BIOMASS AND BIOENERGY 33 (2009) 628–634

Available at www.sciencedirect.com

ScienceDirect

http://www.elsevier.com/locate/biombioe

# Potential availability of urban wood biomass in Michigan: Implications for energy production, carbon sequestration and sustainable forest management in the U.S.A.

*David W. MacFarlane**

Department of Forestry, Michigan State University, 126 Natural Resources Building, East Lansing, MI 48824, USA

ARTICLE INFO

*Article history:*
Received 1 November 2007
Received in revised form
4 September 2008
Accepted 24 October 2008
Published online 28 November 2008

*Keywords:*
Wood biomass
Wood waste
Urban
Carbon sequestration

ABSTRACT

Tree and wood biomass from urban areas is a potentially large, underutilized resource viewed in the broader social context of biomass production and utilization. Here, data and analysis from a regional study in a 13-county area of Michigan, U.S.A. are combined with data and analysis from several other studies to examine this potential. The results suggest that urban trees and wood waste offer a modest amount of biomass that could contribute significantly more to regional and national bio-economies than it does at present. Better utilization of biomass from urban trees and wood waste could offer new sources of locally generated wood products and bio-based fuels for power and heat generation, reduce fossil fuel consumption, reduce waste disposal costs and reduce pressure on forests. Although wood biomass generally constitutes a "carbon-neutral" fuel, burning rather than burying urban wood waste may not have a net positive effect on reducing atmospheric $CO_2$ levels, because it may reduce a significant long term carbon storage pool. Using urban wood residues for wood products may provide the best balance of economic and environmental values for utilization.



## 1. Introduction

Recent interest in developing biologically renewable fuel sources has focused renewed attention on utilizing tree/wood biomass for this purpose. In modern times, wood makes up only 7% of global fuel sources, with an estimated 15% of energy used in developing nations and only about 2% in developed nations [1], excluding some developed countries where substantial efforts have been made to use more wood fuel (e.g., Sweden). Much of this wood comes from forests, but a considerable amount also comes from what the Food and Agricultural Organization of the United Nations has termed "trees outside of forests" [2]. Generally, the availability of wood from non-forest trees is not well documented [1].

Wood from urban areas is one potentially large source of biomass that appears currently underutilized. Wood biomass from urban areas includes both wood waste generated when wood products are damaged or outlive their usefulness [3] and tree/wood biomass that is liberated when urban trees are taken down or parts of woody vegetation are trimmed [4]. At global and national scales, it appears that urban wood biomass may offer a potentially large source of wood that could be reused, burned for fuel or otherwise recycled [1,3,4]. However, some important questions remain regarding how available urban wood biomass resources are and what are the implications for trying to make use of them. In particular, it is important that these questions be answered at local or regional scales where wood utilization potential is most practically assessed.

* Tel.: +1 517 355 2399; fax: +1 517 432 1143.
E-mail address: macfar24@msu.edu
0961-9534/$ – see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.biombioe.2008.10.004

Here, new data and analysis on the potential availability of biomass from urban trees in a 13-county area of Michigan, U.S.A. is combined with existing data from several other sources to examine the potential of urban tree removals and other urban-generated sources of wood biomass to supply locally generated bio-based fuels and primary and secondary (recycled) wood products. The critical points of discussion focus on the implications of urban wood utilization for energy production, carbon sequestration and sustainable forest management at the scale of regional and national economies.

## 2. Regional study: urban tree biomass in southeastern lower Michigan

### 2.1. Study area

A regional assessment of standing urban saw timber in a 13-county region of southeastern lower Michigan (Fig. 1) was recently completed [5]. The study area was comprised of urban portions of the original 13 counties quarantined by the Michigan Department of Agriculture due to the recent introduction of the exotic wood-boring beetle, the emerald ash borer (EAB, *Agrilus plannipennis*). This specific study region was chosen because EAB has caused the death of estimated millions of ash (*Fraxinus* spp.) there [6], which has focused specific attention on the issue of better urban wood utilization. This study area should be reasonably representative of other similar urban areas in the Upper Midwest of the U.S.A.

