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Carbon storage and sequestration by urban trees in the USA

David J. Nowak*, Daniel E. Crane

USDA Forest Service, Northeastern Research Station, 5 Moon Library, SUNY-ESF, Syracuse, NY 13210, USA

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"Capsule": *Urban trees currently store 700 million tons of carbon, with an annual sequestration rate of 22.8 million tons.*

Abstract

Based on field data from 10 USA cities and national urban tree cover data, it is estimated that urban trees in the coterminous USA currently store 700 million tonnes of carbon ($14,300 million value) with a gross carbon sequestration rate of 22.8 million tC/yr ($460 million/year). Carbon storage within cities ranges from 1.2 million tC in New York, NY, to 19,300 tC in Jersey City, NJ. Regions with the greatest proportion of urban land are the Northeast (8.5%) and the southeast (7.1%). Urban forests in the north central, northeast, south central and southeast regions of the USA store and sequester the most carbon, with average carbon storage per hectare greatest in southeast, north central, northeast and Pacific northwest regions, respectively. The national average urban forest carbon storage density is 25.1 tC/ha, compared with 53.5 tC/ha in forest stands. These data can be used to help assess the actual and potential role of urban forests in reducing atmospheric carbon dioxide, a dominant greenhouse gas. Published by Elsevier Science Ltd.

Keywords: Global climate change; Carbon dioxide; Urban forestry; Carbon storage; Carbon sequestration

1. Introduction

Increasing levels of atmospheric carbon dioxide (CO_2) and other "greenhouse" gases [i.e. methane (CH_4), chlorofluorocarbons, nitrous oxide (N_2O), and tropospheric ozone (O_3)] are thought by many to be contributing to an increase in atmospheric temperatures by the trapping of certain wavelengths of radiation in the atmosphere. Some chemicals though, may be reducing atmospheric temperatures (e.g. sulfur dioxide, particulate matter, stratospheric ozone; Graedel and Crutzen, 1989; Hamburg et al., 1997). Globally averaged air temperature at the Earth's surface has increased between 0.3 and 0.6 °C since the late 1800s. A current estimate of the expected rise in average surface air temperature globally is between 1 and 3.5 °C by the year 2100 (Hamburg et al., 1997). Global warming is implicated in the recent discovery that floating ice over the Arctic Ocean has thinned from an average thickness of 10 feet in 1950 to <6 feet in the late 1990s, and a large expanse of ice-free water that has opened up at the North Pole in 2000 (Appenzeller, 2000; BBC News, 2000). As urban areas already exhibit climatic differences compared with rural environments, due in part to multiple artificial surfaces and high levels of fossil fuel combustion, climate change impacts may be exacerbated in these areas (Nowak, 2000).

Carbon dioxide is a dominant greenhouse gas. Increased atmospheric CO_2 is attributable mostly to fossil fuel combustion (about 80–85%) and deforestation worldwide (Schneider, 1989; Hamburg et al., 1997). Atmospheric carbon is estimated to be increasing by approximately 2600 million metric tons annually (Sedjo, 1989).

Trees act as a sink for CO_2 by fixing carbon during photosynthesis and storing excess carbon as biomass. The net long-term CO_2 source/sink dynamics of forests change through time as trees grow, die, and decay. In addition, 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. However, increasing the number of trees might potentially slow the accumulation of atmospheric carbon (e.g. Moulton and Richards, 1990).

Urban areas in the lower 48 United States have doubled in area between 1969 and 1994, and currently occupy 3.5% of the land base with an average tree cover of 27.1% (Dwyer et al., 2000; Nowak et al., 2001b).

* Corresponding author. Tel. +1-315-448-3212; fax: +1-315-448-3216.

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

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Though urban areas continue to expand, and urban forests play a significant role in environmental quality and human health, relatively little is known about this resource. As urban forests both sequester CO_2, and affect the emission of CO_2 from urban areas, urban forests can play a critical role in helping combat increasing levels of atmospheric carbon dioxide.

