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David J. Nowak
USDA Forest Service, dnowak@fs.fed.us

Nathaniel Appleton
USDA Forest Service

Alexis Ellis
The Davey Institute

Eric Greenfield
USDA Forest Service

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Residential building energy conservation and avoided power plant emissions by urban and community trees in the United States

David J. Nowak[a,*], Nathaniel Appleton[a], Alexis Ellis[b], Eric Greenfield[a]

[a] USDA Forest Service, 5 Moon Library, SUNY-ESF, Syracuse, NY 13210, USA
[b] The Davey Institute, 5 Moon Library, SUNY-ESF, Syracuse, NY 13210, USA

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ABSTRACT

Urban trees and forests alter building energy use and associated emissions from power plants by shading buildings, cooling air temperatures and altering wind speeds around buildings. Field data on urban trees were combined with local urban/community tree and land cover maps, modeling of tree effects on building energy use and pollutant emissions, and state energy and pollutant costs to estimate tree effects on building energy use and associated pollutant emissions at the state to national level in the conterminous United States. Results reveal that trees and forests in urban/community areas in the conterminous United States annually reduce electricity use by 38.8 million MWh ($4.7 billion), heating use by 246 million MMBtus ($3.1 billion) and avoid thousands of tonnes of emissions of several pollutants valued at $3.9 billion per year. Average reduction in national residential energy use due to trees is 7.2 percent. Specific designs to reduce energy use using urban trees could increase these values and further reduce energy use and improve air quality in the United States.

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1. Introduction

Energy consumption by homes in the United States (2009) is estimated at 10.18 quadrillion Btus, with 47.7 percent of this energy use coming from space heating and air conditioning (U.S. Energy Information Administration, 2015). This energy consumption not only has substantial monetary costs to residents, but also health costs associated with air pollutant emissions from energy production.

Trees are important elements in many urban areas and alter the local climates by producing shade, blocking winds and reducing air temperatures through evaporation of water from leaves (transpirational cooling) (e.g., Heisler 1986a; Akbari et al., 1992; Akbari 2002; McPherson and Simpson 2003; Heisler and Brazel 2010). These alterations to local climate generally reduce building energy consumption during summer seasons when building cooling is the dominant space conditioning energy use (Heisler 1986b). However, during the winter season when heating energy use dominates, trees can increase energy use if trees cast shade on buildings. This shade is particularly important for trees to the south side of buildings in the United States as solar input on south facing walls at 40° N latitude are 1.5–2 times greater in the winter than in summer (Heisler 1986b). Even deciduous trees cast winter shade and typically block 35 percent of incoming solar radiation when leaf-off (McPherson 1984).

Tree cover in urban/community areas in the United States is estimated at 35.1 percent and varies from 9.6 percent in Nevada to 67.4 percent in Connecticut (Nowak and Greenfield 2012). How this tree cover is oriented around buildings affects building energy use. Various studies have estimated tree effects on energy use at the house, city and regional scale.

In Sacramento, California, shade trees at two monitored houses yielded seasonal cooling energy savings of 30 percent (Akbari et al., 1997). A 25 percent increase in tree cover (three trees per house) was estimated to reduce cooling energy use by 57 percent in Sacramento, 25 percent in Lake Charles, LA and 17 percent in Phoenix, AZ (Akbari et al., 1992). In Los Angeles, annual energy savings from trees is estimated at $10.2 million per year (Nowak et al., 2011), but additional planting of 1 million trees could produce between $76 million to $117 million in energy saving over a 35 year period, depending on tree survival rates (McPherson et al., 2011). Simulations of an additional 11 million shade trees in the Los Angeles basin is projected to reduce energy use from air conditioning by $93 million per year (Rosenfeld et al., 1998; Akbari 2002). Based on energy modeling and field sampling of urban tree locations relative to residential buildings, annual energy saving from trees in other cities are

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* Corresponding author.
E-mail address: dnowak@fs.fed.us (D.J. Nowak).

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estimated at: $216,000 in Minneapolis, MN (Nowak et al., 2006a), $360,000 in Chicago, IL (Nowak et al., 2010b), $380,000 in Morgantown, WV (Nowak et al., 2012c), $1.2 million in Philadelphia, PA (Nowak et al., 2007a), $2.7 million in Washington, DC (Nowak et al., 2006b), and $11.2 million in New York, NY (Nowak et al., 2007b).

At the regional scale, annual energy saving from trees is estimated at $14 million in the 9-county greater Kansas City region (Nowak et al., 2013a) and $44 million in the 7-county Chicago metro region (Nowak et al., 2013c). Annual energy savings from urban trees at the state level were estimated at $519,000 in South Dakota, $3.3 million in North Dakota, $19.7 million in Kansas and $28.2 million in Nebraska (Nowak et al., 2012b), $24.3 million in WI (Cumming et al., 2007), $66 million in Tennessee (Nowak et al., 2012a) and $486 million in California for air conditioning energy use alone (McPherson and Simpson 2003).

While most studies focus on city or regional impacts, one national study concluded that the implementation of large scale heat island mitigation measures (i.e., cool roofs, cool pavement, urban trees) could reduce national cooling demand by 20 percent, with an estimated savings of over $4 billion per year in cooling-electricity savings alone (Akbari et al., 2001). Given the lack of national studies on urban tree effects on building energy use, the goal of this paper is to estimate the existing energy savings to residential buildings across the United States due to urban/community trees and the associated reduction in pollution emission. This analysis does not include cool surfaces, an important attribute of heat island mitigation, but rather focuses only on tree effects based on average distributions of trees around buildings and information on local tree cover and energy costs. Information from this national assessment can be combined with estimates of other national assessments of ecosystem services from urban trees related to carbon sequestration (Nowak et al., 2013b) and air pollution removal (Nowak et al., 2014) to better understand the value of urban forests at the state to national scale.

