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Full Length Research Paper

Assessing forests and lands with carbon storage and sequestration amount by trees in the State of Delaware, USA

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This study illustrates how cover characteristics vary within the State of Delaware by urban, suburban and other developed areas. This study can be used to improve the understanding, management and planning of the urban and community forests in the state. Landsat and the 2000 census data reveal that Delaware has 15.0% urban area (includes area typically considered suburban), 1.5% suburban places (communities outside of urban areas with population greater than 2,500), 1.1% rural places (communities outside of urban areas with population less than 2,500), and 2.3% other developed areas. Tree cover in Delaware averages 18.3%; impervious cover averages 16.8%. The 2000 census data reveal that urban/suburban area in Delaware increased to 16.5% of the state between 1990 and 2000 with most expansion occurring in agriculture (48.7%) and forest (31.7%) lands. There are an estimated 7.1 million trees in Delaware that store about 1.3 million metric tons of carbon and the trees annually remove about 44,000 metric tons of carbon and 1,430 metric tons of air pollution.

Key words: Delaware, forest, developed lands, tree cover, impervious cover.

INTRODUCTION

The urban forest assessment as part of the Forest and Rangeland Renewable Resources Planning Act (RPA) was completed in 2000 (Dwyer et al., 2000; Nowak et al., 2001a; Nowak et al., 2001b; Nowak and Greenfield, 2008). That national assessment used 1-km resolution Advanced Very-High Resolution Radiometer (AVHRR) data (Zhu, 1994) and 1990 U.S. census data to assess the urban tree cover. That study concluded that urban areas (cities, towns and villages) in the conterminous United States have doubled in size between 1969 and 1994 and covered 3.5% the total land area.

In this study, higher resolution (30 m) tree and imper-vious cover maps have been used along with census data to assess existing urban and community forest attributes. This assessment has used Landsat data because of problems that have been noted in using the AVHRR to quantify urban tree cover. These problems included a relatively large pixel size that leads to inaccu-racies in small urban places and in urban areas along water and difficulties associated with calibrating the AVHRR data to higher resolution data within large physiographic regions. The higher resolution Lands at data and smaller physio-Graphic regions for calibrating data sets should overcome many of the limitations of the original the AVHRR- based urban tree cover maps (Kaya et al., 2003; Nowak et al., 2007a).

This study is being produced for the state to provide information on urban change and state–specific urban and community forestry data to assist in local to regional planning and management of urban natural resources.

Urban areas contain approximately 3.8 billion trees with an average tree canopy cover of 27% (Nowak et al., 2007a; Nowak and Greenfield, 2008). Through the growth process of the trees, they remove carbon dioxide from the air. A growing tree sequesters carbon and stores a large amount of it in its tissue each year.

For human and ecological health, urban and commu-nity forests are important. The benefits of urban and community trees are (Nowak and Crane, 2000; Nowak and Greenfield, 2008):

i) Carbon storage and annual carbon sequestration.
ii) Air pollution removal.
iii) Surface air temperature reduction.

iv) Reduced building energy use.
v) Absorption of ultraviolet radiation.
vi) Improved water quality.
vii) Reduced noise pollution.
viii) Improved human comfort.
ix) Increased property value.
x) Improved human physiological and psychological well-being.
xi) Improved esthetics.
xii) Improved community cohesion.

To understand the contribution and magnitude of the forest source in urban and community areas, the total number of trees, carbon storage and annual carbon uptake are estimated for the state.

In cooperation with the U.S. Geological Survey's Earth Resources Observation Systems (EROS) Data Center and other agencies, tree and impervious cover maps have been produced across the United States. One of the first regions to be completed was the Chesapeake Bay area that was produced by Earth Satellite Corpo-ration. This study summarizes some of the findings for the State of Delaware. The key target of this study is to detail tree cover, impervious cover and other covers (e.g. grass, soil, water) in urban areas at the state, county and individual place level and to assess changes in the amount of urban land between 1990 and 2000.

