Urban Forestry & Urban Greening 14 (2015) 519–526

Contents lists available at ScienceDirect

Urban Forestry & Urban Greening

journal homepage: www.elsevier.com/locate/ufug

Original article

Assessing urban vacant land ecosystem services: Urban vacant land as green infrastructure in the City of Roanoke, Virginia

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ARTICLE INFO

Article history:
Received 9 June 2014
Received in revised form 4 May 2015
Accepted 7 May 2015

Keywords:
Ecosystem services
i-Tree
Urban forestry

ABSTRACT

The research reported here quantifies the ecosystem services and values of vacant land using the City of Roanoke, Virginia as a study site. Aerial photo interpretation with ground-truthing was used to identify and catalog vacant parcels of land within the city limits and the results mapped using the i-Tree Canopy and i-Tree Eco models to define land cover classes and quantify ecosystem structure and services. An analysis of urban forest cover in Roanoke's vacant land reveals that this area has about 210,000 trees, with a tree cover of 30.6%. These trees store about 97,500 t of carbon, valued at $7.6 million. In addition, these trees remove about 2090 t of carbon (valued at $164,000), and about 83 t of air pollutants (valued at $916,000) every year, which is high relative to other land uses in Roanoke. Trees on vacant land in the city are estimated to reduce annual residential energy costs by $211,000 for the city's 97,000 residents. The structural value of the trees growing on vacant land is estimated at $169 million. Information on the structure and functions of urban forests on vacant land can be used to evaluate the contribution made by urban vacant land's green infrastructure to improving environmental quality. The methodology applied to assess ecosystem services in this study can also be used to assess ecosystem services of vacant land in other urban contexts.

Introduction

The urban cores of many contemporary American cities are slowly becoming decentralized, with many losing significant numbers of residents, businesses, and industries between 1950 and 2010 (Hall, 2010). This loss of population has led to an increase in the number of vacant lots, often in the urban core. These vacancies become "urban voids" or negative spaces in the urban fabric. Decentralization is most common in post-industrial cities such as St.Louis, Philadelphia, and Detroit. For example, since 1950, Detroit has lost over 50% of its population, 165,000 industrial jobs, and 147,000 housing units (Hall, 2010); between 1978 and 1998, there were 108,000 demolitions and only 9000 new buildings constructed in the city (Oswalt, 2008). As the population of Detroit continues to decline, an estimated 2400 properties become newly vacant every year (Daskalakis et al., 2001) and approximately 32% of the city's land area is now vacant property (King, 2012), more than twice the average in large U.S. cities (Bowman and Pagano, 2004). While Detroit is an extreme case, many cities have vacant land. However, due to a lack of public interest, policies, and economic investment, vacant land often becomes wasted, underused or under-appreciated space. Can urban vacant land perhaps be a valuable resource? Re-imagining urban vacant land is critical to the preservation of our traditional urban environment and quality of life. To achieve this we need to be more open to alternative ways to "reuse wasted land" in urban areas. Can vacant land be valuable ecological resource? Perhaps it can enhance ecosystem health and promote a better quality of life for city residents?

Urban infrastructure consists of the systems that provide services or benefits to people and communities, such as roads for transportation and storm sewers for rainfall runoff removal, but green infrastructure not only provide the primary service for a single benefit, but multiple benefits in the form of environmental and cultural services. The definitions of "green infrastructure (GI)" are numerous. According to the U.S. Environmental Protection Agency (EPA), GI is an "adaptable term used to describe an array of products, technologies, and practices that use natural systems – or engineered systems that mimic natural process – to enhance overall environmental quality and provide utility services" (USEPA, 2011). The EPA suggests that green infrastructure could reduce

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http://dx.doi.org/10.1016/j.ufug.2015.05.003
1618-8667/

the volume of urban stormwater runoff, provide community benefits and also reduce the need for public monetary commitments (Grumbles, 2007). In the late 1980s, the National Science Foundation supported an urban ecology educational effort that used city parks, rights of way, and vacant lots as “nature’s classrooms” (Bowman and Pagano, 1998). Similar thinking is evident in Portland Oregon’s Metropolitan Greenspaces Program (Poracsky and Houck, 1994). This program changed the land use general labels to make them more positive, exchanging labels such as “vacant” or “undeveloped” to biological labels such as “greenspace” or “greenbelt” (Bowman and Pagano, 1998). Rather than being a negative symbol of urban problems, vacant land began to be considered as “fortuitous landscapes.” This new way of thinking is apparent in the title of Timothy Beatley’s book, “Biophilic Cities: Integrating Nature Into Urban Design and Planning” (Beatley, 2011).

Urban vacant land is not normally thought of as green infrastructure, partly because the potential community benefits provided by these spaces are not recognized. One way of addressing this failure is to conduct a comprehensive assessment of urban forests to estimate the environmental benefits and ecosystem services they provide; and thus, demonstrating the role of trees on vacant parcels play in creating healthy, livable and sustainable cities. Therefore the purpose of this paper is to provide such a demonstration of how urban vacant land can function as a form of green infrastructure providing ecosystem services and values, such as air pollution removal, carbon sequestration and storage, and energy saving, as well as the structural value of the trees themselves. In most cities, air pollution is a major environmental problem (USEPA, 2014). Carbon dioxide is the major cause of climate change and also has a strong relationship with energy consumption from power generation (Cox et al., 2000), while the structural value of trees on vacant land can add to our understanding of the compensatory value of vacant land and lead to better urban forest management of vacant land (Nowak et al., 2002a).