The first estimate of national carbon storage by urban trees (between 350 and 750 million tonnes; Nowak, 1993a) was based on an extrapolation of carbon data from one city (Oakland, CA) and tree cover data from various USA 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 at between 600 and 900 million tonnes (Nowak, 1994). The purpose of this paper is to update the national urban tree carbon storage estimate based on data from eight new cities and national urban tree cover data. This paper will also include estimates of carbon storage and sequestration by urban trees at the national, regional and state level. These data can be used to help assess the actual and potential role of urban forests in reducing atmospheric CO_2.

2. Methods

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) of 10 cities: Atlanta, GA; Baltimore, MD; Boston, MA; Chicago, IL (Nowak, 1994); Jersey City, NJ; New York, NY; Oakland, CA (Nowak, 1993a, 1993b); Philadelphia, PA; Sacramento, CA (McPherson, 1998a); and Syracuse, NY. These cities were sampled based on methods developed by the USDA Forest Service for various urban forest research projects (e.g. Nowak and Crane, 2000). These data comprise the entire set of comprehensive USA urban forest structure and carbon data available.

The unpublished city tree data (Atlanta, Baltimore, Boston, Jersey City, New York, Philadelphia, and Syracuse) were collected between 1996 and 1999 and analyzed using the Urban Forest Effects (UFORE) model based on a stratified random sample of approximately 200 0.04-ha plots per city (Nowak and Crane, 2000). Data collection included location, species, stem diameter at 1.37 m above the ground (dbh), tree and crown height, crown width, and canopy condition.

2.2. Biomass equations

Biomass for each measured tree was calculated using allometric equations from the literature (see Nowak, 1994; Nowak et al., 2001a). Equations that predict above-ground biomass were converted to whole tree biomass based on root-to-shoot ratio of 0.26 (Cairns et al., 1997).

Equations that compute fresh-weight biomass were multiplied by species- or genus-specific-conversion factors to yield dry-weight biomass. These conversion factors, derived from average moisture contents of species given in the literature, averaged 0.48 for conifers and 0.56 for hardwoods (see Nowak, 1994).

Open-grown, maintained trees tend to have less above-ground biomass than predicted by forest-derived biomass equations for trees of the same diameter at breast height (Nowak, 1994). To adjust for this difference, biomass results for urban trees were multiplied by a factor 0.8 (Nowak, 1994). No adjustment was made for trees found in more natural stand conditions (e.g. on vacant lands or in forest preserves). As deciduous trees drop their leaves annually, only carbon stored in wood biomass was calculated for these trees. Total tree dry-weight biomass was converted to total stored carbon by multiplying by 0.5.

The multiple equations used for individual species were combined together to produce one predictive equation for a wide range of diameters for individual species. The process of combining the individual formulas (with limited diameter ranges) into one, more general species formula, produced results that were typically within 2% of the original estimates for total carbon storage of the urban forest (i.e. the estimates using the multiple equations). Formulas were combined to prevent disjointed sequestration estimates that can occur when calculations switch between individual biomass equations.

If no allometric equation could be found for an individual species, the average results from equations of the same genus was used. If no genus equations were found, the average results from all broadleaf or conifer equations was used.

Standard errors are given for carbon report sampling error, rather than error of estimation. Estimation error is unknown and likely larger than the reported sampling error. Estimation error also includes the uncertainty of using biomass equations and conversion factors, which may be large, as well as measurement error, which is typically very small.

2.3. Urban tree growth and carbon sequestration

Average diameter growth from the appropriate land use and diameter class was added to the existing tree diameter (year x) to estimate tree diameter in year $x+1$. For trees in forest stands, average dbh growth was estimated as 0.38 cm/year (Smith and Shifley, 1984); for trees on land uses with a park-like structure (e.g. parks, cemeteries, golf courses), average dbh growth was 0.61 cm/year (deVries, 1987); for more open-grown trees, dbh class specific growth rates were used based on

Nowak (1994). Average height growth was calculated based on formulas from Fleming (1988) and the specific dbh growth factor used for the tree.

Growth rates were adjusted based on tree condition. For trees with fair to excellent condition, growth rates were multiplied by 1 (no adjustment); poor condition tree growth rates were multiplied by 0.76; critical trees by 0.42; dying trees by 0.15; and dead trees by 0. Adjustment factors were proportional to percent crown dieback (i.e. the greater the crown dieback, the slower the growth rate) and the assumption that less than 25% crown dieback had a limited effect on dbh growth rates. The difference in estimates of carbon storage between year x and year $x+1$ is the gross amount of carbon sequestered annually.