2. Methods

To estimate the effects of trees on residential building energy use and associated emissions nationally in the conterminous United States, five types of analyses were conducted to determine:

1) average density of trees in energy affecting locations per hectare of urban and community tree cover within National Land Cover Database (NLCD) classes;
2) total urban and community tree cover (ha) in each NLCD class, climate region and state combination using adjusted NLCD tree cover maps;
3) total tree population by size class, deciduous vs. evergreen, and distance and direction from space-conditioned buildings in each NLCD class, climate region and state combination;
4) energy effects and changes in pollutant emission from power plants for each state based on energy and emissions models; and
5) values of energy and emission changes for each state based on state energy costs and estimated emission values.

Urban/community areas were delimited using 2010 Census data and definitions. The definition of urban is primarily based on population density using the U.S. Census Bureau's (2013) definition: all territory, population, and housing units located within urbanized areas or urban clusters. The definition of community, which includes cities, is based on jurisdictional or political boundaries delimited by U.S. Census Bureau definitions of incorporated and designated places (U.S. Census Bureau, 2013). Community areas may consist of all, some, or no urban land within their boundaries. As urban land encompasses the more heavily populated areas (population density-based definition) and community land has varying amounts of urban land that are recognized by their geopolitical boundaries (political definition), the category of "urban/community" was created to classify the union of these two geographically overlapping definitions where most people live. Urban land in 2010 occupied 3.6% (27.5 million ha) of the conterminous United States, while urban/community land occupied 6.4% (48.9 million ha).

2.1. Tree density near space-conditioned residential buildings

Field data were collected from randomly located 0.04 ha plots within 20 cities (Table 1), which included data on tree species, tree cover, tree size and distance and direction to one or two-story space-conditioned residential buildings for trees within 18.3 m (60 ft) of the building. Land use of each plot was classified from local land use or 2006 NLCD maps. As each land cover class will have varying amounts of residential buildings, each plot land use was assigned to one of the following NLCD land cover classes (MRLC, 2013):

a) "Developed, Open Space – areas with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses. Impervious surfaces account for less than 20% of total cover. These areas most commonly include large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes." Plots designated as either park, recreation, cemetery, open space, institutional or vacant land were classified as Developed Open Space.
b) "Developed, Low Intensity – areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 20% to 49% percent of total cover. These areas most commonly include single-family housing units." Plots designated as single family or low-density residential land were classified as Developed, Low Intensity.
c) "Developed, Medium Intensity – areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 50% to 79% of the total cover. These areas most commonly include single-family housing units." Plots designated as medium density residential, other urban or mixed urban were classified as Developed, Medium Intensity.
d) "Developed High Intensity –highly developed areas where people reside or work in high numbers. Examples include apartment complexes, row houses and commercial/industrial. Impervious surfaces account for 80% to 100% of the total cover." Plots designated as either commercial, industrial, high density residential, downtown, multi-family residential, shopping, transportation or utility were classified as Developed, High Intensity.
e) "Forest – areas dominated by trees generally greater than 5 m tall, and greater than 20% of total vegetation cover." Plots designated as forest were classified as Forest.
f) "Planted/Cultivated – Pasture/hay – areas of grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops, typically on a perennial cycle. Pasture/hay vegetation accounts for greater than 20% of total vegetation", and "cultivated crops – areas used for the production of annual crops, such as corn, soybeans, vegetables, tobacco, and cotton, and also perennial woody crops such as orchards and vineyards. Crop vegetation accounts for greater than 20% of total vegetation. This class also includes all land being actively tilled." Plots designated as agriculture were classified as Planted/Cultivated.

Table 1
City data used for tree location and density estimates. Plot size = 0.04 ha.

City/State	Year	No. Plots	Data Collection Group	Reference
Atlanta, GA[a]	1997	205	ACRT, Inc.	
Baltimore, MD[a]	2009	195	US Forest Service (USFS)	
Baton Rouge, LA[a]	2004	299	Southern University	
Boston, MA[a]	1996	217	ACRT, Inc.	
Chicago, IL	2007	745	City of Chicago, Chicago Park District, USFS	Nowak et al. (2010b)
Freehold, NJ[a]	1998	144	NJ Dept. Env. Protection	
Gainesville, FL	2007	93	Univ. Florida, USFS	Escobedo et al. (2009)
Jersey City, NJ[a]	1998	220	NJ Dept. Env. Protection	
Kent, OH[a]	2004	31	Davey Institute	
Lake Forest Park, WA	2010	115	Michael Woodbury, Consulting Arborist	Lake Forest Park (2016)
Los Angeles, CA	2007/08	348	USFS, Univ. Cal., Riverside	Nowak et al. (2011)
Mandeville, LA[a]	2011	150	Southern University	
New York, NY	1996	206	ACRT, Inc.	Nowak et al. (2007b)
Philadelphia, PA	1996	210	ACRT, Inc.	Nowak et al. (2007a)
Roanoke, VA[a]	2010	160	Virginia Tech	
Seattle, WA	2010	186	Green Cities Research Alliance	Green Cities Research Alliance (2012)
Scranton, PA	2006	182	Northeast PA Urban Forestry Program, Keystone College, Penn State Extension, PA Dept. of Conservation and Natural Resources	Nowak et al. (2010a)
Syracuse, NY	2009	198	USFS	Nowak et al. (2013d)
Washington, DC	2004	201	Casey Trees, University of Maryland, National Park Service	Nowak et al. (2006b)
Woodbridge, NJ[a]	2000	215	NJ Department of Environmental Protection	

[a] Unpublished data.