### 2.2. Urban tree wood biomass estimation

Measurements of 1887 trees and stumps on 418 plots in 76 randomly selected urban neighborhoods in the study area [5] were used to estimate urban tree biomass. Biomass equations for urban-grown trees are not widely available, as they are for forest-grown ones. Forest-derived biomass equations overestimate the biomass of urban (open grown) trees by about 25% leading to a rule of thumb of 0.8 units of urban biomass per unit of biomass predicted for a forest-grown tree of comparable size and species [7]. Using a general, composite equation that combines the variety of species occurring in urban areas together into a single predictive equation with species-specific adjustments is considered superior to using many different equations for different species derived from different sources [7]. Thus, general whole tree above-ground biomass models for forest-grown hardwoods and softwoods [8,9] were adjusted to be 80% of predicted values to obtain general whole tree biomass equations for urban hardwoods and softwoods, respectively.

Whole tree biomass was portioned into bark and leaves via urban tree leaf biomass equations [10] and species-specific bark factors [11] and then into wood via subtraction. Wood and bark biomass estimates were adjusted for individual species with heavier or lighter than average wood, using published values of wood and bark specific gravity for each species [11]; an inflation/deflation factor was used that was the ratio of the specific gravity of the species in question divided by the average specific gravity for all of the species considered. Only urban trees $\geq$20 cm diameter at breast height (DBH) were measured in urban neighborhoods [5], so the additional biomass contributed by smaller trees was estimated by regression, contributing an additional 3%. Hence, the final total dry wood biomass (metric tonnes, t) estimates were the total amount for trees $\geq$20 cm (DBH) in urban neighborhoods, inflated by 3% to account for the additional mass of dry wood per urban ha stored in smaller trees.

### 2.3. Scaling up individual tree estimates to the regional scales

Tree biomass estimates (t ha$^{-1}$) were scaled up to the regional landscape scale by expanding neighborhood estimates to the total land area estimated in an urban condition. Two common methods are utilized for urban area estimation: (1) use political boundaries such as city limits or census districts and include any trees or forests in urban zones [12] or (2) use classified satellite images to estimate urban areas remotely [5,13]. Method 2 is overly conservative [5] and biased by confusion between the conflicting tasks of identifying urban areas on satellite images while simultaneously identifying tree cover at the same location [13]. Urban treed areas for this study were computed using a U.S. Census Bureau definition of urban area [14] and percent urban tree cover for Michigan [12]. The ratio of urban tree biomass per % tree cover per ha was used to scale up urban biomass to the census area. Urban tree cover for the study area was previously too low due to use of the satellite method [5] and so revised estimates for urban sawn wood products available from urban trees were also developed, scaled up in the same way as the new biomass estimates.

### 2.4. Estimating potential annual yield from urban trees

In order to calculate the potential availability of urban wood biomass on an annual basis, it was necessary to estimate the rate at which urban trees would become available for utilization. Most studies of potential wood biomass availability focus on growth rates of different vegetation types [1]. Since urban trees in the U.S. are not typically planted as crops or harvested live, a reasonable estimate of availability was derived from the mortality rate of urban trees; about 2% of the standing volume of trees for this study area [5].

### 2.5. Estimating current utilization

Current utilization of wood residues was derived from interviews with 1500 companies within the same 13-county region [15].

### 2.6. National level estimates

Data from this study were combined with a national study of tree cover and urban forest carbon sequestration [12] to extrapolate regional results to the U.S.A.; carbon was converted to total biomass assuming 0.5 t carbon per t biomass and then to above ground biomass deducting the 21% of mass in roots [12]. National utilization estimates were extrapolated via data describing land filling of US wood [4]. Availability of