Tree death leads to the eventual release of stored carbon. To estimate the net amount of carbon sequestered by the urban trees, carbon emissions due to decomposition after tree death must be considered. To calculate the potential release of carbon due to tree death and decomposition, estimates of annual mortality rates by condition class were derived from a study of street-tree mortality (Nowak, 1986). Annual mortality was estimated as 1.92% for trees 0–3 inches in the good-excellent condition class; 1.46% for trees >3 inches in the good-excellent condition class; 3.32 % for trees in fair condition; poor condition = 8.86%; critical condition = 13.08%; dying = 50%; and dead = 100%.

Two types of decomposition rates were used: (1) rapid release for above-ground biomass of trees that are projected to be removed; and (2) delayed release for standing dead trees and tree roots of removed trees. Trees that are removed from urban areas are not normally developed into wood products for long-term carbon storage (i.e. removed trees are often burned or mulched), therefore they will most likely release their carbon relatively soon after removal.

If dead trees are not removed annually, they have an increased probability of being measured in the tree sample and decomposition rates must reflect this difference. All trees on vacant, transportation and agriculture land uses, and 50% of trees in parks, were assumed to be left standing (i.e. not removed) as these trees are likely within forest stands and/or away from intensively maintained sites. These trees were assumed to decompose over a period of 20 years.[1] Trees on all other land uses are assumed to be removed within 1 year of tree death. For removed trees, above-ground biomass was mulched with a decomposition rate of 3 years;[2] below-ground biomass was assumed to decompose in 20 years.

Estimates of carbon emissions due to decomposition were based on the probability of the tree dying within the next year and the probability of the tree being removed using the formula:

$$\text{Emission} = C \times M_c \times \sum p_i((D_{\text{remove}}) + (D_{\text{stand}}))$$
$$D_{\text{remove}} = (p_{ab}/y_i)(1/d_m) + ((1 - p_{ab})/y_i)(1/d_r)$$
$$D_{\text{stand}} = ((y_i - 1)/y_i)(1/d_r)$$

where Emission = individual tree contribution to carbon emissions; C = carbon storage in the next year; M_c = probability of mortality based on condition class; i = decomposition class (based on number of years left standing before removal); p_i = proportion of the land use tree population in decomposition class i; p_{ab} = proportion of tree biomass above ground; y_i = number of years left standing before removal ($y_i \rightarrow \infty$ for dead trees that will never be cut down (natural decomposition)); d_m = decomposition rates for mulched above-ground biomass (3 years); and d_r = decomposition rate for standing trees and tree roots (20 years).

Individual tree estimates of mortality probability and decomposition rates were aggregated upward to yield total estimates of decomposition for the tree population. The amount of carbon sequestered due to tree growth was reduced by the amount lost due to tree mortality to estimate the net carbon sequestration rate.

2.4. State and regional level estimates

Data for individual trees in each city were used to determine the total carbon storage and sequestration for the city. To estimate the carbon values of urban trees nationally, total carbon storage and sequestration value of each city was divided by total city tree cover (m^2) to determine average carbon density value per unit tree cover (kgC/m^2 cover). The median standardized carbon value (kgC/m^2 cover) was multiplied by total urban tree cover in the conterminous USA (Dwyer et al., 2000; Nowak et al., 2001) to estimate the national carbon totals for urban trees. Tree cover estimates were based on 1991 advanced very high resolution radiometer (AVHRR) data (Zhu, 1994).

State urban tree cover values were multiplied by the national median standardized carbon values to estimate the carbon totals for each state. State carbon totals were combined to reveal variation among eight regions of the country:

California: CA
Great Plains: KS, NE, ND, SD
North Central: IN, IL, IA, MN, MI, MO, OH, WI
Northeast: CN, DE, ME, MD, MA, NH, NJ, NY, PA, RI, VT, WV

[1] Data on tree decomposition rates is limited. However, using decomposition rates from 10 to 50 years had little effect on overall net decomposition within a single year.

[2] Although no mulch decomposition studies could be found, studies on decomposition reveal that 37–56% of carbon in tree roots and 48–67% of carbon in twigs is released within the first 3 years (Scheu and Schauermann, 1994).