For each NLCD class, plot data were analyzed to estimate the average number of trees per hectare within 18.3 m of one or two-story space-conditioned residential buildings by tree-height class, leaf class (deciduous or evergreen species), and distance and direction from building. Height classes were defined as small (6–10 m tall), medium (10.1–15 m) and large (>15 m). Distances were categorized as adjacent (<6 m from building), near (6.1–12 m) or far (12.1–18 m). Any tree that is smaller than 6 m in height or farther than 18 m from a building is considered to have no effect on building energy use. Directions were classified as north, northeast, east, southeast, south, southwest, west and northwest within 45° wedges centered at the cardinal or ordinal direction (Table 2). These classes were defined to match the classes needed for building energy modeling (McPherson and Simpson, 1999).

The number of sampled trees in each NLCD class was divided by total sampled tree cover (ha) in the class to produce a standardized estimate of number of energy-affecting trees per hectare of tree cover within 18.3 m of one or two-story space-conditioned residential buildings by size class, leaf class, distance and direction to building for each NLCD class. In addition to the six NLCD classes listed above, all other NLCD land cover classes (i.e., water, barren land, wetlands) were analyzed, but did not have any trees located near buildings in the field samples.

2.2. Urban/community tree cover nationally

Tree cover within each urban/community area was derived from 2001 National Land Cover Database (NLCD) 30-m resolution tree cover maps (USGS, 2008) as these were the most recent data at the time of the analysis. However, these maps generally underestimate tree cover (Nowak and Greenfield 2010). To adjust for potential underestimates, NLCD percent tree cover within each urban area NLCD land-cover class was modified according to the Nowak and Greenfield (2010) photo-interpreted values within individual mapping zones (i.e., tree cover estimates were adjusted to match the photo-interpreted estimates for each land cover class within each mapping zone). Adjusted NLCD tree cover estimates were within 0.1 percent of estimates derived from photo-interpretation (PI) of the conterminous United States (PI = 34.2 percent, adjusted NLCD = 34.1 percent), but this difference could be greater at the local scale. The adjusted tree cover estimates (c. 2005) align temporally with the 2006 land cover estimates. Total tree cover (ha) within urban/community land in each NLCD class was estimated for each climate region (McPherson and Simpson 1999) within each state.

2.3. Total urban tree population near space-conditioned buildings

The average energy-affecting tree density per hectare of tree cover in each NLCD class was multiplied by tree cover (ha) in each NLCD class to produce an estimate of number of energy-affecting trees in each climate region in each state. Number of trees was calculated within each size class, leaf class, distance and direction to building class combination. An example of this type of information for one NLCD class is given in Table 2.

2.4. Tree effects on building energy use and power plant emissions

The total number of trees within 18.3 m (60 ft) of the building by size class, leaf class, and distance and direction to building combination was input into the i-Tree Eco model (Nowak et al., 2008) to estimate building energy effects. The energy effects are estimated in i-Tree Eco based on methods from McPherson and Simpson (1999), which used various energy simulations (e.g., simulations of tree effects on building energy use due to shade, windbreaks and local climate (temperature) effects) to estimate the effect of individual trees on building energy use and carbon emissions for various climate regions and tree classes across the United States.

McPherson and Simpson (1999) calculate default energy effects per tree (in units of carbon dioxide emissions) for each climate region, vintage building type (period of construction), tree-height class, distance from building, energy use (heating or cooling) and/or leaf type (deciduous or evergreen). The amount of carbon avoided is converted into the amount of MWh (megawatt h) for cooling, and

Table 2
Average number of energy-affecting trees per hectare of tree cover within the Developed Low Intensity NLCD class by direction from building subdivided by leaf class, tree size and distance from building, based on the sample of 20 cities.

			North		Northeast		East		Southeast		South		Southwest		West		Northwest	
Leaf[a]	Size[b]	Dist[c]	No.	SE	No.	SE	No.	SE	No.	SE	No.	SE	No.	SE	No.	SE	No.	SE
D	S	A	5.5	0.9	1.1	0.3	3.2	0.7	1.7	0.5	2.7	0.5	2.4	0.5	3.1	0.6	1.5	0.4
D	S	N	2.7	0.5	1.1	0.3	2.9	0.6	1.8	0.4	1.2	0.3	2.4	0.5	3.1	0.6	1.5	0.3
D	S	F	2.3	0.4	1.0	0.3	1.9	0.4	1.9	0.5	1.4	0.3	2.3	0.5	2.6	0.5	1.0	0.3
D	M	A	2.2	0.5	0.9	0.3	1.6	0.5	0.9	0.3	1.8	0.4	1.4	0.4	1.5	0.4	1.1	0.3
D	M	N	3.9	0.9	1.1	0.2	2.8	0.7	2.5	0.5	1.6	0.4	2.2	0.4	3.4	1.0	1.1	0.2
D	M	F	2.6	1.0	1.4	0.5	1.2	0.3	1.5	0.3	0.8	0.2	1.2	0.3	2.0	0.5	1.0	0.3
D	L	A	0.8	0.3	0.5	0.2	0.6	0.2	0.1	0.1	0.4	0.2	0.8	0.4	0.9	0.4	0.6	0.3
D	L	N	8.1	1.3	1.8	0.4	3.9	0.7	3.5	0.6	3.8	0.7	3.5	0.7	4.7	0.9	1.5	0.5
D	L	F	3.3	1.1	2.2	1.4	1.1	0.3	1.2	0.3	0.8	0.2	1.9	0.6	1.2	0.4	1.5	0.6
E	S	A	2.4	0.7	0.8	0.3	1.1	0.3	1.2	0.3	1.5	0.5	1.5	0.4	2.7	0.9	0.9	0.3
E	S	N	2.0	0.6	1.2	0.3	0.9	0.3	0.8	0.2	1.1	0.5	1.4	0.4	0.9	0.3	0.9	0.3
E	S	F	2.1	0.8	0.9	0.4	0.5	0.2	0.8	0.2	1.2	0.6	1.0	0.4	0.5	0.2	0.6	0.2
E	M	A	1.4	0.4	0.7	0.3	1.1	0.3	0.3	0.1	1.0	0.4	0.8	0.3	0.8	0.3	0.5	0.2
E	M	N	1.8	0.7	0.7	0.3	1.7	0.5	0.5	0.2	0.9	0.3	0.7	0.2	1.1	0.4	0.9	0.2
E	M	F	1.3	0.7	0.7	0.3	0.7	0.2	0.8	0.2	0.4	0.2	0.5	0.2	0.6	0.3	0.4	0.2
E	L	A	1.1	0.3	0.5	0.2	1.1	0.4	0.9	0.3	0.3	0.2	0.8	0.3	0.8	0.3	1.3	0.5
E	L	N	2.8	1.2	1.2	0.7	2.1	0.6	2.3	0.7	0.7	0.3	1.2	0.3	2.5	0.6	0.8	0.3
E	L	F	0.8	0.3	0.5	0.2	1.5	0.6	1.0	0.4	0.9	0.4	0.7	0.2	1.4	0.6	0.5	0.3
			47.0	3.2	18.4	2.0	29.8	2.0	23.6	1.6	22.6	1.7	26.7	1.7	33.7	2.3	17.5	1.4

