Environmental Pollution 178 (2013) 229–236

Contents lists available at SciVerse ScienceDirect

Environmental Pollution

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

Carbon storage and sequestration by trees in urban and community areas of the United States

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ARTICLE INFO

Article history:
Received 17 December 2012
Received in revised form
10 March 2013
Accepted 12 March 2013

Keywords:
Ecosystem services
Global climate change
Urban forestry
Tree cover
Forest inventory

ABSTRACT

Carbon storage and sequestration by urban trees in the United States was quantified to assess the magnitude and role of urban forests in relation to climate change. Urban tree field data from 28 cities and 6 states were used to determine the average carbon density per unit of tree cover. These data were applied to statewide urban tree cover measurements to determine total urban forest carbon storage and annual sequestration by state and nationally. Urban whole tree carbon storage densities average 7.69 kg C m^{-2} of tree cover and sequestration densities average 0.28 kg C m^{-2} of tree cover per year. Total tree carbon storage in U.S. urban areas (c. 2005) is estimated at 643 million tonnes ($50.5 billion value; 95% CI = 597 million and 690 million tonnes) and annual sequestration is estimated at 25.6 million tonnes ($2.0 billion value; 95% CI = 23.7 million to 27.4 million tonnes).

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1. Introduction

Urban trees and forests affect climate change, but are often disregarded because their ecosystem services are not well-understood or quantified. Trees act as a sink for carbon dioxide (CO_2) by fixing carbon during photosynthesis and storing carbon as biomass. The net long-term CO_2 source/sink dynamics of forests change through time as trees grow, die, and decay. Human influences on forests (e.g., management) can further affect CO_2 source/sink dynamics of forests through such factors as fossil fuel emissions and harvesting/utilization of biomass (Nowak et al., 2002). Trees in urban areas (i.e., urban forests) currently store carbon, which can be emitted back to the atmosphere after tree death, and sequester carbon as they grow. Urban trees also influence air temperatures and building energy use, and consequently alter carbon emissions from numerous urban sources (e.g., power plants) (Nowak, 1993). Thus, urban trees 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).

Urban areas in the conterminous United States have increased from 2.5% of the U.S. land area (19.5 million ha) in 1990 to 3.1% (24.0 million ha) in 2000, an increase in area the size of Vermont and New Hampshire combined (Nowak et al., 2005). If the growth patterns of the 1990s continue, urban land is projected to reach 8.1% by 2050, an increase greater than the area of Montana (Nowak and Walton, 2005). Within these urban areas, tree cover (circa 2005) is estimated at 35.0% (Nowak and Greenfield, 2012b).

Given the growing expanse of urban areas, trees within these areas have the potential to store and annually sequester substantial amounts of carbon. Understanding this national carbon effect can aid in preparing annual inventories of greenhouse gas (GHG) emissions and sinks (U.S. EPA, 2010; Heath et al., 2011). Numerous cities in the United States have analyzed carbon storage and sequestration of the trees and forests among various land-use types using the i-Tree methodology (www.itreetools.org) (Table 1) or other methods (Hutyra et al., 2011; Raciti et al., 2012). In addition, cities outside the United States have also analyzed carbon storage by urban vegetation (e.g., Brack, 2002; Jo, 2002; Chaparro and Terradas, 2009; Zhao et al., 2010; Davies et al., 2011; Strohbach and Haase, 2012).

In the past, city analyses of carbon storage and sequestration have been extrapolated to national estimates using limited data. The first estimate of national carbon storage by urban trees (between 350 and 750 million tonnes; Nowak, 1993) was based on an extrapolation of carbon data from one city (Oakland, CA) and tree cover data from various U.S. cities (e.g., Nowak et al., 1996). A later assessment, which included data from a second city (Chicago, IL), estimated national carbon storage by urban trees between 600 and

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0269-7491/$ – see front matter Published by Elsevier Ltd.
http://dx.doi.org/10.1016/j.envpol.2013.03.019

Table 1
City and state data used for carbon estimates. Plot size = 0.04 ha unless noted otherwise.