Table 1
Estimated carbon storage, gross and net annual sequestration, number of trees, and percent tree cover for ten U.S. cities

City	Storage (tC)		Annual sequestration Gross (tC/yr)		Annual sequestration Net (tC/yr)		No. Trees ($\times 10^3$)	
	Total	SE	Total	SE	Total	SE	Total	SE
New York, NY	1,225,200	150,500	38,400	4,300	20,800	4,500	5,212	719
Atlanta, GA	1,220,200	91,900	42,100	2,800	32,200	4,500	9,415	749
Sacramento, CA[a]	1,107,300	532,600	20,200	4,400	na	na	1,733	350
Chicago, IL[b]	854,800	129,100	40,100	4,900	na	na	4,128	634
Baltimore, MD	528,700	66,100	14,800	1,700	10,800	1,500	2,835	605
Philadelphia, PA	481,000	48,400	14,600	1,500	10,700	1,300	2,113	211
Boston, MA	289,800	36,700	9,500	900	6,900	900	1,183	109
Syracuse, NY	148,300	16,200	4,700	400	3,500	400	891	125
Oakland, CA[c]	145,800	4,900	na	na	na	na	1,588	51
Jersey City, NJ	19,300	2,600	800	90	600	100	136	22

SE = Standard error na = not analysed.
[a] McPherson (1998).
[b] Nowak (1994).
[c] Nowak (1993).

Pacific Northwest: OR, WA
Rocky Mountains: AZ, CO, ID, MT, NV, NM, UT, WY
South Central: AL, AR, KY, LA, MS, OK, TN, TX
Southeast: FL, GA, NC, SC, VA

To estimate monetary value associated with urban tree carbon storage and sequestration, carbon values were multiplied by \$20.3/tC based on the estimated marginal social costs of carbon dioxide emissions (Fankhauser, 1994).

3. Results and discussion

Carbon storage in individual cities varies between 1.2 million tonnes in New York to 19,300 t in Jersey City (Table 1). Gross sequestration rates ranged from 42,100 tC/year in Atlanta to 800 tC/year in Jersey City. Total carbon storage and sequestration within cities generally increases with increased urban tree cover (city area multiplied by percent of tree cover) and increased proportion of large and/or healthy trees in the population. Large healthy trees greater than 77 cm in diameter sequester approximately 90 times more carbon than small healthy trees less than 8 cm in diameter (Nowak, 1994). Large trees also store approximately 1000 times more carbon than small trees (Nowak, 1994). Moreover, large trees with relatively long life spans will generally have the greatest overall positive effect on carbon dioxide as fossil fuel carbon emissions resulting from tree planting and removal will happen less frequently.[3]

3.1. Factors affecting carbon storage and sequestration

Net sequestration rates were highest in Atlanta (32,200 tC/year) and lowest in Jersey City (600 tC/year; Table 1). Net sequestration rates were generally around 75% of the gross carbon sequestration rate. However, in New York City, net carbon sequestration was only 54% of the gross sequestration rate. This difference was due to the relative high proportion of dead trees and large diameter trees in New York's urban forest. Estimates of net sequestration are approximate based on tree conditions, sizes, and estimated mortality, but give a general indication of the state of net sequestration in a city. Net annual carbon sequestration in forests is positive for growing forests, but sequestration rates will diminish through time as the forest matures, and can become negative during periods of forest decline and/or loss when carbon emissions from dead trees (e.g. decomposition, fire) exceed carbon uptake by live trees.

Carbon storage per hectare ranged from 46,900 t/ha in Sacramento to 5000 t/ha in Jersey City (Table 2). Total carbon storage per hectare of tree cover was also highest in Sacramento (36.1 kgC/m^2 cover) and lowest in Jersey City (4.4 kgC/m^2 cover) with a median value of 9.25 kgC/m^2 cover. Two dominant factors that affect carbon storage density (tC/ha) are tree density (trees/ha) and diameter distribution. Carbon densities will tend to increase with tree density and/or increased proportion of large diameter trees. Sacramento's urban forest, which has only 13% tree cover and 73 trees/ha has a very high carbon density estimate (46.9 tC/ha; 36.1 kgC/m^2 cover) relative to other cities sampled and the average carbon density for trees in forest stands (53.5 tC/ha; 5.3 kgC/m^2 cover—conservative estimate assuming 100% tree canopy cover; Birdsey and Heath, 1995). One

[3] Nowak, D.J., Stevens, J.C., Sisinni, S.M., and Luley, C.J. in review. Effects of urban tree management and species selection on atmospheric carbon dioxide. J. Arboric.