Methods

To assess the ecosystem services and values derived from urban vegetation, the i-Tree model (www.itreetools.org) was used. This software is designed to use standardized field data from randomly located plots and local hourly air pollution and meteorological data to quantify urban forest structure and its numerous effects (Nowak et al., 2008a). The results from the i-Tree model can then be used to identify the urban forest structure in order to improve urban forest policies, planning, and management (e.g., Nowak et al., 2011). The model also provides data to support the potential inclusion of trees within environmental regulations, and determine how trees affect the environment and consequently enhance human health and environmental quality in urban and rural areas (Nowak et al., 2011). In this study, the i-Tree Eco model was used to assess the green infrastructure value of vacant land in the City of Roanoke, Virginia.

An i-Tree Eco analysis is usually based on a random sampling or inventory of urban forest characteristics from a study area in order to estimate the urban forest structure and ecosystem services for a particular urban area. However, in this study we were also interested in identifying the forest structure and ecosystem services of different types of vacant land. In most cities, different types of vacant land are not equally represented or evenly distributed across the city and a random sample may not capture all vacant land types in the city. Therefore, a proportionally weighted, stratified random sampling of the study area was used. It was stratified to assure that all types of vacant land were represented, but the sample of each type of vacant land was proportional to the area that each type occupied within the city to provide an accurate estimate of the total ecosystem services provided by each vacant land type. This study used 5 different categories of vacant land as strata to assess the ecosystem services associated with each vacant land type in Roanoke. In addition, ecosystem services were compared among vacant, commercial, industrial, and residential lands throughout Roanoke. This land use differentiation was done to determine if vacant lands represent structural assets with economic value similar to that of other land use in the city.

The precision and cost of the estimate is dependent on the sample and plot size. Generally, 200 plots (0.04 ha each) in a random sample will produce a 12% relative standard error for an estimate covering the entire study area (Nowak et al., 2008b). As the number of plots increase from 200 to 500, the relative standard error will decreases on the total number of trees to 7.7% (a 36% reduction) (Nowak et al., 2008b) and provides more precise estimates. However, as the number of plots increases, so does the time and cost of field data collection. The estimates of ecosystem services values obtained here match well with other field estimates of ecosystem services (e.g., Nowak et al., 2008a, 2013; Morani et al., 2014).

Study area

The City of Roanoke, Virginia was selected as the site for this study. The age and industrial heritage of the city have resulted in a range of vacant parcel types and conditions that provide an excellent opportunity to define and assess vacant land categories. The City of Roanoke became a hub for railroad and other industrial activities in the first half of the 20th century, when the city’s population grew from 21,495 in 1900, to 91,921 in 1950 (Blakeman et al., 2008). However, as economic conditions and technologies changed, many traditional manufacturing operations and industries closed and ceased production in the city. As a result, there are many left-over industrial areas with underused or abandoned properties (Blakeman et al., 2008). The city has a current population of 97,032 (US Census Bureau, 2010), and covers an area of 113.3 km^2. Roanoke enjoys a mild climate that is classified as a humid subtropical climate and has a monthly high temperature of 7.6 °C in January and 28.6 °C in June. It has a mean annual precipitation of 1047.7 mm (NowData – NOAA Online Weather Data, 1981–2010). The City of Roanoke is located in Southwest Virginia, at about 37°16′N and 79°56′W, in the valley and ridge region of the state.

Aerial field sampling of vacant lots

In quantifying urban forest structure and ecosystem services in a city, i-Tree results are typically stratified by land use. Vacant land is only one of many land use classes and most of the time is not subdivided into different classes of vacant land. Different types of vacant land have different physical characteristics. Therefore, dividing vacant land into smaller, more homogeneous types can help assess variations in vacant land and offer a more precise picture of the role that vacant land plays in providing different forest structure and ecosystem services. The vacant land in Roanoke was categorized into 5 types that are described below.

Within Roanoke, 1000 points on Google Maps aerial imagery were photo-interpreted, using i-Tree Canopy to estimate the amount of each type of vacant land in the city. Each point that fell upon a vacant parcel was classified into one of the vacant types through the aerial photo-interpretation process (Table 2). Photo-interpreted estimates of vacant land types and their associated land cover are beneficial for providing essential information related to natural resources and development planning and policies at the local to national scale (Nowak and Greenfield, 2010). After the area of each vacant land type was determined, field plots were laid to assess the ecosystem services derived from the trees on these

Table 1
Categories of Roanoke's vacant land.

Category	Characteristics
Post-industrial sites	By-product of rapid urbanization and urban sprawl types by: e.g., power plants, landfills, brownfields, water treatment plants, military sites, airports
Derelict sites	Building or house remains empty or unused. Previously developed land that is now vacant and often wasted or unused sites: e.g., unsafe, place for illegal activity
Unattended sites with vegetation	Vacant land sites that are empty and inactive. The site may contain natural vegetation and contain ecosystem value that has a relatively high potential for development: e.g., unimproved vacant parcels, unimproved natural forest, conservation areas
Natural sites	The sites have physical constraints by environment conditions: e.g., drainage areas, wetlands, hillsides, river banks/river flood plains
Transportation-related sites	Spaces are related to transportation systems: e.g., railroad tracks, highways, conservation areas

Table 4
Annual energy conservation and carbon avoidance due to trees on urban vacant land near residential buildings in the City of Roanoke, Virginia.