City/State	Year	No. plots	Data collection group	Reference
Arlington, TX[a]	2009	233	City of Arlington	
Atlanta, GA[a]	1997	205	ACRT, Inc.	
Baltimore, MD[a]	2009	195	US Forest Service (USFS)	
Boston, MA[a]	1996	217	ACRT, Inc.	
Casper, WY	2006	234	City of Casper	Nowak et al., 2006c
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
Golden, CO[a]	2007	115	Inst. of Environmental Solutions	
Hartford, CT[a]	2007	200	Knox Parks Foundation	
Jersey City, NJ[a]	1998	220	NJ Dept. Env. Protection	
Lincoln, NE[a]	2008/09	178	Nebraska Forest Service	
Los Angeles, CA	2007/08	348	USFS, Univ. Cal., Riverside	Nowak et al., 2011
Milwaukee, WI[a]	2008	216	City of Milwaukee	
Minneapolis, MN	2004	110	Davey Resource Group	Nowak et al., 2006a
Moorestown, NJ[a]	2000	206	NJ Dept. Env. Protection	
Morgantown, WV	2004	136	West Virginia University	Nowak et al., 2012c
New York, NY	1996	206	ACRT, Inc.	Nowak et al., 2007d
Oakland, CA[b]	1989	1350	USFS	Nowak, 1991
Omaha, NE[a]	2008/09	189	Nebraska Forest Service	
Philadelphia, PA	1996	210	ACRT, Inc.	Nowak et al., 2007b
Roanoke, VA[a]	2010	160	Virginia Tech	
Sacramento, CA[a]	2007	300	Sacramento Tree Foundation	
San Francisco, CA	2004	194	San Francisco Dept. of the Environment	Nowak et al., 2007c
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[a]	2009	198	USFS	
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	
Indiana[c]	2002	32	State Forestry personnel, USFS	Nowak et al., 2007a
Kansas[c]	2008/09	188	State Forestry personnel	Nowak et al., 2012b
Nebraska[c]	2008/09	200	State Forestry personnel	Nowak et al., 2012b
North Dakota[c]	2008/09	299	State Forestry personnel	Nowak et al., 2012b
South Dakota[c]	2008/09	200	State Forestry personnel	Nowak et al., 2012b
Tennessee[c]	2005–09	255	State Forestry personnel, USFS	Nowak et al., 2012a

[a] Unpublished data.
[b] Variable plot size.
[c] 0.067 ha plot size.

900 million tonnes (Nowak, 1994). The most recent analysis, which used data from 10 cities and urban tree cover estimates (Nowak et al., 2001) derived from 1991 Advanced Very High Resolution Radiometer (AVHRR) data, estimated national carbon storage by urban forests at 700 million tonnes (range: 335 million–980 million tonnes) (Nowak and Crane, 2002). Above and below ground biomass in all forestland across the United States, which includes forest stands within urban areas, stored approximately 20.2 billion tonnes of carbon in 2008 (Heath et al., 2011).

The purpose of this paper is to update the national urban tree carbon storage and sequestration estimates using urban field data from 28 cities and 6 states and newer estimates of urban land area and urban tree cover. This new assessment produces more refined statistical estimates of the uncertainty of the national estimates and investigates the overlap between urban forest carbon estimates and U.S. forestland carbon estimates. These carbon storage and sequestration estimates provide better, more up-to-date information for national carbon estimates (e.g., IPCC, 2006) and can be used to help assess the actual and potential role of urban forests in reducing atmospheric CO_2.

2. Materials and methods

The methods of this study used: (a) field data and model analyses from several cities and states to estimate total carbon storage and sequestration in these areas, (b) photo-interpretation of tree cover in these areas to determine carbon densities per unit of tree cover, and (c) photo-interpretation of tree cover in urban and community areas in each U.S. state to estimate statewide urban forest carbon values. As forest values from the national Forest Inventory and Analysis (FIA) program (hereby referred to as "forestland") overlap with urban estimates (because there are forest stands within urban areas), analysis of forestland plots within urban areas was conducted to determine the overlap between national forestland carbon estimates and national urban forest carbon estimates.

The definition of urban is based on population density using the U.S. Census Bureau's (2007) 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 or designated places (U.S. Census Bureau, 2007). Community areas may include all, some, or no urban land within their boundaries, but city areas are often dominated by urban land. 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 2000 occupied 3.1% (24.0 million ha) of the conterminous United States (Nowak et al., 2005), while urban/community land occupied 5.3% (40.4 million ha) (Nowak and Greenfield, 2012b).

Forestlands at the national scale, as defined by the U.S. Department of Agriculture (USDA) Forest Service Forest Inventory and Analysis (FIA) program, are areas at least 0.4 ha (1 ac) in size, at least 36.6 m (120 feet) wide, and at least 10% stocked. To be measured as "forestland", plots must also not be affected by a land use that prevents normal tree regeneration and succession such as mowing, intensive grazing, or recreational activities (USDA Forest Service, 2010). Forestlands are estimated to cover 304 million ha in the United States (Smith et al., 2009). These forestlands include some areas that fall within urban and community areas.

2.1. Field data

Field data were used to determine the entire urban forest structure (e.g., tree species composition and number of trees on all land uses) for 28 U.S. cities and urban areas in 6 states (Table 1). These cities were sampled based on methods developed by the USDA Forest Service for various urban forest research projects (e.g., Nowak