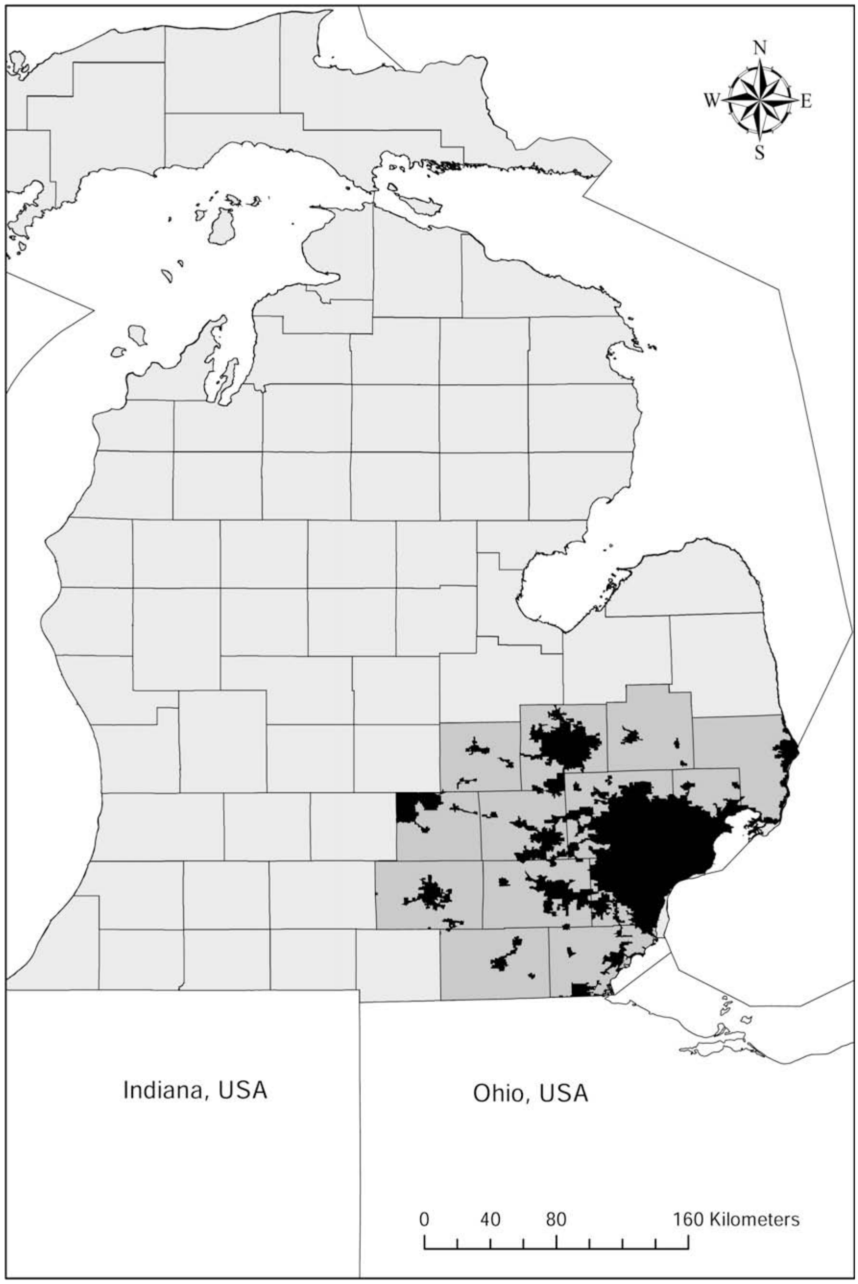


**Fig. 1 – Urban U.S. Census areas (black) in the 13-county study area (medium gray) in Michigan, U.S.A. (light gray).**

urban tree biomass was also assumed to be 2% of standing stocks per annum at the national level.

## 3. Results - biomass from urban tree removals

### 3.1. *Biomass from urban tree removals in 13 counties in Michigan*

The 2.2 million ha study area includes about 73% of all urban area in Michigan and about 2% of U.S. urban area (Table 1). Estimates of annual yield of wood biomass in the study area range from about 367 to 517 thousand dry tonnes of biomass from routine removal of dead and dying urban trees, with the variability in the estimates (standard error, Table 1) stemming largely from the high variability in tree size and coverage in different urban neighborhoods within the region. The bulk of this urban tree biomass is wood (85.7%), with the remaining material being bark and leaves, 11.8% and 2.5%, respectively. Note that these annual yield numbers were not based on catastrophic losses of ash trees in the study areas due to EAB, which are already accounted for, but instead were based on an expected average background rate of tree removal from mortality of currently standing trees.

The annual yields of wood biomass from dead and dying urban trees described are the equivalent in energy content to between 1.2 and 1.7 million barrels of oil per year,

**Table 1 – Biomass (dry metric tonnes, t) and sawn wood products ($m^3$) potential from urban tree removals in a 13-county area of Michigan and in the conterminous U.S.A.**