MATERIALS AND METHODS

Urban forest attributes

Human population characteristics: Population, population density and geographic distribution are important measurements of the urban environment because they all affects on Urban forest dynamics (Nowak and Greenfield, 2008). Data of population, population density and the changes between 1990 and 2000 have been collected from U.S. Census Data (U.S. Census Bureau, 2003).

According to U.S. Census Data, populations have been increasing throughout most areas in Delaware between 1990 and 2000, with total population in Delaware increasing from 666,168 in 1990 to 783,600 in 2000, a 17.6% increase (U.S. Census Bureau, 2002).

Urban and community definitions

To analyze Urban forest cover and changes in the amount of urban land, the boundaries of urban areas need to be determined. Urban land definitions are based on population density and was delimited using the 2000 U.S. Census Bureau's urban definition of all territory, population and housing units located within either urbanized areas or urban clusters (U.S. Census Bureau, 2003). Urbanized area and urban cluster boundaries encompass densely settled territories, which commonly include (Kaya et al., 2003; Nowak et al., 2007a):

i) A cluster of one or more block groups or census blocks with a population density of at least 1,000 people per square mile.
ii) Surrounding block groups and census blocks with a population density greater than 500 people per square mile.
iii) Less densely settled blocks that form enclaves or are used to connect discontinuous areas.

Urbanized areas include densely settled territory that contains 50,000 or more people; urban clusters include densely settled territory that has at least 2,500 people but less than 50,000 people. This new definition tends to be more restrictive than the 1990 census urban definitions (Nowak et al., 2005; Nowak et al., 2007a). The 1990 definition of urban was areas with population density of at least 1,000 people/mi^2 (urbanized area) and areas outside these urbanized areas with a minimum population of 2,500 people (Table 2). The 2000 census definition of urban was applied to 1990 census data to analyze change in urban land between 1990 and 2000 (Nowak et al., 2005) . Both the old and new definition of urban also includes areas that are typically thought of as suburban lands (Nowak et al., 2005).

This study uses four developed land cover types: urban, suburban, rural and other developed lands (Table 1). The first three definitions are based on census data, the last area (other developed) is based on satellite land use classification and includes lands with developed features (e.g., buildings, roads) that are found outside of urban, suburban and rural areas.

Cover analyses

Boundaries for urban, suburban and rural lands were based on U.S. Census data (U.S. Census Bureau, 2003). Boundaries for other developed land were based on 2000 National Land Cover Data maps from the U.S. Geological Survey (USGS, 2003). Estimates of percent of tree, impervious, other (grass/herbaceous, soil, water) cover were derived through Geographic Information Systems (GIS) analysis of land cover maps and maps of census -designated entities. The land cover maps were developed by the USGS and cooperators for the Chesapeake Bay region using circa 2000 Landsat data from three different time periods (pre-, mid-, and late-growing season) (Homer et al., 2002). Regression models were developed to predict the percen- tage of impervious surface and tree cover within each 30 m grid based on high resolution (1 m) calibration cover maps in conjunction with the Landsat thematic mapper (TM) data (Huang et al., 2001; Yang et al., 2003). These 30-meter high resolution cover databases were subsequently combined with various GIS boundary layers to estimate land cover (tree, impervious or other) within each boundary classification (e.g., urban, suburban places).

To quantify the amount of space available for vegetation and the amount of available space filled with trees, percent greenspace and percent stocking were calculated. Greenspace is the amount of per-vious space in the area, which is calculated as the sum of tree and other (grass/herbaceous, soil and water) cover. As not all water areas could be removed from the analysis (e.g., ponds, streams), this estimate includes some water areas and thus slightly overestimates the actual greenspace area. Stocking is the percent of greenspace area that is currently occupied by tree cover.

RESULTS

Urban growth

The amount of urban land in Delaware increased from

Table 1. Urban type definitions (2000).