No. – number of trees per hectare of tree cover.
SE = standard error.

[a] Leaf class: D = deciduous, E = evergreen.
[b] Size class: S = small (6–10 m tall), M = medium (10–15 m), L = large (>15 m).
[c] Distance to building: A = adjacent (<6 m from building), N = near (6–12 m), F = far (12–18 m).

MMBtus (1 million British Thermal Units) and MWh for heating (e.g., fuel oil, heat pump, electricity, and natural gas) avoided due to the tree. Carbon conversion to cooling and heating electricity use (MWh) had state specific conversion factors; non-electrical heating fuels (MMBtus) used a standard conversion factor as this factor does not vary by region (McPherson and Simpson 1999). Vintage building type distribution was based on the average distribution for each climate region (McPherson and Simpson 1999). More details on energy methods can be found in McPherson and Simpson (1999) and Nowak et al. (2008).

Energy effects were estimated for all energy-affecting trees (based on tree height, leaf type and distance and direction from building) within each climate region by state. These effects were summed to estimate the total amount of MWh and MMBtus avoided by the urban/community tree population in each state.

Energy use was converted to pollutant emissions using state estimates of pollutant emission per MWh or MMBtu. Pollutant emissions were estimated for carbon dioxide (CO_2), nitrogen oxides (NO_x), sulfur dioxide (SO_2), carbon monoxide (CO), methane (CH_4), volatile organic compounds (VOCs), particulate matter less than 10 μm (PM_{10}) and less than 2.5 μm ($PM_{2.5}$). As PM_{10} includes all particles less than 10 μm and $PM_{2.5}$ includes all particles less than 2.5 μm, the PM_{10} estimate includes the $PM_{2.5}$ values. To adjust for this overlap, $PM_{2.5}$ concentration was subtracted from PM_{10} concentration to produce an adjusted PM_{10} concentration (denoted PM_{10^*}), which estimates pollution concentration of 2.5–10-μm particles. This separation of PM into two classes: $PM_{2.5}$ (particle less than 2.5 μm) and PM_{10^*} (particles between 2.5 and 10 μm) prevents double counting of $PM_{2.5}$ values.

State electricity conversions to pollutants (t/MWh) were based on the U.S. EPA Emissions and Generation Resource Integrated Database (eGRID) (Deru and Torcellini 2007; Cai et al., 2012; U.S. EPA, 2013), which provides environmental characteristics of almost all electrical power generated in the United States. MMbtu conversion factors (t/MMbtu) were based on fuel type (e.g., natural gas, fuel oil, wood). State MMbtus conversion factors were used for CO_2, NO_x and SO_2 based on eGRID data (Deru and Torcellini 2007; U.S. EPA, 2013). For CO, CH_4, VOCs, and PM_{10}, national average conversion factors were applied (Leonardo Academy, 2011). For $PM_{2.5}$, no value could be found for MMbtus so the ratio of electricity emissions between $PM_{2.5}$ and PM_{10} was applied to PM_{10} MMbtus emissions to estimate $PM_{2.5}$ from MMbtus. Pollutant emissions by fuel type were weighted by state average fuel use for heating (McPherson and Simpson 1999) to estimate total state emissions associated with changes in energy use.

2.5. Value of altered energy use and pollutant emission

State energy costs were derived from the U.S. Energy Information Administration (2012) based on 2009 costs for natural gas, 2010/2011 heating season fuel oil costs (U.S. Energy Information Administration 2011a), 2009 residential electricity costs (U.S. Energy Information Administration 2011b) and 2008 costs of wood (U.S. Energy Information Administration 2011c). Fuel oil costs were not available for all states. For states missing fuel oil values, the national average value was used.

Various approaches were used to estimate the values of the changes in emissions. The CO_2 value was estimated at $40 per tonne based on the estimated social costs of carbon for 2015 with a 3% discount rate in 2014 dollars (U.S. EPA, 2015; Interagency Working Group 2015). The CH_4 value was estimated at $980 per tonne based on the ratio of the estimated social costs of methane to carbon dioxide (24.5) for 2010 with a 3% discount rate (Marten and Newbold, 2011). This ratio was applied to the most recent CO_2 value to update the value for CH_4. Social costs estimate the monetized damages associated with incremental increases in emissions and include changes in net agricultural productivity, human health, property damages from increased flood risk, and the value of ecosystem services due to climate change (Interagency Working Group, 2015).