Table 2
Estimated carbon storage per hectare, gross and net annual sequestration per hectare, tree density, and standardized carbon density per hectare of tree cover for ten U.S. cities

	Annual sequestration								Carbon density (C / m^2 cover)					
	Storage (kgC/ha)		Gross (kgC/ha/yr)		Net (kg/ha/yr)		Density (trees/ha)		Storage (kg)		Gross Seq. (kg/yr)		Net Seq. (kg/yr)	
City	Tot.	SE	Tot.	SE	Tot.	SE	Avg	SE	Tot.	SE	Tot.	SE	Tot.	SE
Sacramento, CA[a]	46,910	22,640	850	190	na	na	73	15	36.1	17.4	0.66	0.14	na	na
Atlanta, GA	35,740	2,690	1,230	80	940	130	276	22	9.7	0.7	0.34	0.02	0.26	0.04
Baltimore, MD	25,280	3,160	710	80	520	70	136	29	10.0	1.3	0.28	0.03	0.20	0.03
Syracuse, NY	22,820	2,490	730	60	540	70	137	19	9.4	1.0	0.30	0.03	0.22	0.03
Boston, MA	20,300	2,570	670	60	490	60	83	8	9.1	1.1	0.30	0.03	0.22	0.03
New York, NY	15,330	1,890	480	50	260	60	65	9	7.3	0.9	0.23	0.03	0.12	0.03
Chicago, IL[b]	14,190	2,140	670[c]	80	na	na	68	10	12.9	1.9	0.61[c]	0.07	na	na
Philadelphia, PA	14,090	1,420	430	40	310	40	62	6	9.0	0.9	0.27	0.03	0.20	0.02
Oakland, CA[d]	11,010	370	na	na	na	na	120	4	5.2	0.2	na	na	na	na
Jersey City, NJ	5,020	680	210	20	150	30	36	6	4.4	0.6	0.18	0.02	0.13	0.03

Tot. = total; SE = Standard error; Avg = average, na = not analyzed.
[a] McPherson (1998).
[b] Nowak (1994).
[c] Tree growth and sequestration are relatively high as growth rate in this estimate were not effected by tree condition (i.e., all trees accumulated carbon based on average healthy tree growth rates).

possible reason for the very high carbon density per unit of canopy cover in Sacramento's urban forest is an unusually large diameter structure with approximately 10% of its trees greater than 76 cm dbh (McPherson, 1998b). Other urban forest populations typically have around 2% of its tree population greater than 76.2 cm dbh. Oakland's urban forest, which has a relatively low carbon storage compared to cities with comparable tree densities, had approximately 0.8% of its tree population greater than 76.2 cm dbh (Nowak, 1993b).

Another possible reason for the very high estimates in Sacramento may be an artifact of the sample design or size, as standard errors for Sacramento are relatively high with a coefficient of variation of 48%. This relatively high standard error leads to less certainty of the carbon estimate for Sacramento.

3.2. Urban versus non-urban forests

Urban forests, due to their relatively low tree cover, typically store less carbon per hectare in trees (25.1 tC/ha) than forest stands (53.5 tC/ha). Estimated urban tree gross sequestration rates per hectare (0.8 tC/ha/year; 0.3 kgC/m^2 cover) are also typically less than within forest stands. The gross sequestration rates compare with 2.6 t/ha/year (0.26 kgC/m^2 cover assuming 100% tree canopy cover) for a 25-year old loblolly pine (*Pinus taeda* L.) plantation with genetically improved stock on a high yield site, and 1.0 t/ha/year (0.1 kgC/m^2 cover) for a 25-year old natural regeneration spruce-fir forest on an average site (Birdsey, 1996).