Term	Definition
Urbanized Area (UA)[1]	Census block groups or blocks that have a population density of at least 1,000 people per square mile
Urban Cluster (UC)[2]	Census blocks (surrounding urbanized areas) that have an overall density of at least 500 people per square mile[2].
Suburban Area[2]	Incorporated or unincorporated (census-designated) places outside of urbanized areas and urban clusters having a population of greater than 2,500.
Rural Area	Incorporated or unincorporated (census -designated) places outside of urbanized areas and urban clusters having a population of less than 2,500.
Other Developed Lands	National Land Cover Data classified as commercial, industrial, transportation or residential outside of urban, suburban and rural lands.

[1]Urban area is defined as the combination of urbanized areas and urban clusters. These urban areas contain many areas typically thought to be suburban. The 1990 "urban areas" (from the first urban forest assessment (Dwyer et al., 2000) included many suburban areas and was defined as the combination of urbanized areas and urban areas (incorporated or unincorporated places outside of urban areas and urban clusters having a population of greater than 2,500). The change in urban definition was due to the census addition of the urban cluster and the removal of the urban place definition. The 1990 urban places are reclassified as suburban area.

[2] not a census definition, but comparable to 1990 urban places definition. These areas were part of the 1990 urban area definition, but are now separated out as suburban. Some land typically through of as suburban is also included in the urban area definition.

Table 2. Comparison of 1990 and 2000 Definitions.

Definition	1990	2000
Urban	Urbanized areas and places >2,500 pop. outside of urbanized areas	Urbanized areas and urban clusters (see Table 1).
Suburban	-	Places >2,500 pop. outside of urban.
Rural	Places <2,500 pop. outside of urbanized areas	Places <2,500 pop. outside of urban.
Other Developed	-	National Land Cover Data classified as commercial, industrial, transportation or residential outside of urban, suburban and rural lands.

10.8% in 1990 to 13.5% in 2000 based on the original 1990 urban definition (Table 3; Figure 1). The areas where urban area expanded into were agriculture lands (48.7%), forest lands (31.7%), urban/suburban and rural areas (11.6%), wetlands (6.2%) and other developed areas (1.8%) . The other developed areas determine the type of land uses that have been occupied by urban expansion, 1992 national land cover (NLCD) data (USGS, 2003) were used. The land cover types analyzed were:

i. Developed (e.g., commercial, industrial, transportation, residential).
ii. Herbaceous cultivated and non-natural woody vegetation (e.g., agriculture, orchards and vineyards).
iii. Forest.
iv. Wetland (woody and herbaceous).
v. Others (shrub-land, barren, herbaceous non-cultivated).

The greatest increase occurred in New Castle County (36.5 to 43.5%). Total state population increased by 17.6% from 666,168 in 1990 to 783,600 in 2000. Based on the new 2000 urban definition, Urban/Suburban land has increased to 16.5% of the state area (Table 4). Suburban definition has been comparable to 1990 urban places, though many 1990 urban places are now included in 2000 urban definition due to definition change. Delaware has:

i.) 15.0% urban land (includes land typically considered suburban).
ii) 1.5% suburban places.
iii) 1.1% rural places.
iv) 2.3% other developed land.

Approximately 20% of Delaware is classified as urban, suburban places, rural places, or other developed lands (Table 4 and Figure 2).

Cover attributes

Urban areas in Delaware average:

i) 18.3% tree cover (Table 4 and Figure 3).

Table 3. Summary of Change in Urban Land Area between 1990 and 2000 by Counties in Delaware Based on 1990 definition of Urban[a].

State	County	Land type	Area		Population			
					2000	1990	Change 90-00	
			(km²)	(%)	(#)	(#)	(#)	(%)
Delaware	Kent	Urban 1990	116.9	7.5[b]	126,697	110,993	15,704	14.1
		Urban 2000	158.8	10.2[b]				
	New Castle	Urban 1990	422.8	36.5[b]	500,265	441,946	58,319	13.2
		Urban 2000	504.2	43.5[b]				
	Sussex	Urban 1990	28.9	1.1[b]	156,638	113,229	43,409	38.3
		Urban 2000	43.9	1.7[b]				
	State Total	Urban 1990	568.6	10.8[c]	783,600	666,168	117,432	17.6
		Urban 2000	706.9	13.5[c]				

[a] 1990 Urban definition: Urbanized areas plus places outside of urbanized areas with population > 2,500.
[b] Percent of county total land area.
[c] Percent of state total land area.
Source of area (Tiger geographic boundary data) and population data: (U.S. Census Bureau, 2003).