Pollution removal value for CO was estimated using national median externality values (Murray et al., 1994). These values, in dollars per tonne, were updated to 2011 values using the producer price index (U.S. Department of Labor 2012): CO = $1599 t^{-1}. Externality values can be considered the estimated cost of pollution to society that is not accounted for in the market price of the goods or services that produced the pollution.

Table 3
Average number of energy-affecting trees per hectare of tree cover within each NLCD class by direction from building based on the sample of 20 cities.

	North		Northeast		East		Southeast		South		Southwest		West		Northwest		Total	
NLCD Class	No.	SE	No.	SE	No.	SE	No.	SE	No.	SE	No.	SE	No.	SE	No.	SE	No.	SE
Dev. Low	47.0	3.2	18.4	2.0	29.8	2.0	23.6	1.6	22.6	1.7	26.7	1.7	33.7	2.3	17.5	1.4	219.3	5.8
Dev. Medium	48.4	8.2	8.6	2.0	17.3	3.8	15.9	3.0	21.3	6.8	8.0	1.8	26.6	5.5	3.8	0.9	149.9	13.2
Plant/Cultiv.	20.8	20.6	0.0	0.0	65.1	46.1	0.5	0.4	0.0	0.0	0.3	0.3	62.5	35.6	0.2	0.2	149.3	61.8
Dev. High	23.7	2.9	4.1	0.9	17.1	2.7	7.9	1.2	25.6	6.8	12.4	1.7	18.2	3.4	12.4	4.1	121.3	9.8
Open Space	3.0	0.6	0.4	0.2	3.2	0.8	1.9	0.6	1.3	0.4	0.5	0.2	3.3	0.9	0.7	0.3	14.5	1.6
Forest	1.3	0.8	1.3	0.9	1.4	0.8	0.1	0.1	0.0	0.0	2.3	1.7	0.8	0.8	0.2	0.2	7.3	2.4

No. – number of trees per hectare of tree cover.
SE – standard error.

Median air pollution cost factors from Europe (2008), which are similar to externality values and include health costs, building and material damage, and crop losses (Van Essen et al., 2011), were used to estimate the values of NO_x (\$9411 t^{-1}), SO_2 (\$8929 t^{-1}), VOCs (\$1207 t^{-1}), PM_{10} (\$56,346 t^{-1}) and $PM_{2.5}$ (\$140,926 t^{-1}).

3. Results

The density of trees around buildings per unit of tree cover varies by NLCD cover class with the tree density highest for Low Intensity Developed land (219.3 trees/ha cover), followed by Medium Intensity Developed (149.9), Planted/Cultivated (149.3), High Intensity Developed (121.3), Developed Open Space (14.5) and Forest (7.3) (Table 3). Though Planted/Cultivated had the third highest density, it also had the highest standard error (61.8) due to the relative small sample size of trees in these agricultural areas, as agricultural land within urban areas is relatively uncommon.

Overall, the U.S. urban/community forest is estimated to save $7.8 billion per year in energy costs, $4.7 billion from reduced electricity use and $3.1 billion from reduced heating costs. The states with greatest energy cost savings were Florida ($643 million), Texas ($601 million), and California ($410 million). States with the lowest energy cost savings were North Dakota ($13.3 million), Wyoming ($14.2 million) and Vermont ($18.2 million) (Table 4). Focusing just on the urban area (not urban/community), total annual energy savings would drop to $4.7 billion and avoided emissions to $2.3 billion. Average value of energy savings per hectare of tree cover in U.S. urban/community areas is $455 per year, plus $228 per year from avoided emissions.

The greatest avoided emissions nationally due to energy conservation came from CO_2 (43.8 million tonnes), followed by SO_2 (113,000 t) and NO_x (39,000 t). The greatest associated savings from avoided emissions came from CO_2 (\$1.8 billion), followed by SO_2 (\$1.0 billion) and $PM_{2.5}$ (\$638 million). The overall value for avoided emissions nationally was \$3.9 billion per year (Table 5).

4. Discussion

There is much literature on tree effects on building energy use, but limited estimates at the national scale. There have been national estimates of energy savings from proposed plantings of millions of trees (Akbari et al., 1988; Akbari et al., 2001), but none could be found estimating the effects of the current urban forest. While the estimates in this analysis are first-order approximations, they provide information on the magnitude and variation of services of the current urban forest in the United States related to building energy conservation.

Overall, the U.S. urban/community forest is estimated to save approximately $7.8 billion per year by reducing electricity use by 38.8 million MWh and heating needs by 246 million MMBtus. An additional value of $3.9 billion is provided through reduced emissions of various pollutants from power plants. Converting these MWh savings to Btus reveals that the U.S. urban/community forests reduce energy use by about 0.38 quadrillion Btus. Given national energy consumption by homes in the United States of about 4.86 quadrillion Btus from space heating and air conditioning (U.S. Energy Information Administration, 2015), or 5.23 quadrillion Btus if trees did not exist, trees in urban/community areas are estimated to reduce space-conditioning energy use by about 7.2 percent. Values per hectare of tree cover from energy savings averaged $455, but varied from a low of $123 in Montana to a high of $1811 in Washington, DC. This variation has to do with the variation in density of residential buildings (Washington, DC has a relatively high population and building density), energy usage between heating and cooling seasons, and local energy costs. In some areas, much of the tree cover is in cover classes that have few trees near buildings (e.g., forest cover class), so the average effect on energy use per unit of tree cover in these areas would be reduced.