	Heating	Cooling	Total
MBTU[a]	2127	n/a	2127
MWH[b]	41	1705	1746
Carbon avoided (mt[c])	37	321	358

[a] One million British Thermal Units.
[b] Megawatt-hour.
[c] Metric ton.

Table 5
Annual savings[a] ($) in residential energy expenditure due to vacant land trees during heating and cooling seasons.

	Heating	Cooling	Total
MBTU[b]	26,077	n/a	26,077
MWH[c]	4350	180,901	185,251
Carbon avoided	2905	25,199	28,103

[a] Based on state-wide energy costs for Virginia: $106.1 per MWH and $12.26 per MBTU.
[b] One million British Thermal Units.
[c] Megawatt-hour.

vacant lands. Overall, 114 (0.04 ha) plots, located on both public and private property, were sampled using a stratified random sampling method across five urban vacant land categories: post-industrial sites (15 plots), derelict sites (14 plots), unattended sites with vegetation (53 plots), natural sites (17 plots), and transportation-related sites (15 plots) (Table 1). Plots were assigned proportionate to the land area of each stratum.

To select the 114 field plot locations, the city was divided into 120 grid cells (Fig. 1) and 53 individual grid cells were then randomly selected for sampling. From the center of each grid cell, the closest vacant lot within each of the 5 vacant classes was selected based on the researcher's visual observation. Vacant parcels were categorized into one of the 5 types based on their existing and past use, and their potential for future development. For each selected vacant parcel, one (0.04 ha) field plot was randomly selected within the parcel. If some of the vacant land classes were not present in the grid cell, additional grids cells were selected until the target sample size (15) was attained for each vacant land class.

As standard error of strata estimates is partially dependent upon sample size, vacant land classifications with relatively few plots (e.g., 15 plots) will have a relatively high percent standard error. However, as these vacant lands are relatively small in area, the absolute standard error can be minimal (Tables 3 and 6–9).

To compare of the ecosystem services among vacant, commercial, industrial, and residential lands, an additional 137 (0.04 ha) plots were measured using a stratified random sample of 0.04 ha plots across three land use types: commercial (14 plots), industrial (40 plots), residential (83 plots) during 2010 using i-Tree Eco sampling protocols and analysis tools. Plots were assigned proportionated to tree canopy cover and land area within each stratum based on existing canopy data and land use zoning (Wiseman and King, 2012).

For each plot, the percentage covered by tree canopies, shrubs and other cover types was assessed. For each woody plant with a

Table 2
Existing urban vacant land area and percentages with completed plots for the City of Roanoke, VA: summary data are provided from the City of Roanoke, analyzed using the i-Tree Canopy.

Typology of urban vacant land	Existing urban vacant land				Number of plots selected for analysis
	km^2	±SE	% of total area	±SE	
Post-industrial sites	3.34	±0.60	3.0%	±0.54	15
Derelict sites	4.01	±0.66	3.6%	±0.59	14
Unattended sites with vegetation	17.3	±1.27	15.5%	±1.14	53
Natural sites	2.78	±0.55	2.5%	±0.49	17
Transportation-related sites	5.01	±0.73	4.5%	±0.66	15
Non-vacant land	78.9	±1.60	70.9%	±1.44	0
City total	111.34		100%		114

±SE: standard error.

Table 3
Comparison of urban forests: city totals for tree effects by land use. Summary data are provided for the City of Roanoke and analyzed using the i-Tree Eco model.

Land use	Percentage tree cover (SE)	Number of trees (SE)	Accumulated carbon storage (t) (SE)	Gross carbon sequestration (t/yr) (SE)	Net carbon sequestration (t/yr) (SE)
Commercial	7.9 (1.0)	165,996 (101,460)	11,311 (4807)	913 (483)	812.7 (423.6)
Industrial	9.7 (0.6)	195,355 (70,208)	17,930 (5939)	1186 (342)	1079.9 (305.3)
Residential	31.4 (0.7)	1,626,880 (240,005)	214,089 (27,439)	13,207 (1684)	9254.7 (1787.5)
Vacant	30.6 (2.5)	210,263 (23,979)	97,508 (16,274)	2091 (287)	1959.9 (266.9)

SE: standard error of the total.