| | Michigan, U.S.A., 13-county study | U.S.A. |
|---|---|---|
| Area | | |
| Urban area (ha) | 545,690[b] | $28.1 \times 10^{6}$[a] |
| % Tree canopy cover[a] | 29.7% | 27.1% |
| Biomass[c] | | |
| Mean ($t\,ha^{-1}$) | 40.5 [6.9] | 39.6 |
| Standing (t) | $22.1 \times 10^6$ [$3.8 \times 10^6$] | $1112 \times 10^6$ |
| Ann. yield[d] ($t\,ha^{-1}\,y^{-1}$) | 0.81 [0.14] | 0.79 |
| Ann. yield[d] ($t\,y^{-1}$) | 442,009 [75,142] | $22.2 \times 10^6$ |
| Barrels oil[e] $y^{-1}$ | $1.44 \times 10^6$ [$2.4 \times 10^5$] | $72.6 \times 10^6$ |
| People's oil[f] $y^{-1}$ | 57,302 [9741] | $2.8 \times 10^6$ |
| MW electricity[g] $y^{-1}$ | 97.5 [16.5] | 4836 |
| Sawn wood products | | |
| Mean ($m^3\,ha^{-1}$) | 23.2 [4.0] | 23.2 |
| Standing ($m^3$) | $12.7 \times 10^6$ [$2.2 \times 10^6$] | $651.9 \times 10^6$ |
| Ann. yield[d] ($m^3\,y^{-1}$) | 253,674 [43,125] | $13.0 \times 10^6$ |
| Homes[h] $y^{-1}$ | 5565 [946] | 285,189 |

[ ] Standard error of estimates.
a Area and % tree cover for 48 states excluding Alaska and Hawaii; includes water bodies in area estimates (see Ref. [12]).
b Census urban area (see Ref. [14]).
c MI 13 county biomass includes wood + bark + leaves. USA biomass estimates were computed as 2 times t C (see Ref. [12]), assuming non-root = 0.79*total.
d Dead and dying trees (see Ref. [5]).
e Based on 18,960 BTU per kg oven dry wood and 5.8 million BTUs per barrel crude oil; 1 BTU = 1.055 kJ (see Ref. [16]).
f Based on 20.8 million barrels of oil consumed per day (see Ref. [17]) by 302 million people (see Ref. [14]).
g Based on Oak Ridge National Laboratories estimate of 4535 t per MW electricity (see Ref. [18]); 1 US ton = 0.907 t.
h Based on 13,000 board feet of framing lumber per average US home (see Ref. [19]), converted to $m^3$ equivalents.

supplying the annual oil consumption equivalents of about 57,300 people, or the equivalent of one 97.5 MW power plant (Table 1). This 13-county region already supports a 35 MW power plant that was designed specifically for burning urban wood [20], but this capacity could be increased (Table 1). Alternatively, substantial amounts of sawn wood products, which have a dramatically higher commercial value than fuel wood, could be derived from routine urban tree removals in the study region (Table 1), the dimensional lumber equivalent of over 5500 average-sized residential homes per year.

Interviews with 1500 regional companies regarding wood residue utilization in the study region indicated that about 58% of wood residues were discarded annually, including pallets, skids, shipping crates, edgings and cutoffs, chips, shavings and sawdust, construction debris and tree trunks limbs and stumps [15]. About 48% of the discarded material went to landfills, or about 28% of the total wood residues [15].

### 3.2. *Biomass from urban tree removals in U.S.A.*

The possibility to recover utilizable biomass from urban trees in the U.S. appears large. Extrapolating the regional study results to the national level (Table 1, and see Ref. [12]), biomass from routine urban tree removals in the U.S. is estimated to be about 22.2 million tonnes per year (Table 1). For the U.S. as a whole, these annual yields could supply an estimated 2.8 million people with electricity annually, or the equivalent of about 72.6 million barrels of oil per year (Table 1). Alternatively, an equivalent amount of wood to build more than 285 thousand homes per year could be derived from urban tree removals across the U.S.A.

Over 180 million tonnes of municipal solid waste per year are generated and about 21 million tonnes of this is wood waste (11.8%) [4]. The two main pools that comprise this wood waste are wood from wood products (42.4% or 9 million tonnes) and urban trees and wood yard residues (57.6% or 12 million tonnes) [4]. The latter includes whole trees and parts of trees and shrubs removed from urban areas. Combined with the U.S. annual yields presented here (Table 1), approximately 54% of the urban trees and woody yard residues available may be going into U.S. landfills.

## 4. Discussion

### 4.1. *U.S. potential for increased urban tree and urban wood waste recovery*

The results of this study suggest that the potential for recovering usable biomass from urban trees and wood waste is substantial within the 2.2 million ha study region in Michigan. When combined with the national scale data, these data suggest that urban wood biomass is an abundant and underutilized resource across the U.S.A., with significant enough amounts available to make an impact at local or regional economic scales. It has been estimated that only about 15% of urban wood waste is burned for energy annually [1], leaving the bulk of material available for expanding fuel supply or for other uses. An estimated 816 thousand tonnes of pallet material alone is land filled per year in the U.S.A., which represents about 85% of discarded pallets; of the remaining 15% utilized about 39.3% is used for fuel [21]. An estimated 245,000 homes per year demolished on purpose or through disaster in the U.S.A. [19]. This study suggests that there is enough wood from annual urban tree removals to rebuild all of these homes (Table 1). Clearly, recovery of urban wood biomass from trees and discarded wood products could be increased.