However, on a per unit tree cover basis, carbon storage by urban trees (9.25 kgC/m^2 cover) and gross sequestration (0.3 kgC/m^2 cover) may be greater than in forest stands due to a larger proportion of large trees in urban environments and relatively fast growth rates due to the more open urban forest structure (e.g. Nowak, 1994). Given that forest stands typically have about twice the tree density as urban areas, and about half the average carbon density per unit of tree cover (urban = 9.25 kgC/ha cover versus forest = 5.3 kgC/ha cover), individual urban trees, on average, contain approximately four times more carbon than individual trees in forest stands. This difference is largely due to differences in tree diameter distributions between urban and forest areas. As large trees can store 1000 times more carbon than small trees (Nowak, 1994), a fourfold difference in average individual tree carbon storage is not unreasonable given the more open structure of urban forests. Although forest carbon storage and sequestration rates per unit of tree canopy cover are not directly comparable with urban forests (as natural forests do not have 100% tree canopy cover), differences in stand structure between urban and natural forests will lead to differences in storage and sequestration rates.

3.3. State and regional carbon estimates

States with the highest estimated storage and sequestration rates are Georgia, Alabama, and Ohio (Table 3). States with the highest estimated carbon storage and sequestration densities (tC/ha) are Georgia, Montana, and New Hampshire. USA regions with the highest carbon storage and sequestration are the north central, northeast, south central and southeast (Table 4). Carbon storage and sequestration per hectare were highest in the southeast, north central, northeast and Pacific northwest regions, respectively. Carbon storage and sequestration in a region is a function of the amount of urban land and percent tree cover (i.e. total amount of urban tree cover). The northeast region has the highest proportion of urban land (8.5%) and the south central region has the greatest total amount of urban land (65,930 km^2; Table 4). Forested regions of the country

Table 3
Estimated carbon storage and gross annual sequestration, including percent urban tree cover, amount of urban land, and proportion of state in urban land, by state (from Dwyer et al., 2000; Nowak et al., 2001)

State	Carbon storage		Gross sequestration		Urban tree cover	Urban area[a]	Portion of state
	t	t/ha	t/yr	t/ha/yr	%	Km^2	%
Georgia	42,651,000	51.2	1,383,000	1.7	55.3	8,338	5.4
Alabama	37,839,000	44.6	1,227,000	1.4	48.2	8,487	6.3
Ohio	35,155,000	35.4	1,140,000	1.1	38.3	9,923	8.5
Florida	31,329,000	17.0	1,016,000	0.6	18.4	18,407	10.8
Tennessee	29,976,000	40.6	972,000	1.3	43.9	7,382	6.8
Virginia	28,960,000	32.7	939,000	1.1	35.3	8,869	8.0
Illinois	28,570,000	31.2	927,000	1.0	33.7	9,165	6.1
California	27,574,000	10.1	894,000	0.3	10.9	27,348	6.4
Pennsylvania	26,611,000	31.8	863,000	1.0	34.4	8,363	7.0
New Jersey	26,485,000	38.3	859,000	1.2	41.4	6,916	30.6
Texas	25,809,000	9.7	837,000	0.3	10.5	26,573	3.8
North Carolina	25,472,000	39.7	826,000	1.3	42.9	6,419	4.6
New York	24,636,000	24.3	799,000	0.8	26.3	10,127	7.2
Minnesota	23,438,000	34.6	760,000	1.1	37.4	6,775	3.0
Michigan	20,588,000	27.5	668,000	0.9	29.7	7,494	3.0
Montana	19,946,000	45.7	647,000	1.5	49.4	4,365	1.1
Washington	17,650,000	31.1	572,000	1.0	33.6	5,679	3.1
Maryland	16,784,000	37.1	544,000	1.2	40.1	4,525	14.1
Massachusetts	16,131,000	23.4	523,000	0.8	25.3	6,893	25.2
South Carolina	16,125,000	36.8	523,000	1.2	39.8	4,380	5.3
Missouri	16,006,000	28.3	519,000	0.9	30.6	5,655	3.1
Indiana	14,430,000	28.9	468,000	0.9	31.2	5,000	5.3
Maine	12,738,000	44.1	413,000	1.4	47.7	2,887	3.1
Louisiana	12,577,000	23.4	408,000	0.8	25.3	5,374	4.0
Mississippi	12,015,000	35.7	390,000	1.2	38.6	3,365	2.7
Wisconsin	10,894,000	23.9	353,000	0.8	25.8	4,565	2.7
Oklahoma	10,650,000	13.4	345,000	0.4	14.5	7,940	4.4
Kentucky	10,424,000	30.9	338,000	1.0	33.4	3,374	3.2
Arizona	9,720,000	10.5	315,000	0.3	11.4	9,218	3.1
Iowa	9,638,000	30.6	313,000	1.0	33.1	3,148	2.2
Connecticut	8,237,000	20.2	267,000	0.7	21.8	4,085	28.5
Arkansas	7,943,000	23.1	258,000	0.8	25.0	3,435	2.5
New Hampshire	7,621,000	45.4	247,000	1.5	49.1	1,678	6.9
Oregon	6,411,000	28.1	208,000	0.9	30.4	2,280	0.9
Colorado	5,225,000	12.0	169,000	0.4	13.0	4,345	1.6
Kansas	4,883,000	19.0	158,000	0.6	20.5	2,575	1.2
West Virginia	4,239,000	39.0	137,000	1.3	42.2	1,086	1.7
Utah	3,337,000	13.0	108,000	0.4	14.0	2,577	1.2
Nevada	2,926,000	9.2	95,000	0.3	9.9	3,195	1.1
Delaware	2,424,000	42.8	79,000	1.4	46.3	566	8.8
Idaho	2,287,000	23.7	74,000	0.8	25.6	966	0.4
Nebraska	2,071,000	19.5	67,000	0.6	21.1	1,061	0.5
Vermont	1,385,000	33.3	45,000	1.1	36.0	416	1.7
South Dakota	1,096,000	17.8	36,000	0.6	19.2	617	0.3
New Mexico	1,028,000	4.4	33,000	0.1	4.8	2,316	0.7
Rhode Island	762,000	8.2	25,000	0.3	8.9	926	23.2
North Dakota	330,000	7.2	11,000	0.2	7.8	457	0.2
Wyoming	265,000	3.3	9,000	0.1	3.6	797	0.3
Total, U.S.[b]	704,397,000	25.1	22,845,000	0.8	27.1	281,000	3.5