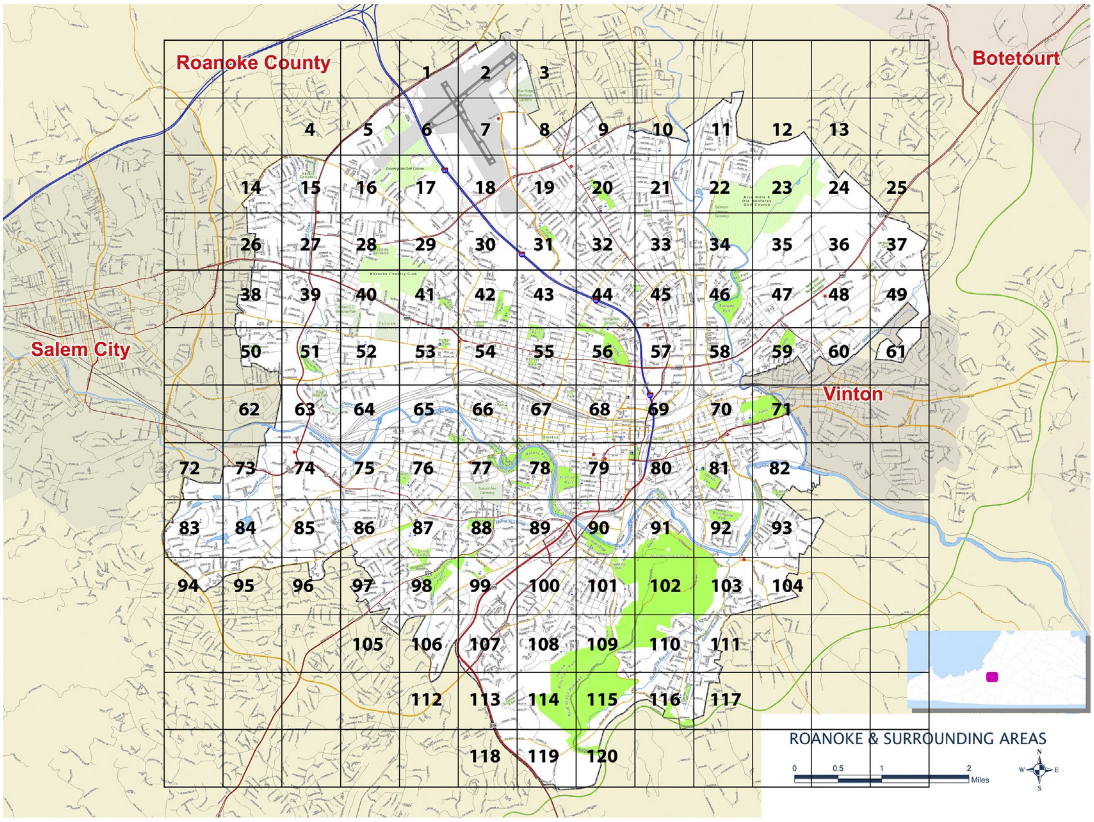

Fig. 1. Study area and grid cell in the City of Roanoke, Virginia.

Table 6
Comparison of urban forests in Roanoke by land use: Per-ha values of trees' structural and functional values.

Land use	Number of trees per ha (SE)	Carbon storage (kg/ha) (SE)	Carbon storage value (US$) per ha (SE)	Carbon sequestration (kg/yr/ha) (SE)	Carbon removal value (US$) per ha (SE)	Structural value (US$) per ha (SE)
Commercial	153.3 (94.9)	10,585 (4499)	825.6 (350.9)	854.8 (452.2)	66.7 (35.2)	97,599 (50,223)
Industrial	79.7 (28.6)	7314 (2422)	570.5 (188.9)	483.8 (139.5)	37.7 (10.8)	60,822 (17,580)
Residential	280.7 (41.4)	36,997 (4735)	2885.8 (369.3)	2279.0 (290.5)	177.8 (22.6)	241,202 (30,605)
Vacant	63.4 (7.2)	29,407 (4908)	2293.7 (382.8)	630.7 (86.7)	49.2 (6.7)	50,943 (7341)

SE: standard error of the total.

Table 7
Comparison of urban forests in Roanoke by land use: city totals for trees' structural and functional values.

Land use	Number of trees (SE)	Carbon storage (t) (SE)	Carbon storage value (US$) (SE)	Carbon sequestration (t/yr) (SE)	Carbon removal value (US$) (SE)	Structural value (US$) (SE)
Commercial	165,996 (101,460)	11,311 (4807)	882,258 (374,946)	913 (483)	71,214 (37,674)	104,290,019 (53,666,145)
Industrial	195,355 (70,208)	17,930 (5939)	1,398,540 (463,242)	1186 (342)	92,508 (26,676)	149,105,020 (43,096,984)
Residential	1,626,880 (240,005)	214,089 (27,439)	16,698,942 (2,140,242)	13,207 (1684)	1,030,146 (131,352)	1,397,770,766 (177,354,411)
Vacant	210,263 (23,979)	97,508 (16,274)	7,605,624 (1,269,372)	2091 (287)	163,098 (22,386)	168,911,300 (24,340,915)

SE: standard error of the total.

Table 8
Comparison of urban forests in Roanoke by vacant land category: Per-ha values of tree's structural and functional values.

Category	Number of trees per ha (SE)	Carbon storage (kg/ha) (SE)	Carbon storage value (US$) per ha (SE)	Carbon sequestration (kg/yr/ha) (SE)	Carbon removal value (US$) per ha (SE)	Structural value (US$) per ha (SE)
Derelict	61.8 (15.2)	31,404 (13,467)	2449.5 (1050.4)	534.8 (150.7)	41.7 (11.7)	50,175 (16,580)
Natural	90.1 (16.5)	32,436 (15,109)	2530(1178)	854.1(274.4)	66.6 (21.3)	60,076(22,462)
Post-industrial	21.4 (9.8)	1576(754.5)	122.9 (58.8)	99.4 (46.7)	7.8 (3.6)	4920(2387)
Transportation-related	56.0 (11.6)	15,070 (5022)	1175.5 (391.7)	454.9 (111.2)	35.5 (8.6)	33,898 (10,649)
Unattended with vegetation	69.9 (12.3)	38,271 (8270)	2985.1 (645.1)	774.8 (151.9)	60.4 (11.8)	63,897(12,469)

SE: standard error of the total.