Energy conservation and associated values could be enhanced through strategic planting of trees around buildings. Tree size, species (evergreen vs. deciduous), and tree distance and direction from the building all affect building energy use. While results vary by climate zone, in general, large trees to the west side of the building provide the greatest average reduction in cooling energy savings and large trees to the south side tend to lead to the greatest increase in winter energy use (Heisler 1986a). Typically trees closer to the building have the greatest effect on energy use (McPherson and Simpson 1999).

These values related to energy conservation are just a few of many values derived from urban forests nationally. Other values are related to air temperature reductions, air pollution removal, carbon sequestration, reduced runoff and water quality improvement, reduced ultraviolet radiation, wildlife habitat, aesthetics, etc. (e.g., Dwyer et al., 1992; Nowak and Dwyer, 2007). While the services provided by urban trees tend to improve human health and well-being, there are also various economic and environmental costs associated with trees (e.g., pollen, volatile organic compound emissions, tree maintenance, sidewalk repair) and not all services are positive all the time (e.g., trees can increase energy use in winter or increase pollutant concentrations, depending upon design) (e.g., Nowak and Dwyer, 2007; Escobedo et al., 2011; Nowak et al., 2014).

The energy and avoided emission estimates in this paper are derived for urban/community land, which occupies 6.4 percent of the conterminous United States. Adjusting these values to the 3.6 percent urban land, the energy savings nationally drops to $4.7 billion and avoided emissions to $2.3 billion. These annual urban forest values are comparable to other national annual urban forest values ascribed to air pollution removal ($4.7 billion; Nowak et al., 2014) and carbon sequestration ($2.0 billion – based on 2000 urban land area; Nowak et al., 2013b). The total for these four services (energy conservation, avoided emissions, pollution removal and carbon sequestration) in urban areas totals $13.7 billion annually, or $1450 per hectare of tree cover per year. These values do

Table 4
Estimated energy savings and associated value by state due to trees around residential buildings.

	Energy Savings				Value					
State	MWh (x10^3)	SE	MMBtus (x 10^3)	SE	MWh $ (x 10^6)	SE	BTU $ (x10^6)	SE	Total $ (x10^6)	SE
AL	1,453.8	94.1	1,375.6	544.3	162.5	10.5	21.4	8.5	184.0	13.5
AR	468.0	31.9	3,355.3	430.2	41.0	2.8	39.3	5.0	80.2	5.8
AZ	2,232.8	103.7	1,194.3	80.6	257.4	12.0	20.1	1.4	277.5	12.0
CA	2,676.3	123.6	−133.2	614.9	411.3	19.0	−1.2	5.5	410.2	19.8
CO	60.9	5.7	1,306.4	190.9	7.1	0.7	15.4	2.3	22.5	2.3
CT	551.9	24.1	2,468.0	480.0	105.8	4.6	35.5	6.9	141.3	8.3
DC	23.6	0.9	325.1	22.5	3.3	0.1	5.1	0.4	8.4	0.4
DE	126.1	10.8	1,938.8	216.6	17.9	1.5	31.2	3.5	49.1	3.8
FL	4,910.9	315.4	3,696.8	574.8	577.5	37.1	65.5	10.2	643.0	38.5
GA	1,677.2	92.0	−116.7	555.1	177.9	9.8	−1.6	7.7	176.3	12.4
IA	143.8	13.2	7,421.4	715.9	15.9	1.5	82.3	7.9	98.2	8.1
ID	100.3	4.1	1,999.5	97.6	8.1	0.3	23.7	1.2	31.8	1.2
IL	629.9	19.3	21,414.9	853.6	74.0	2.3	238.6	9.5	312.6	9.8
IN	325.3	20.1	10,442.8	805.1	33.2	2.1	124.1	9.6	157.3	9.8
KS	354.5	17.4	9,155.9	484.1	36.4	1.8	119.9	6.3	156.3	6.6
KY	429.2	37.8	6,856.4	805.6	38.5	3.4	82.8	9.7	121.4	10.3
LA	1,846.8	132.6	1,552.7	238.0	173.4	12.5	18.2	2.8	191.6	12.8
MA	980.8	38.0	6,818.7	856.1	149.0	5.8	98.9	12.4	247.9	13.7
MD	649.0	40.4	7,544.3	780.3	97.7	6.1	102.8	10.6	200.5	12.2
ME	110.8	14.6	1,742.9	595.0	17.6	2.3	27.4	9.3	45.0	9.6
MI	618.1	29.2	13,664.5	1,119.2	78.3	3.7	166.0	13.6	244.3	14.1
MN	325.5	42.2	9,101.2	1,667.1	35.1	4.5	92.1	16.9	127.2	17.5
MO	759.7	43.9	12,682.7	996.9	74.4	4.3	175.5	13.8	249.9	14.5
MS	820.0	35.1	1,279.3	189.9	82.3	3.5	12.9	1.9	95.3	4.0
MT	92.1	13.1	3,059.8	714.0	9.0	1.3	33.8	7.9	42.8	8.0
NC	1,508.4	95.4	3,655.0	657.2	159.1	10.1	45.2	8.1	204.3	12.9
ND	18.4	1.9	1,051.2	99.0	1.7	0.2	11.6	1.1	13.3	1.1
NE	65.8	2.4	3,340.7	134.1	6.7	0.2	36.6	1.5	43.3	1.5
NH	94.2	5.8	776.3	218.9	15.8	1.0	11.8	3.3	27.6	3.5
NJ	915.7	39.2	9,359.6	798.5	159.1	6.8	134.1	11.4	293.2	13.3
NM	403.7	24.1	949.5	85.9	43.6	2.6	10.1	0.9	53.7	2.8
NV	372.9	13.3	2,018.5	102.7	46.3	1.6	28.5	1.5	74.9	2.2
NY	1,034.8	43.6	13,124.8	1,512.0	206.7	8.7	200.4	23.1	407.2	24.7
OH	776.0	35.7	18,358.2	1,444.5	92.3	4.2	242.9	19.1	335.1	19.6
OK	771.4	113.5	926.4	444.4	78.3	11.5	9.7	4.6	88.0	12.4
OR	257.9	12.8	1,212.1	202.3	23.4	1.2	17.9	3.0	41.3	3.2
PA	1,080.0	61.9	16,636.0	1,602.6	140.5	8.1	239.7	23.1	380.2	24.5
RI	142.0	6.1	1,249.1	145.0	22.3	1.0	19.7	2.3	42.0	2.5
SC	805.7	43.2	2,211.3	325.2	82.9	4.4	28.5	4.2	111.4	6.1
SD	23.6	1.3	1,357.4	81.7	2.3	0.1	16.5	1.0	18.8	1.0
TN	1,078.2	80.6	5,017.0	720.1	106.0	7.9	54.8	7.9	160.8	11.2
TX	4,514.8	184.8	8,091.8	500.1	518.8	21.2	82.1	5.1	600.9	21.8
UT	197.2	13.6	4,114.5	325.4	17.7	1.2	47.9	3.8	65.6	4.0
VA	1,070.5	52.9	5,051.9	461.8	113.6	5.6	61.9	5.7	175.5	8.0
VT	35.0	4.2	767.4	177.8	5.6	0.7	12.6	2.9	18.2	3.0
WA	508.4	23.2	3,153.4	388.3	42.3	1.9	44.7	5.5	87.0	5.8
WI	463.8	39.9	11,074.5	1,514.5	59.7	5.1	122.8	16.8	182.6	17.6
WV	263.7	14.9	1,425.3	278.1	24.5	1.4	21.4	4.2	45.9	4.4
WY	38.9	4.3	867.0	108.8	3.7	0.4	10.5	1.3	14.2	1.4
Total	38,808.4	503.5	245,936.4	4,904.5	4,657.9	59.1	3,141.6	63.3	7,799.5	86.6