### 4.2. *Economic considerations for enhanced urban wood biomass utilization*

The logistics of actually gathering up and utilizing urban wood waste and urban trees may seem daunting relative to, e.g., harvesting a bioenergy crop from point sources such as plantations. Urban wood biomass is generally an extensive rather than intensive resource, although land clearing and random destructive events can supply substantial amounts over short periods of time. For example, from 2002 to 2005, about 200,000 *additional* dry tonnes of ash tree biomass was supplied to the Genesee Power Station, within the study region, from widespread death of ash trees in the Detroit-

Metropolitan area, providing an additional 22.4 MW of electricity [20]. However, the latter was orchestrated in part, via government incentives to sanitize infested trees [20]. Thus, under typical conditions, incentives in the form of avoided costs or direct gains may be necessary to make collecting urban wood waste attractive. For example, a nationwide average cost reduction of about $9 per tonne was reported in the U.S.A. in 1995, if pallets were simply disposed of at a wood waste processing facility ($26 per tonne) instead of land filling as is ($35 per tonne) [21].

When wood biomass is a product in demand, as well as a disposal cost to be avoided, the economics of urban wood biomass becomes even more appealing. The "total benefit" of using urban wood waste can be calculated as the costs avoided plus the unit price for the material; it ranges from $48 to $132 U.S. per tonne across the U.S.A. (Table 2). In regions where the cost of land filling is high, generally through a combination of high land values and environmental regulations, the general benefit of utilizing wood waste increases regardless of the market value for the biomass (Table 2). Obviously, some wood waste is not strictly recyclable and is destined for landfills, because it is contaminated, such as in the case of demolition or natural disaster cleanup, where trees and wood become hopelessly mixed with soils, rubble and other materials; extracting utilizable wood from such materials can have a very high cost (see Ref. [19]).

The U.S. national trend has been for continued steady increases in land filling fees nationwide, tripling over a twenty year period from 1985 to 2005 [23]. Surely this will continue to make conversion of wood waste to usable biomass more attractive. At a bare minimum, the cost of land filling wood, which does not compress well and takes up large volumes relative to more compressible waste, could be offset, even if burning, sawing or other uses of urban wood waste and trees are not profitable by themselves (Table 2). In highly populated regions of developed nations, where land is limited for land filling waste or otherwise (e.g., Taiwan, the Netherlands), offsetting land filling costs through urban wood utilization may amount to an enormous savings as well as a boon for land conservation.

If transportation costs are also added into the equation, the value of urban wood biomass for energy is even greater, because wood waste is produced in its greatest abundance in areas where energy demand is the greatest. The best case scenario for wood waste combustion is when the waste is burned directly on site, as is practiced in paper mills [24]. The average hauling distance traveled to dispose of urban wood waste (including discarded trees) was 16 km in the 13-county study region [15]. Thus, urban wood waste can claim the additional large benefit of being a biomass resource that is generated near the center of demand.

Fuel may not be the best economic choice for urban wood utilization. A power plant that burns wood biomass in the U.S.A. can only afford to pay a relatively low price when competing with power or heat generation supplied by fossil fuels, meaning that other biomass users (such as the mulch or pulpwood industries) may be able to outbid energy producers for urban wood biomass. Data from the Oak Ridge National Laboratory [22] suggest that much of the potentially available biomass for fuel will come from urban wood waste as long as the value of biomass remains low (<$22 per dry tonne) (Table 2). A substantial amount of urban wood biomass from trees is of saw timber quality (Table 1, and see Ref. [5]). It would be extravagant to burn up saw grade wood, wherever it could be cost effectively extracted from tree removals or recycled from discarded wood products, unless the price for biomass fuel were to increase substantially.