Table 9
Comparison of urban forests in Roanoke by vacant land categories: city totals for trees' structural and functional values.

Category	Percentage tree cover (SE)	Number of trees (SE)	Carbon storage (t) (SE)	Carbon storage value (US$) (SE)	Carbon sequestration (t/yr) (SE)	Carbon removal value (US$) per yr (SE)	Structural value (US$) (SE)
Derelict	32.5 (6.7)	25,725 (6354)	12,974 (5608)	1,023,550 (442,428)	220 (62)	17,430 (4912)	20,894,595 (6,904,317)
Natural	48.2 (6.9)	26,514 (4861)	9468 (4445)	746,905 (350,654)	249 (80)	19,667 (6318)	17,675,472 (6,608,554)
Post-industrial	13.5 (6.1)	7488 (3460)	546 (263)	43,132 (20,776)	34 (16)	2719 (1279)	1,720,407 (834,790)
Transportation-related	40.6 (6.5)	28,923 (6029)	7721 (2593)	609,080 (204,551)	233 (57)	18,389 (4498)	17,505,068 (5,499,140)
Unattended with vegetation	27.7 (3.7)	121,613 (21,510)	66,025 (14,381)	5,208,723 (1,134,519)	1336 (262)	105,449 (20,679)	111,115,757 (21,684,099)

SE: standard error of the total.

minimum Diameter at Breast Height (DBH, diameter at 1.37 m from base of tree), the following variables were measured: species, DBH, total height, crown width (N–S, E–W), percentage of canopy missing and dieback, crown light exposure, and trees near buildings (distance and direction from trees). All field data were collected during the 2010 and 2013 (additional sampling of vacant lots) leaf-on season (June–July) to properly assess the tree canopies. Field data were input into the i-Tree Eco model to assess the tree structural characteristics and ecosystem services derived for each vacant land class. Details of the i-Tree Eco methods are available at the i-Tree website (www.itreetools.org) and in several publications (e.g., Nowak et al., 2003, 2008a,b).

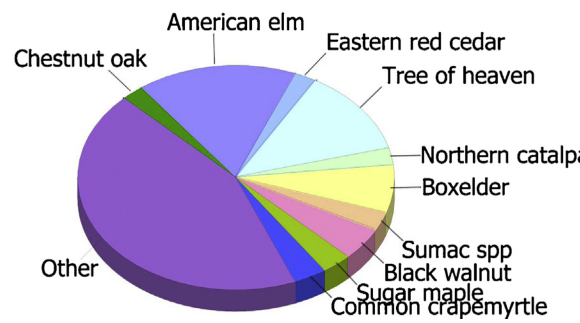

Fig. 3. Tree species growing on urban vacant land, City of Roanoke, Virginia.

Results

Tree characteristics on Roanoke's urban vacant land

The urban forest of Roanoke's vacant land has an estimated population of 210,000 trees and a tree cover of 30.6%. Trees that have diameter less than 15.2 cm constitute 40.8% of the population. The three most common species growing in this area are *Ulmus americana* (American Elm) (16.4%), *Ailanthus altissima* (Tree of Heaven) (12.3%), and *Acer negundo* (Box elder) (6.7%) (Fig. 3). The overall tree density on Roanoke's vacant land is 63.4 trees per hectare, which is the lowest of any of the land use types (Table 3). Large trees provide substantially more ecosystem services, such as improving air quality and public health, cooling the air, reducing demand for air conditioning, and supporting climate change adaptation than smaller trees (Rosenthal et al., 2008). Most trees in the study area are small with diameters less than 15.2 cm, and constitute 40.8% of the tree population (Fig. 4). However, these relatively young trees have the potential to increase in size over time. Thus they will make an increasing contribution to ecosystem services in Roanoke for years to come.

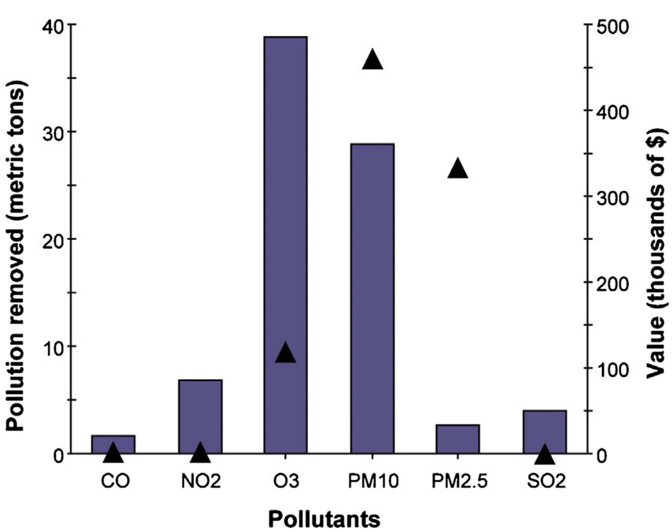

Fig. 2. Pollution removal (bars) and associated economic value (line) for trees on urban vacant land, City of Roanoke, Virginia. Pollution removal value is calculated based on the following prices: $1252 per metric ton (carbon monoxide), $3048 per metric ton (ozone), $315 per metric ton (nitrogen dioxide), $112 per metric ton (sulfur dioxide), $15,984 per metric ton (particulate matter less than 10 μm and greater than 2.5 μm), $124,499 per metric ton (particulate matter less than 2.5 μm).