SE – standard error.

not include values from other ecosystem services or costs (except for negative energy effects, which are included in this analysis).

The standard errors of the estimates are based on sampling standard errors of trees around buildings based on a sample from 20 cities. These estimates of uncertainty are conservative as they do not include estimates of uncertainty associated with modeling energy effects of trees or the error associated with tree cover estimates. The energy modeling errors are unknown. The tree cover estimates based on NLCD data, which tend to underestimate tree cover (Nowak and Greenfield, 2010) were adjusted to photo-interpreted cover estimates. These photo-interpreted values have a standard error nationally of 0.4 percent, but this error is increased at the state level and the process of adjusting the NLCD values to photo-interpreted estimates also increases uncertainty.

Other limitations of the energy estimates are related to using national average data on the density of number of trees, distance and direction, and deciduous vs evergreen trees near buildings to characterize state conditions. Local and state conditions will vary from the national average, but given the lack of local or state data on urban forest structure, the national average conditions provide the best means to estimate tree positions around buildings. In comparing known state estimates of energy conservation due to trees (i.e., estimates in CA (McPherson and Simpson 2003), DC (Nowak et al., 2006b), KS, ND, NE, SD (Nowak et al., 2012b), TN (Cumming et al., 2007) and WI (Nowak et al., 2012a)) to model estimates in this paper, the values in this paper come out 74 percent higher. However, the state estimates are typically only based on urban land area, not urban/community lands, which is larger. Adjusting for this difference in land area, the results from this paper overestimate the combined states estimate by 14 percent, with individual state differences ranging from a low of $0.8 million (ND; 20 percent difference), to overestimates of $78 million (KS; 80 percent difference), to an underestimate of $130 million (CA; 37 percent difference). The tendency to overestimation compared to the state

Table 5
Avoided emissions from power plants and associated values due to urban/community trees by state.

