippi Resources. Conserv. Recycl. 102, 20–26.

Lehmann, J., Rillig, M.C., Thies, J., Masiello, C.A., Hockaday, W.C., Crowley, D., 2011. Biochar effects on soil biota - A review. Soil Biol. Biochem. 43, 1812–1836.

Lough, J., 2012. Chicago's Urban Wood Utilization Program. USDA Forest Service, Wood Education and Resource Center. Webcast Archive. http://www.na.fs.fed.us/werc/eab.shtm (November 2012).

MacFarlane, D., 2009. Potential availability of urban wood biomass in Michigan: Implications for energy production, carbon sequestration, and sustainable forest management in the U.S.A. Biomass Bioenergy 33 (4), 628–634.

McKeever, D.B., Skog, K.E., 2003. Urban Tree and Woody Yard Residues: Another Wood Resource. Res. Note FPL-RN-0290. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI 4 p.

Michigan Urban Wood Network, 2019. The Urban Wood Toolkit. https://www.miurbanwoodnetwork.com/toolkit (April 2019).

Muley, P.D., Henkel, C., Abdollahi, K.K., Marculescu, C., Boldor, D., 2016. A critical comparison of pyrolysis of cellulose, lignin, and pine sawdust using an induction heating reactor. Energy Convers. Manage. 117, 273–280.

New Hampshire Department of Revenue Administration (NH DRA), 2019. Formulas for Conversion. https://www.revenue.nh.gov/mun-prop/property/documents/timber-conversion-formulas.pdf.

New York State Department of Environmental Conservation (NY DEC), 2019. Stumpage Price Report, Summer 2018. NY DEC, Albany, NY #93. https://www.dec.ny.gov/docs/lands_forests_pdf/paststumpage.pdf.

Noble Research Institute, 2008. Is Fertilizer Worth the Cost? https://www.noble.org/news/publications/ag-news-and-views/2008/december/is-fertilizer-worth-the-cost/.

Nowak, D.J., 1994. Atmospheric carbon dioxide reduction by Chicago's urban forest. In: McPherson, E.G., Nowak, D.J., Rowntree, R.A. (Eds.), Chicago'S Urban Forest Ecosystem: Results of the Chicago Urban Forest Climate Project. USDA Forest Service General Technical Report NE-186, pp. 83–94.

Nowak, D.J., 1996. Estimating leaf area and leaf biomass of open-grown urban deciduous trees. For. Sci. 42 (4), 504–507.

Nowak, D.J., Aevermann, T., 2019. Tree compensation rates: compensating for the loss of current and future tree values. Urban For. Urban Green. 41, 93–103.

Nowak, D.J., Dwyer, J.F., 2007. Understanding the benefits and costs of urban forest ecosystems. In: Kuser, J. (Ed.), Urban and Community Forestry in the Northeast. Springer, New York, pp. 25–46.

Nowak, D.J., Greenfield, E.J., 2018. U.S. Urban forest statistics, values and projections. J. For. 116 (2), 164–177.

Nowak, D.J., Crane, D.E., Stevens, J.C., Ibarra, M., 2002a. Brooklyn's Urban Forest. USDA Forest Service Gen. Tech. Rep. NE-290 107p.

Nowak, D.J., Stevens, J.C., Sisinni, S.M., Luley, C.J., 2002b. Effects of urban tree management and species selection on atmospheric carbon dioxide. J. Arboric. 28 (3), 113–122.

Nowak, D.J., Kurodo, M., Crane, D.E., 2004. Urban tree mortality rates and tree population projections in Baltimore, Maryland, USA. Urban For. Urban Green. 2 (3), 139–147.

Nowak, D.J., Buckelew-Cumming, A., Twardus, D., Hoehn, R., Mielke, M., 2007. National Forest Health Monitoring Program, Monitoring Urban Forests in Indiana: Pilot Study 2002, Part 2: Statewide Estimates Using the UFORE Model. Northeastern Area Report. NA-FR-01-07 13 p.

Nowak, D.J., Hoehn, R.E., Crane, D.E., Stevens, J.C., Walton, J.T., Bond, J., 2008. A ground-based method of assessing urban forest structure and ecosystem services. Arboric. Urban For. 34 (6), 347–358.

Nowak, D.J., Cumming, A., Twardus, D., Hoehn, R.E., Brandeis, T.J., Oswalt, C.M., 2012a. Urban Forests of Tennessee. USDA Forest Service Southern Research Station General Technical Report SRS-149, Asheville, NC 52 p.

Nowak, D.J., Hoehn, R., Crane, D.E., Bodine, A., 2012b. Assessing Urban Forest Effects and Values in the Great Plains States: Kansas, Nebraska, North Dakota, South Dakota. USDA Forest Service, Northern Research Station Resource Bulletin NRS-71, Newtown Square, PA 75 p.

Nowak, D.J., Greenfield, E.J., Hoehn, R., LaPoint, E., 2013a. Carbon storage and sequestration by trees in urban and community areas of the United States. Environ. Pollut. 178, 229–236.

Nowak, D.J., Hirabayshi, S., Bodine, A., Hoehn, R., 2013b. Modeled PM2.5 removal by trees in ten U.S. Cities and associated health effects. Environ. Pollut. 178, 395–402.

Nowak, D.J., Hoehn, R.E., Bodine, A.R., Greenfield, E.J., O'Neil-Dunne, J., 2016. Urban Forest Structure, Ecosystem Services and Change in Syracuse, NY. Urban Ecosyst. 19, 1455–1477.

Nowak, D.J., Bodine, A.R., Hoehn, R.E., Rideout, R., Stoltman, A., Lorentz, L., 2017. Urban Forests of Wisconsin, 2012. Wisconsin Department of Natural Resources Forestry Division, Madison, WI PUB-FR-615 2017 78 p.