Air pollution removal by urban vacant land

Air quality is a major problem in most cities. It can negatively affect human health, ecosystem health, and visibility. Trees on vacant land can help to remove air pollutants, reduce air temperature (transpiration), save energy consumption in buildings,

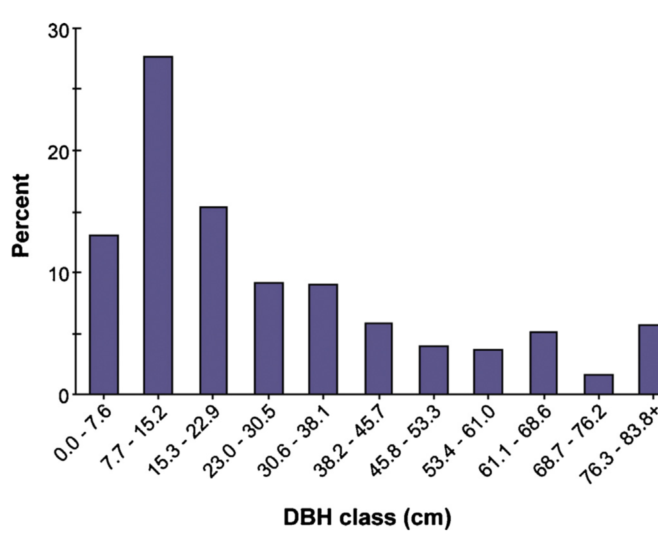

Fig. 4. Percentage of tree population by diameter class (DBH = stem diameter at 1.37 m above the ground line.

and indirectly reduce air pollution from power plants. Trees also influence ozone formation by emitting volatile organic compounds (VOCs) (Chameides et al., 1988). However, a comprehensive study suggests that urban trees, particularly low VOC emitting species, can decrease urban ozone levels in spite of their total VOC emissions, particularly through tree functions of removing air pollutant (dry deposition to plant surfaces), reducing air temperatures (transpiration), and reducing building energy and consequent power plant emission (e.g., temperature reductions; tree shade) (Cardelino and Chameides, 1990; Taha, 1996; Nowak et al., 2000). Air pollution removal estimates are derived from calculated hourly tree-canopy resistance for ozone, and sulfur and nitrogen dioxides based on a hybrid of big-leaf and multi-layer canopy deposition model (Baldocchi, 1988; Baldocchi et al., 1987). As the removal of carbon monoxide and particulate matter by vegetation is not directly related to transpiration, removal rates (deposition velocities) for these pollutants were based on average values from the literature (Bidwell and Fraser, 1972; Lovett, 1994). The estimate of the pollution removal value of trees was based on field data and current pollution and weather data (2011). As shown in Fig. 2, ozone (O_3) had the greatest pollution removal value. Overall, an estimated 83 t of air pollutants (CO, NO_2, O_3, PM10, and SO_2) were removed by trees on vacant land in Roanoke in 2011 which translates to a value of $ 916,000.

Carbon storage and sequestration

Climate change is a major issue across the world. Trees can remove carbon dioxide (CO_2) through photosynthesis in their tissue and storing carbon as biomass (Nowak et al., 2013), which can help counteract climate change. Trees also alter energy consumption by reducing carbon dioxide emission from the fossil-fuels burned by power plants (Abdollahi et al., 2000). Trees can also influence air temperatures and building energy use, and consequently alter carbon emissions from numerous urban sources (e.g., power plants) (Nowak, 1993). Thus, trees can influence local climate, carbon cycles, energy use and climate change (e.g., Abdollahi et al., 2000; Wilby and Perry, 2006; Gill et al., 2007; Nowak, 2010; Lal and Augustine, 2012). Trees on urban vacant land reduce the amount of carbon in the atmosphere by sequestering carbon in new growth every year. The amount of carbon annually sequestered increases with the size and health of the trees (Nowak et al., 2002b). To calculate current carbon storage, biomass for each tree was calculated using allometric equations from the literature and measured tree data (Nowak, 1994; Nowak et al., 2002a). Open-grown, maintained trees tend to have less biomass than predicted by forest-derived biomass equations (Nowak, 1994). To adjust for this difference, biomass results for open-grown urban trees were multiplied by 0.8 (Nowak, 1994). No adjustment was made for trees found in natural stand conditions (e.g., on vacant lands or in forest preserves). Because deciduous trees drop their leaves annually, only carbon stored in wood biomass is calculated for these trees (Nowak et al., 2008a). Total tree dry weight biomass is converted to total stored carbon by multiplying by 0.5 (Forest Products Laboratory, 1952; Chow and Rolfe, 1989).