[a] Includes land and water.
[b] U.S. total includes the District of Columbia and 492 square kilometers that crossed state borders and could not be assigned to an individual state, but does not include Alaska and Hawaii.

Table 4
Estimated carbon storage and gross annual sequestration, including percent urban tree cover, amount of urban land, and proportion of state in urban land, by region

Region	Carbon storage		Gross sequestration		Urban tree cover	Urban area[a]	Portion of region
	t	t/ha	t/yr	t/ha/yr	%	Km^2	Percent
North Central	158,720,000	30.7	5,148,000	1.0	33.2	51,725	3.9
Northeast	148,056,000	30.5	4,802,000	1.0	33.0	48,468	8.5
South Central	147,233,000	22.3	4,775,000	0.7	24.1	65,930	4.1
Southeast	144,536,000	31.1	4,688,000	1.0	33.7	46,413	7.1
Rocky Mountain	44,735,000	16.1	1,451,000	0.5	17.4	27,779	1.2
California	27,574,000	10.1	894,000	0.3	10.9	27,348	6.4
Pacific Northwest	24,062,000	30.2	780,000	1.0	32.7	7,959	1.8
Great Plains	8,379,000	17.8	272,000	0.6	19.2	4,710	0.5
Total, U.S.[b]	704,397,000	25.1	22,845,000	0.8	27.1	281,000	3.5

[a] Includes land and water.
[b] U.S. total includes the District of Columbia and 492 square kilometers that crossed state borders and could not be assigned to an individual state, but does not include Alaska and Hawaii.

generally have higher percent urban tree cover (34.4%), than grassland cities (17.8%) and desert cities (9.3%; Dwyer et al., 2000; Nowak et al., 2001). Thus, forested regions will typically have the greatest urban forest carbon densities.

Regional factors such as species composition, tree density, and growth and mortality rates could not be factored into these regional and state estimates due to limited data sets. More research is needed on local and regional variations in urban forest structure and functions to yield better national estimates of urban forest carbon storage and sequestration.