Ovington, J.D., 1956. The composition of tree leaves. Forestry 29 (1), 22–28.

Pardo, L.H., Robin-Abbott, M., Duarte, N., Miller, E.K., 2005. Tree chemistry database (version 1.0). https://www.treesearch.fs.fed.us/pubs/9464 (January 2017).

Peterson, 2019. Pulp and Paper Chips. Peterson, an Astec Industries Co. https://www.petersoncorp.com/applications/pulp-paper-chips/ (April 2019).

Plumb, T.R., Wolf, M.M., Shelly, J., 1999. California Urban Woody Green Waste Utilization. Urban Forest Ecosystems Institute, California Polytechnic State University, San Luis Obispo, California.

Rackemann, F.M., Randolph, T.G., Cuba, E.F., 1938. The specificity of fungous allergy. J. Allergy 447–453.

Schnitkey, G., 2018. Weekly Farm Economics. Illinois Farmdocdaily. https://farmdocdaily.illinois.edu/2018/09/fertilizer-prices-higher-for-2019-crop.html (March 2019).

Shelly, J.R., 2007. Woody biomass definitions and conversion factors. University of California, Berkeley. https://ucanr.edu/sites/WoodyBiomass/newsletters/IG003_-_Woody_Biomass_Definitions_and_Conversions_Factors31510.pdf (April 2019).

Sherrill, S., 2003. Harvesting Urban Timber. Linden Publishing 200 p.

Sherrill, S., Bratkovich, S., 2018. Estimates of Carbon Dioxide Withheld from the Atmosphere by Urban Hardwood Products. 38 p. http://www.dovetailinc.org/dovetailurbanwood318.pdf (May 2019).

Smith, W.H., 1990. Air Pollution and Forests. Springer-Verlag, New York 618 p.

Solid Waste Association of North America, 2002. Successful Approaches to Recycling Urban Wood Waste. General Technical Report FPL-GTR-133. USDA Forest Service. Forest Products Laboratory, Madison, WI 20 p.

Southern Maine Forestry Services, Inc, 2019. Timber market: recent range in stumpage prices received. https://www.someforest.com/timber-market (March 2019).

Springer, T.L., 2012. Biomass yield from an urban landscape. Biomass Bioenergy 37, 82–87.

Stai, S.M., Wiseman, P.E., Fernholz, K., 2017. Urban Wood Utilization in Virginia, North Carolina, and Georgia: A Comparison of Industry Practices and Perceptions. 19 p. Dovetail Partners. http://www.dovetailinc.org/report_pdfs/2017/dovetailurbanwoodvancga102017.pdf.

Timber Update, 2019. Current Timber Prices. (March 2019). https://timberupdate.com/timber-prices/.

Timilsina, N., Staudhammer, C.L., Escobedo, F.J., Lawrence, A., 2014. Tree biomass, wood waste yield, and carbon storage changes in an urban forest. Landsc. Urban Plan. 127, 18–27.

U.S. Census Bureau, 2017. 2010 Census Urban and Rural Classification and Urban Area Criteria. last accessed March 22, 2017. https://www.census.gov/geo/reference/ua/urban-rural-2010.html.

USDA Forest Service, 2004. Northeast Forest Inventory and Analysis: Common Definitions Used by the FIA. (February 2013). http://www.fs.fed.us/ne/fia/methodology/def_qz.htm.

USDA Forest Service, 2019a. Baltimore Wood Project. (April 2019). https://www.fs.fed.us/research/urban/baltimore-wood-project.php.

USDA Forest Service, 2019b. Fuel Value Calculator. Forest Product Laboratory TechLine. (April 2019). https://www.fpl.fs.fed.us/documnts/techline/fuel-value-calculator.pdf.

USDA Forest Service, 2019c. Urban Forest Inventory and Analysis (FIA). (April 2019). https://www.nrs.fs.fed.us/fia/urban/.

USDA Forest Service, 2019d. Wood Education and Resource Center. (April 2019). https://www.fs.usda.gov/naspf/index.php?q = programs/wood-education-and-resource-center.

U.S. Energy Information Administration, 2019. U.S. Energy Facts Explained. (April 2019). https://www.eia.gov/energyexplained/?page = us_energy_home.

U.S. Environmental Protection Agency, 2007. Biomass Combined Heat and Power Catalog of Technologies. EPA Combined Heat and Power Partnership (April 2013). http://www.epa.gov/chp/documents/biomass_chp_catalog.pdf.

U.S. Environmental Protection Agency, 2013. Municipal Solid Wastes in the United States: 2011 Facts and Figures. Office of Solid Waste (5306P) EPA530-R-13-001. 160 p.

U.S. Environmental Protection Agency, 2019. Composting at Home. (April 2019). https://www.epa.gov/recycle/composting-home.

U.S. Geologic Survey, 2016. Multi-resolution Land Characteristics Consortium. www.mrlc.gov.

Urban Wood Network, 2019. Urban Wood Network. (April 2019). http://urbanwoodnetwork.org/about.

Vinje, E., 2019. Using Autumn's Bounty. Planet Natural Research Center (April 2019). https://www.planetnatural.com/leaf-mold/.

Wenger, K.F. (Ed.), 1984. Forestry Handbook. John Wiley and Sons, New York 1335 p.

Whittier, J., Rue, D., Haase, S., 1995. Urban tree residues: results of the first national survey. Journal of Arboriculture 21 (2), 57–62.

Widmann, R.H., 1991. Pulpwood Production in the Northeast – 1989. Resource Bulletin NE-119. USDA Forest Service, Northeastern Forest Experiment Station, Radnor, PA 28 p.