The gross sequestration of Roanoke's urban vacant land trees is about 2090 t of carbon per year (Table 3), with an associated value of $164,000. Net carbon sequestration (accounting for losses from carbon dioxide release through tree decomposition) in urban vacant land is about 1960 t annually, which is relatively high compared to other land uses (Table 3).

Carbon storage and carbon sequestration values are based on $78.5 per metric ton of carbon (Interagency Working Group on Social Cost of Carbon United States Government, 2010). The carbon storage in the urban vacant land is about 97,500 t, with an associated value of $7.6 million, which is very high relative to other land uses (Table 3). Of the species sampled, American elm stores and sequesters the most carbon (approximately 19% of the total carbon store and 18.8% of all sequestered carbon) (Fig. 5) The overall tree density on vacant land in the city is 63.4 trees per ha, which is the lowest relative to other land uses (Table 6). However, the gross sequestration of vacant land in Roanoke trees is about 630.7 kg of carbon per ha annually, so trees on urban vacant land are estimated to accumulate 29,410 kg of carbon per ha, which is higher than in the industrial land use (Table 6).

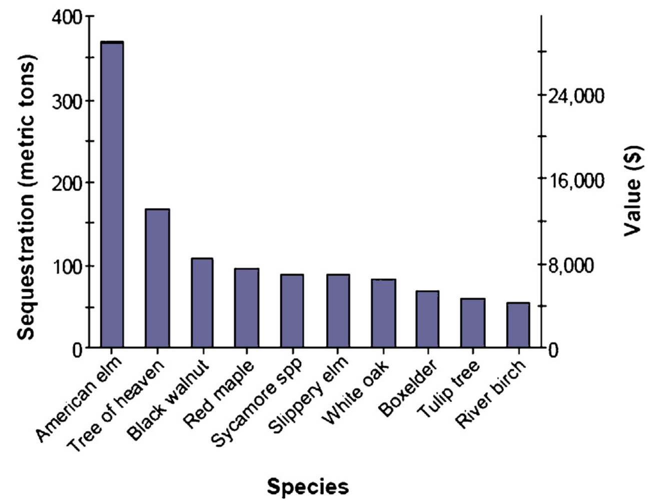

Fig. 5. Carbon sequestration and value for species with greatest overall carbon sequestration in Roanoke's vacant land.

Among the categories of urban vacant land, the gross carbon sequestration of trees on unattended sites with vegetation is about 1340 t per year and net carbon sequestration is about 1240 t annually, which is highest relative to other types (Table 9). The carbon storage on unattended sites with vegetation is about 66,000 t, which is highest relative to other types (Table 9). Unattended sites with vegetation make up a major percentage of the urban vacant land and thus represent a significant resource that can provide ecosystem services of carbon storage and sequestration. However, the highest tree densities occur in natural sites, followed by unattended sites with vegetation and derelict sites (Table 8). The carbon sequestration in the unattended sites with vegetation is about 774.8 kg of carbon per ha annually and the accumulated carbon storage is about 38,271 kg of carbon per ha, which is high relative to other vacant land types (Table 8).

Urban vacant land and building energy use

Trees on urban vacant land affect energy consumption by shading buildings, providing evaporative cooling, and blocking winter winds, thus reducing building energy consumption in the summer months, and either increasing or decreasing building energy use in the winter months, depending on the location of trees around the building. Estimates of tree effects on energy use are based on field measurements of tree distance and direction to space conditioned residential buildings (McPherson and Simpson, 1999). Using the tree size, distance, direction to building, climate region, leaf type (deciduous or evergreen), and percent cover of buildings and trees on the plot, the amount of carbon avoided from power plants as a result of the presence of trees is calculated (Nowak et al., 2008a). As a result of tree energy effects, the amount of carbon avoided are categorized into the amount of MWh (cooling) and MBtus and MWh (heating) (Nowak et al., 2008a). Default energy effects per tree are created based on each climate region, vintage building types (period of construction), tree size class, distance from building, energy use (heating or cooling), and leaf type (deciduous or evergreen) depending on energy effect of the tree (tree shade, windbreak effects, and local climate effect) (McPherson and Simpson, 1999). Default shading and climate effect values are applied to all trees; heating windbreak energy effects are assigned to each evergreen tree (Nowak et al., 2008a). Because shading effect default values are given for only one vintage building type (post-1980), vintage adjustment factors (McPherson and Simpson, 1999) are applied to obtain shading effects values for all other vintage types (Nowak et al., 2008a). To calculate the monetary value of energy saving, local or custom prices per MWH or MBTU are utilized. Based on state-wide energy costs for Virginia ($106.1 per MWH and $12.26 per MBTU), the trees growing on urban vacant land in Roanoke reduced energy consumption for residential buildings by around $211,000 annually (Tables 4 and 5). Trees on vacant land also reduced the amount of carbon released by fossil-fuel based power plants (a reduction of 358 t), with an associated value of $28,103 annually.

Structural and functional values of urban vacant land

Roanoke's vacant lands represent structural assets with economic value, just as other infrastructure in the city. This value is based on the price of replacing existing trees with other similar types of trees. In addition, they also have functional ecosystem service values (both positive and negative) based on the functions the trees perform annually. The structural values applied here were based on valuation procedures laid down by the Council of Tree and Landscape Appraisers (CTLA, 1992), which uses tree species, diameter, condition, and location information (Nowak et al., 2002b). The number and size of healthy trees contribute to the increased structural and functional value of an urban forest (Nowak et al., 2002b). The structural value of Roanoke's vacant land trees is $169 million with a carbon storage value of $7.6 million. The annual functional values of Roanoke's vacant land trees are: carbon sequestration ($164 thousand); pollution removal ($916 thousand); lower energy costs and carbon emission reduction ($239 thousand).