	Metric Tons Avoided								Value ($ x 10^3)								
State	CO$_2$ (x10^3)	NO$_x$	SO$_2$	CH$_4$	CO	PM$_{2.5}$	PM$_{10^*}$	VOC	CO$_2$	NO$_x$	SO$_2$	CH$_4$	CO	PM$_{2.5}$	PM$_{10^*}$	VOC	Total
AL	833	593	3164	13	368	225	33	18	33,321	5584	28,247	13	588	31,736	1886	21	101,396
AR	549	614	1244	4	147	16	23	5	21,966	5774	11,107	4	236	2284	1324	6	42,701
AZ	1237	1356	742	16	647	70	25	14	49,476	12,758	6621	16	1035	9843	1409	17	81,175
CA	728	262	184	41	709	390	182	603	29,122	2465	1646	40	1133	54,954	10,274	728	100,363
CO	171	249	187	1	23	3	2	1	6833	2344	1672	1	37	386	113	1	11,387
CT	318	201	207	16	204	56	33	5	12,722	1893	1851	16	326	7856	1886	6	26,557
DC	53	99	399	1	222	2	3	1	2138	929	3566	1	354	323	172	1	7486
DE	292	333	1167	2	124	39	42	2	11,669	3131	10,417	2	198	5539	2372	2	33,329
FL	3157	2709	5810	95	4346	769	393	57	126,289	25,494	51,875	93	6949	108,331	22,123	69	341,223
GA	1052	780	3520	16	430	322	72	22	42,083	7340	31,425	16	687	45,360	4052	26	130,987
IA	1231	1229	2838	2	82	5	2	3	49,231	11,566	25,337	2	131	715	124	3	87,110
ID	109	101	154	1	8	11	4	1	4347	952	1372	1	13	1584	212	1	8482
IL	2387	1695	5534	4	144	14	10	6	95,494	15,955	49,413	4	230	1923	545	8	163,572
IN	1339	1288	4723	4	147	38	13	5	53,548	12,120	42,169	4	236	5345	725	6	114,152
KS	1200	1512	1584	3	160	10	3	5	47,992	14,234	14,141	3	256	1465	141	6	78,237
KY	1101	939	2997	5	150	72	20	7	44,043	8834	26,763	5	240	10,110	1119	8	91,123
LA	1128	1208	1894	20	883	227	75	37	45,124	11,373	16,913	20	1412	31,995	4228	45	111,110
MA	1017	733	1881	35	896	110	35	13	40,671	6899	16,791	34	1433	15,558	1985	16	83,387
MD	1155	843	8737	10	390	157	154	10	46,209	7935	78,012	10	623	22,188	8677	12	163,666
ME	94	108	119	8	75	85	10	5	3767	1014	1060	7	119	12,008	590	6	18,573
MI	1754	1969	6456	9	192	49	25	14	70,173	18,532	57,646	9	307	6850	1397	17	154,930
MN	1077	1300	1632	8	106	33	23	5	43,072	12,232	14,572	8	169	4587	1286	6	75,932
MO	1939	1382	6137	8	295	28	28	9	77,551	13,002	54,797	7	471	3942	1561	11	151,343
MS	540	556	858	8	473	127	33	11	21,581	5232	7662	8	756	17,869	1882	14	55,004
MT	429	487	772	1	38	23	39	1	17,171	4582	6895	1	61	3262	2189	2	34,162
NC	1201	755	2046	13	318	284	59	15	48,042	7109	18,268	13	508	39,965	3309	18	117,230
ND	127	227	472	0.2	9	4	0.02	0.4	5060	2136	4213	0.2	15	622	1	0.5	12,047
NE	391	663	1074	1	20	1	0.3	1	15,622	6239	9592	1	31	130	15	1	31,631
NH	74	59	425	3	50	7	2	1	2943	553	3794	3	80	1018	86	1	8479
NJ	939	551	813	10	308	148	83	14	37,577	5190	7262	10	493	20,857	4677	17	76,083
NM	440	814	235	4	168	3	1	5	17,604	7665	2099	4	269	386	80	7	28,114
NV	327	254	132	3	131	10	1	4	13,069	2388	1180	3	209	1435	30	5	18,319
NY	1190	862	1540	12	870	69	21	14	47,607	8115	13,746	12	1390	9747	1178	17	81,812
OH	2459	2050	12,579	8	237	146	108	8	98,378	19,295	112,312	8	379	20,541	6063	10	256,986
OK	637	888	1132	8	325	29	11	10	25,476	8360	10,106	8	520	4067	615	13	49,165
OR	122	105	138	2	34	17	6	1	4874	989	1231	2	54	2431	351	2	9933
PA	2067	2005	10,488	13	309	128	29	10	82,696	18,872	93,641	12	495	17,981	1646	12	215,354
RI	130	25	1	1	58	2	0.1	4	5181	231	11	1	92	267	3	5	5792
SC	514	313	1316	6	124	101	48	7	20,559	2944	11,753	5	199	14,198	2698	8	52,364
SD	149	503	486	0.1	6	2	2	0.2	5971	4736	4339	0.1	10	220	126	0.3	15,403
TN	1072	738	2755	7	220	145	40	12	42,896	6947	24,601	7	352	20,460	2258	14	97,535
TX	3352	2215	6172	39	2129	213	13	191	134,083	20,845	55,109	38	3404	30,025	758	231	244,494
UT	564	895	349	2	66	20	37	2	22,567	8422	3114	2	105	2773	2079	3	39,066
VA	979	908	2760	20	526	215	49	16	39,166	8547	24,640	20	841	30,300	2769	19	106,301
VT	1.01	47	4.7	1	1	6	0	0.4	41	446	42	1	2	794	0	0.4	1326
WA	301	265	96	3	44	19	5	2	12,047	2492	861	2	70	2710	283	3	18,468
WI	1383	1104	3415	5	159	20	16	10	55,315	10,394	30,489	5	254	2871	914	12	100,253
WV	388	204	971	3	80	47	13	3	15,512	1919	8670	3	129	6560	705	4	33,501
WY	123	175	196	0.4	16	14	33	1	4917	1647	1750	0.4	26	1954	1882	1	12,177
Total	43,820	39,172	112,538	493	17,467	4529	1860	1194	1,752,798	368,657	1,004,793	484	27,928	638,322	104,799	1441	3,899,213

estimates (7 of the 8 states were overestimated) is likely, in part, due to increases in energy costs between the years of the studies. The difference in California is partially due to different models and methods used to estimate energy use effects. To improve national and state estimates in the future, field data on urban forests are needed at the state and local level (Cumming et al., 2008; Nowak et al., 2008) and more research is needed related to building energy modeling. Through quantification of urban forest benefits and costs, national, regional and local policies and management plans can be developed to optimize tree and forest benefits to sustain human health and well-being in urban/community areas.

5. Conclusion

Modeling tree effects on residential building energy use in urban/community areas in the United States reveals annual energy savings for space conditioning of about 7.2 percent, valued at $7.8 billion. An additional $3.9 billion per year is derived from reduced emissions from power plants. This first-order approximation can be improved with more field data on urban forest structure across the United States as well as improved local scale building energy modeling. This $11.7 billion annual value adds to existing national urban forest estimates of air pollution removal ($4.7 billion) and carbon sequestration ($2.0 billion) to provide a broadened estimate of the national value of urban/community forests.

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