Total carbon storage by urban trees in the coterminous United States is estimated at 700 million tonnes (between 335 million tC and 980 million tC based on the range of city data excluding Sacramento[4]; Tables 3 and 4). These data correspond with previous analyses that estimated national carbon storage by urban trees as between 350 and 750 million tC (Nowak, 1993a) and between 600 and 900 million tC (Nowak, 1994). Carbon storage by urban trees nationally is only 4.4% of the estimated 15,900 million tC stored in trees in USA non-urban forest ecosystems (Birdsey and Heath, 1995). The estimated carbon storage by urban trees in USA is equivalent to the amount of carbon emitted from USA population in about 5.5 months based on average per capita emission rates (Energy Information Administration, 1997).

Annual gross carbon sequestration by USA urban trees is estimated at 22.8 million tC/year (Tables 3 and 4). National annual carbon sequestration by urban trees is equivalent to USA population emissions over a 5-day period. The total monetary value of carbon storage by USA urban trees is $14,300 million, with an annual sequestration value of $460 million.

[4] Sacramento data were excluded from the range estimate due to the relatively large standard error and unusually large proportion of the population greater than 76.2 cm dbh.

3.4. Additional urban forest effects

In addition to direct carbon storage and sequestration, urban trees can also affect carbon emissions in urban areas. Planting trees in energy-conserving locations around buildings (e.g. Heisler, 1986) can reduce building energy use and consequently chemical emissions from power plants. In a simulation of planting 10 million trees annually in energy conserving locations over a 10-year period with 100% survival rates, carbon storage by these trees at year 50 was estimated to be 77 million tonnes of carbon, with carbon avoidance from power plants at 286 million tC (Nowak, 1993a). In this case, the potential carbon avoidance was four times greater than the direct carbon sequestration rate. The total carbon stored and avoided by the 100 million trees (363 million tC) is $<1\%$ of the estimated amount of carbon emitted in the USA over the same 50-year period. Increasing fuel efficiency of passenger automobiles by 0.5 km/l over 50 years would also produce the same carbon effects as the 100 million trees (Nowak, 1993a).

Urban tree management practices also need to be considered when estimating the net effects of urban trees on atmospheric carbon dioxide as various maintenance activities emit carbon back to the atmosphere via fossil-fuel combustion (e.g. from chain saws, trucks, chippers, etc.). If carbon (via fossil-fuel combustion) is used to maintain vegetation structure and health, urban forest ecosystems will eventually become net emitters of carbon unless secondary carbon reductions (e.g. energy conservation) or limiting of decomposition via long-term carbon storage (e.g. wood products, landfills) can be accomplished to offset the maintenance carbon emissions.[3]

Another area of the urban forest carbon cycle that this paper does not analyze is urban soils. Sixty-one percent of the total carbon in non-urban forest ecosystems in the USA is stored in the soil environment (Birdsey and Heath, 1995). The amount of carbon from trees that is retained in urban soils, its residence time, and the amount of carbon currently stored in these soils remains to be investigated. It is likely, however, that urban soils contain less carbon per hectare than forest soils due to lower carbon inputs and increased soil decomposition rates due to warmer air and soil temperatures (e.g. Pouyat et al., 1997).

4. Conclusions

Urban forests can play a significant role in helping to reduce atmospheric carbon dioxide levels. Urban forests likely will have a greater impact per area of tree canopy cover than non-urban forests due to faster growth rates, increased proportions of large trees, and possible secondary effects of reduced building energy use and consequent carbon emissions from power plants. However, urban tree maintenance emissions can offset some of the carbon gains by urban forest systems.

The estimates given in this paper are based on limited field data and become more uncertain as they refine from national to regional and state estimates. More field measurements are needed in urban areas to help improve carbon accounting and other functions of urban forest ecosystems. In particular, more field data are needed to assess regional variation in forest structure; long-term permanent plot data are needed to assess urban forest growth, regeneration, and mortality; and improved satellite monitoring of urban cover types is needed to more accurately assess changes in urban forest cover. In addition, research needs to develop better urban tree biomass equations, improve estimates of tree decomposition and maintenance emissions, and investigate the effect of urban soils on carbon storage and flux in cities. A better understanding and accounting of urban ecosystems can be used to develop management plans and national policies that can significantly improve environmental quality and human health across the nation.

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