Discussion

The results of the comparison of urban forests effects and values by land use suggest that residential land use offers the greatest current ecosystem benefits on a per ha basis. However, city totals for carbon storage and carbon removal on urban vacant land in Roanoke is high relative to other land uses (Table 6). Trees on urban vacant land that are growing in natural stand condition have more large trees with low density and a higher percent cover. They are likely large on average and thus have more above-ground biomass (carbon storage) than open-grown, maintained trees located on other types of land. When comparing biomass equations for trees of the same DBH, biomass results for open-grown urban trees were multiplied by a factor 0.8 (Nowak, 1994), but no adjustment was necessary for trees found in more natural stand conditions (i.e. on vacant land or in forest preserves).

Among the categories of urban vacant land, the "unattended sites with vegetation" have a particularly high value for carbon storage, carbon sequestration, and structural value relative to other types (Tables 8 and 9). "Unattended sites with vegetation" make up a major percentage of urban vacant land, with many large trees in natural stand conditions. "Unattended sites with vegetation" can thus be one of the most effective land use types, providing ecosystem services in a city.

The comparison of the effects and values of urban forest on different vacant land categories indicates that "unattended sites with vegetation" could be the best vacant land type at providing ecosystem services for the city. This suggests that the high ecosystem values of "unattended sites with vegetation" could be acknowledged and protected. Thus, if these sites are developed, it could be done in a manner that protects their current ecosystem values. Less sensitive "post-industrial" sites that have lower ecosystem values could be given priority for development to different types of land use (e.g. housing, commercial, industry and green re-use options) that have the greatest potential for increasing ecosystem benefits. Those "post-industrial" sites with historical significance that have remediation potential could be developed in a manner that preserves their historical value with a historically appropriate use. If other natural sites and transportation-related sites have low ecosystem values and are not threatened by development, their current low ecosystem values have the potential to be enhanced through proper management.

Reliability and validity

Urban forest structure is complex and it is often difficult to assess the relevant tree attributes and to quantify the ecosystem services of trees. The i-Tree analysis is based on sampling the entire study area and provides a reasonable estimate of the entire population and the ecosystem service contribution of different tree species (Nowak et al., 2003). The main advantage to using the i-Tree Eco model is to estimate urban forest functions, based on locally measured field data and peer-reviewed literature procedures (Nowak et al., 2008a). However, the i-Tree Eco model has limitations. Ecosystem function estimates require accurate field data collection (Nowak et al., 2008a). If field data is not accurately collected then the accuracy of estimate of the entire population structure and ecosystem benefits of individual tree species are thrown into question. Also, the model only estimates current urban forest structure and functions, with only a one-year estimate of growth and carbon sequestration. Urban forest conditions are dynamic and changeable, so urban forest should be monitored through time to help understand how urban forests are changing through time.

Conclusions

The purpose of this study was to demonstrate how urban vacant land functions as green infrastructure that provides ecosystem services and values to society. Urban vacant land is a key component of Roanoke's green infrastructure, providing ecosystem services, such as air pollution removal, carbon sequestration and storage, energy saving, and the structural value of trees on vacant land. Understanding an urban forest's structure, function and value can promote decision-making that will improve human health and environmental quality. This study captured the current structure of Roanoke's urban forest growing on vacant land and quantified a subset of the ecosystem functions and economic values it provides to the Roanoke city's residents. By capturing carbon in new growth each year, trees on urban vacant land in Roanoke store 97,500 t ($7.6 million) of carbon, adding another 2090 t ($164,000/year) annually, which is relatively high compared to other types of land in Roanoke. Vacant land is an important component of Roanoke's green infrastructure, removing a significant amount of air pollution from the city's environment. The trees on Roanoke's vacant land also remove an estimated 83 t ($916,000/year) of air pollutants per year and reduce energy-related costs from residential buildings by $211,000 annually, with an accompanying reduction in fossil-fuel power plant emissions of an additional $28,100 (a reduction of 358 t of carbon emissions).

These results suggest that urban vacant land is a vital resource and a useful component to Roanoke's green infrastructure that provides significant benefits and could be managed to increase its effectiveness. The i-Tree Eco model, used in this study, seems to be a valuable tool in assessing the ecosystem services of the urban vacant land in Roanoke and has potential to be used in setting priorities and in creating planning and design guidelines for future development or preservation of vacant lands. It also seems reasonable that the methodology applied to assess ecosystem services in this study could also be a valuable tool in assessing ecosystem services of vacant land in other urban contexts. Although vacant land types are now beginning to receive more attention, as yet there are no strategic plans for utilizing them more effectively. This study suggests new ways to understanding and using these spaces in terms of their ecological value. An analysis of the structure, function, and economic benefits of urban vacant land can be a useful reference for local authorities, landowners and regeneration professionals, as well as providing a rationale for a change in current policies and approaches to planning for urban vacant land.

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