### 4.3. *Implications for carbon sequestration*

One of the many benefits touted for using urban wood waste [3] is enhanced carbon sequestration attributable to a reduction in virgin material being utilized, as well as the fact that burning wood is intrinsically carbon neutral, because its

**Table 2 – Total benefit and predicted supply rates of urban wood waste in the U.S.A. at different market prices, with consideration of regional land filling costs.**

| Region | Land filling costs[b] (US$ $t^{-1}$) | Market price of biomass[a] (US$ $t^{-1}$)[b] | | | |
|---|---|---|---|---|---|
| | | <$22 | <$33 | <$44 | <$55 |
| | | Percentage of available biomass comprised of urban wood waste at market price[a] | | | |
| | | 92.5% | 35.0% | 11.7% | 7.2% |
| | | Total benefit of urban wood biomass (US$ $t^{-1}$) (cost avoided plus profit) | | | |
| South Central | $26.53 | $48.58 | $59.60 | $70.63 | $81.65 |
| West Central | $26.60 | $48.65 | $59.68 | $70.71 | $81.73 |
| South | $34.15 | $56.20 | $67.22 | $78.25 | $89.27 |
| Midwest | $38.54 | $60.60 | $71.62 | $82.65 | $93.67 |
| West | $41.61 | $63.66 | $74.69 | $85.71 | $96.74 |
| Mid-Atlantic | $51.04 | $73.09 | $84.11 | $95.14 | $106.16 |
| Northeast | $77.76 | $99.81 | $110.84 | $121.86 | $132.89 |
| Nationwide | $37.81 | $59.86 | $70.88 | $81.91 | $92.93 |

a From Nationwide 1999 estimates by Marie Walsh at Oak Ridge National Laboratories (see Ref. [22]) converted from US$ per US ton; 1 US ton = 0.907 metric tonnes.
b NSWMA Research Bulletin 05-3 (see Ref. [23]), also converted from US$ per US ton.

ultimate energy source is solar. While all wood-derived sources are superior in this regard to fossil fuels, consumption of wood from different sources will have a different impact on net $CO_2$ sequestration, because the life expectancy of wood carbon (i.e., decomposition rate) is not equal for wood in all of its forms [25].

Table 3 shows the possible implications of utilizing woody biomass for fuel production from different sources. Here, this impact is specifically quantified as a $CO_2$ *impact factor*, which is the net flux rate divided by the size of the pool, i.e., the relative impact of liberating carbon from a biomass pool. This analysis (Table 3) suggests a much higher penalty, measured in terms of net relative loss in $CO_2$ sequestration, for burning rather than burying wood residues in landfills. When this impact is considered in the narrow context of carbon markets, this may dramatically increase the social cost of capitalizing on the fuel potential of urban wood residues. However, it is equally clear that there are considerable social and environmental costs associated with land filling wood, e.g., decreasing open land area available for other uses, which casts some doubt on the value of burying wood waste to offset atmospheric carbon levels. Recovering sawn wood products from urban wood biomass, rather than burning or burying it, may provide superior carbon sequestration benefits when co-realized with the increased feedstock value for sawn- versus fuel- wood products.

### 4.4. *Implications for sustainable forest management*

Increasing global demand for a wide range of wood products [26,27] has strong implications for sustainable forest management. Under current global trends in population expansion (e.g., U.S.A., see Ref. [28]), the associated contraction of forested lands available for harvesting, and concerns regarding the ecological sustainability of expanding forest biomass utilization [29], the possibility for using wood from forests for biomass energy is constrained [30]. Urban land expansion increases the demand for wood and necessarily increases the pool that constitutes urban wood biomass, so, increasingly, urban wood will need to be utilized to absorb some of the burden from forests. Clearly the potential is there; since 2000, the volume of urban tree and woody yard residues now exceeds the volume of wood harvested from U.S. National Forests [4].

How much urban area it would take to replace wood biomass that would be extracted from a forested area of equal size? Data from U.S.D.A. Forest Service Forest Inventory and Analysis (FIA) Program [31] were used to estimate that the woody biomass growth rate on average timberlands in Michigan is about 3.2 $t\,ha^{-1}\,y^{-1}$, which falls within the typical range of 2.3–4.5 $t\,ha^{-1}\,y^{-1}$ reported for the U.S.A., and is considerably lower than the typical range for pulpwood pine plantations 6.8–9.1 $t\,ha^{-1}\,y^{-1}$or intensively managed energy crop plantations with growth rates of 15.8–22.7 $t\,ha^{-1}\,y^{-1}$ [18]. At an estimated 0.8 $t\,ha^{-1}\,y^{-1}$ (Table 1), the yield rate of urban trees through mortality is surprisingly high relative to growth rates achievable for live trees in forests; about 25% of the growth rate on timberlands in Michigan and about 4% of that yielded from high energy plantations.

This relatively high yield from dead and dying urban trees is logical because there are well established and continuing to expand urban forests comprised largely of more open-grown trees that have growth rates which exceed that of the average forest-grown tree [12]. Perhaps most critically, some level of yield is all but guaranteed, as a steady proportion of dead and dying trees in urban areas will be removed for reasons of safety or aesthetics [32], unlike dead and dying forest-grown trees, which, while offering a potentially large supply of wood biomass [1], will not likely be salvaged for reasons relating to ecological sustainability [30].

Translated into area, the results presented here suggest that the potential wood biomass from annual tree mortality on 4 urban ha is equivalent to the average annual growth found on 1 ha of Michigan timberlands. About 31% of new growth is actually removed each year from Michigan timberlands [31], about 1.0 $t\,ha^{-1}\,y^{-1}$. By contrast, the actual removals rates for standing live and standing dead trees was estimated at 3.8% and 8.4% per year, respectively in Baltimore, Maryland, U.S.A. [32], indicating that dead urban trees are not typically removed right away, i.e., the potential availability of dead tree wood biomass described here is not currently capitalized. The total area of timberlands in Michigan is about 10 times larger (7.59 million ha of timberlands) [31] than the 749 thousand ha categorized as census urban in Michigan [12]. Thus, about 8% of the statewide average annual dry biomass removed from Michigan's timberlands (7.5 million $t\,y^{-1}$ over the last inventory cycle from 2000 to 2004) [31] could be supplied by the removal of dead and dying trees from the Michigan's urban areas.

**Table 3 – U.S. Carbon pools, fluxes and potential $CO_2$ impact factor of wood removal from those pools.**

| Carbon pools[a] | Stocks% | Net change (%) | $CO_2$ impact factor (Net/Stocks) |
|---|---|---|---|
| Landfilled trees/trimmings[b] | 4.1% | 26.9% | 6.59 |
| Landfilled wood products | 3.0% | 19.7% | 6.59 |
| Wood products | 2.0% | 7.3% | 3.66 |
| Downed dead wood | 3.0% | 8.0% | 2.68 |
| Urban trees[c] | 1.2% | 1.5% | 1.16 |
| Forest trees | 29.7% | 34.4% | 1.16 |
| Forest floor | 8.0% | 0.7% | 0.09 |
| Forest soils | 48.0% | 1.5% | 0.03 |
| Forest understory | 1.0% | 0.0% | 0.00 |

a Modified from Woodbury et al (see Ref. [25]); total biomass pool sizes recalculated to equal 100%.
b Landfilled woody yard trimming are 1.36 times the pool of landfilled wood products (see Ref. [4]).
c Assumes 4.4% of carbon in trees is in urban trees (see Ref. [12]).

## 5. Conclusions

Urban trees and wood offer a modest, yet substantial and reliable amount of wood that could contribute significantly to regional and national bio-based economies. Biomass derived from urban trees and wood waste offers the potential for: 1) deriving local wood products from urban trees, 2) deriving locally generated fuel sources for power and heat generation, 3) reducing fossil fuel consumption, 4) reducing waste disposal costs, and 5) reducing pressure on forests.

Although wood biomass generally constitutes a "carbon-neutral" fuel, burning rather than burying urban wood waste may not have a net positive effect on reducing atmospheric $CO_2$ levels, because it may reduce a significant long term carbon storage pool. Using urban wood residues for wood products may provide the best balance of economic and environmental values for utilization.

## Acknowledgements

The author would like to thank the Michigan Agricultural Experiment Station and the Southeast Michigan Resource Conservation and Development Council for funding this research. The author would also like to thank E.P. Barrett for useful comments on this manuscript.

## REFERENCES

[1] Mead DJ. Forest for energy and the role of planted trees. Critical Reviews in Plant Sciences 2005;24:407–21.
[2] FAO. Trees outside of forests. In: Bellfontaine R, Petit S, Pain-Orcet M, Deletorte P, Bertault JG, editors. FAO conservation guide 35. Rome: Food and Agricultural Organization of the United Nations; 2002.
[3] Solid Waste Association of North America. Successful approaches to recycling urban wood waste. Gen. Tech. Report. FPL-GTR-133. Madison, WI: USDA Forest Service, Forest Products Laboratory; 2002. p. 20.
[4] McKeever DB, Skog KE. Urban tree and wood yard residues another wood resource. Research note: FPL-RN-0290. Madison, WI: USDA Forest Service, Forest Products Laboratory; 2003. p. 4.
[5] MacFarlane DW. Quantifying urban saw timber abundance and quality in southeastern lower Michigan, U.S.A. Arboriculture and Urban Forestry 2007;33(4):253–63.
[6] Poland TM, McCullough DG. Emerald ash borer: invasion of the urban forest and the threat to North America's ash resource. Journal of Forestry 2006;104(3):118–24.
[7] Nowak DJ, Crane DE, Stevens JC, Ibarra M. Brooklyn's urban forest. General Technical report, GTR-NE-290. Newtown Square, PA: USDA Forest Service, North Central Research Station; 2001. p. 107.
[8] Monteith DB. Whole-tree weight tables for New York. Syracuse University of New York; 1979. AFRI Res. Rep. 40. p. 67.
[9] Tritton LM, Hornbeck JW. Biomass equations for major tree species of the northeast. U.S.A.D.A. Forest Service, Northeastern Forest Experiment Station; 1982. GTR NE-69.
[10] Nowak DJ. Estimating leaf area and leaf biomass of open-grown deciduous urban trees. Forest Science 1996;42(4):504–7.
[11] Smith WB. Factors and equations to estimate forest biomass in the north central region. U.S.A.D.A. Forest Service, North Central Forest Experiment Station; 1985. Research Paper NC-268.
[12] Nowak DJ, Crane DE. Carbon storage and sequestration by urban trees in the U.S.A. Environmental Pollution 2002;166:381–9.
[13] Fang S, Gertner G, Wang G, Anderson A. The implication of misclassification in land use maps in the prediction of landscape dynamics. Landscape Ecology 2006;21:233–42.
[14] Available from: <http://www.census.gov/geo/www/ua/ua_bdfile.html> [accessed 27.08.08].
[15] Sherrill SB, MacFarlane DW. Measures of wood resources in lower Michigan: wood residues and the saw timber content of urban forests. Technical report to the southeast Michigan resource conservation and development council and the U.S. D.A. forest service; May 2007. p. 178.
[16] Available from: <http://bioenergy.ornl.gov/papers/misc/energy_conv.html> [accessed 27.08.08].
[17] Available from: <http://www.eia.doe.gov/basics/quickoil.html> [accessed 27.08.08].
[18] Available from: <http://bioenergy.ornl.gov/resourcedata/powerandwood.html> [accessed 27.08.08].
[19] Falk B. Wood-framed building deconstruction a source of lumber for construction? Wood Products Journal 2002;52(3): 8–15.
[20] Edward P. Barrett, Manager. Mid-Michigan recycling, pers. com.
[21] Bush RJ, Araman PA. Construction & demolition landfills and wood pallets - what's happening in the U.S.A. Pallet Enterprise; March 1997. p. 27–31.
[22] Available from: <http://bioenergy.ornl.gov/main.aspx> [accessed 27.08.08].
[23] Repa EW. NSWMA's 2005 tip fee survey. NSWMA Research Bulletin 05-3. Washington, D.C.: National Solid Waste Management Association; March 2005. p. 3.
[24] Singer JG. Combustion fossil power. A reference book on fuel burning and steam generation. Windsor, Connecticut: Combustion Engineering, Inc.; 1993. p. 140.
[25] Woodbury PB, Smith JE, Heath LS. Carbon sequestration in the U.S.A. forest sector from 1990 to 2010. Forest Ecology and Management 2007;241:14–27.
[26] Whiteman A, Brown C. Modelling global forest products supply and demand: recent results from FAO and their potential implications for New Zealand. New Zealand Journal of Forestry 2000;44(4):6–9.
[27] Zhu S, Buongiorno J, Brooks DJ. Global effects of accelerated tariff liberalization in the forest products sector to 2010. Research paper: PNW-RP-534. Corvallis, OR: USDA Forest Service, Forest Science Laboratory; 2002. p. 50.
[28] Nowak DJ, Walton JT, Dwyer JF, Kaya LG, Myeong S. The increasing influence of urban environments on U.S.A. forest management. Journal of Forestry 2005;103(8):377–82.
[29] Egnell G, Valinger E. Survival, growth, and growth allocation of planted scots pine trees after different levels of biomass removal in clear-felling. Forest Ecology and Management 2003;177:65–74.
[30] Raison RJ. Opportunities and impediments to expansion of forest bioenergy in Australia. Biomass & Bioenergy 2006;30: 1021–4.
[31] USDA forest service forest inventory and analysis data, Michigan 2004, complete panel, <http://fia.fs.fed.us/> [accessed 17.9.07].
[32] Nowak DJ, Kuroda M, Crane DE. Tree morality rates and tree population projections in Baltimore, Maryland, U.S.A. Urban Forestry & Urban Greening 2004;2:139–47.