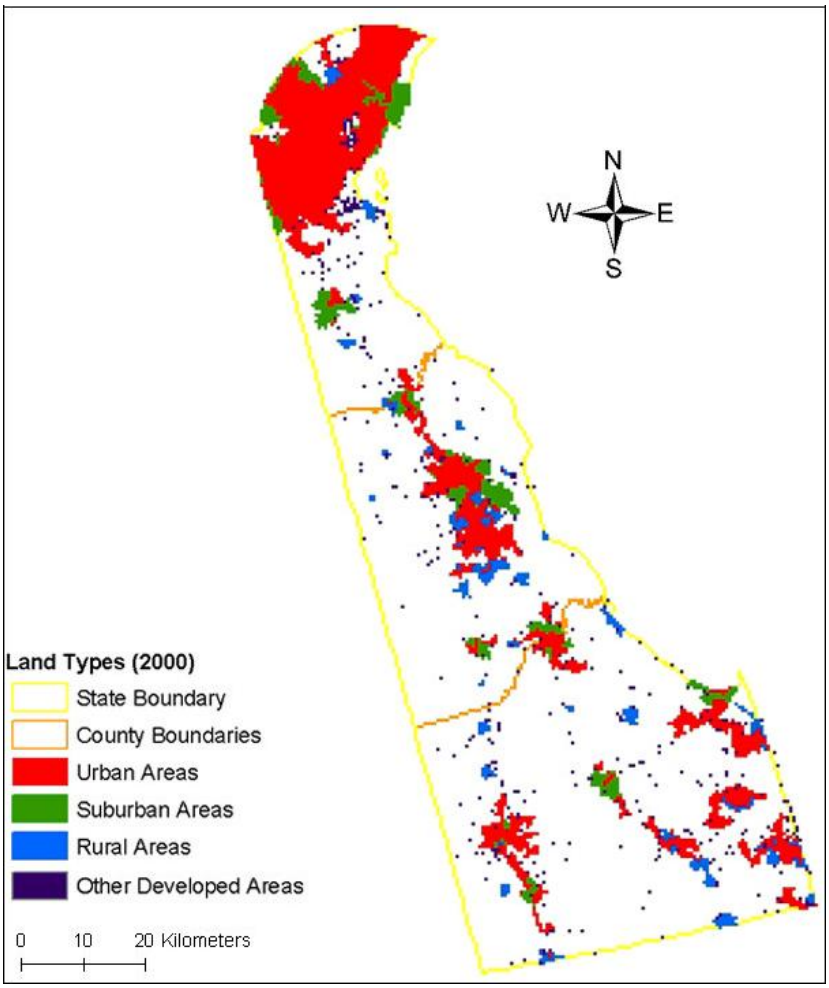

Figure 1. Urban, suburban, rural and other developed areas in Delaware.

Table 4. Summary of Cover Data within 2000 Urban, Suburban, Rural and Other Developed Lands by Counties in Delaware.

State	County	Land type	Area[e] (km²)	Area[e] (%)	Cover: Tree (%)	Cover: Imperv[f] (%)	Cover: Other[g] (%)	Stocking[h] (%)	Greenspace[i] (%)
Delaware									
	Kent								
		Urban	141.8	9.1[j]	13.8	12.1	74.0	15.7	87.9
		Suburban	30.7	2.0[j]	10.7	13.1	76.2	12.3	86.9
		Rural	21.9	1.4[j]	14.3	5.8	79.9	15.2	94.2
		Other developed	25.2	1.6[j]	4.4	22.7	72.9	5.7	77.3
		Total	219.6	14.2[j]	12.4	12.8	74.8	14.2	87.2
	New Castle								
		Urban	473.0	40.8[j]	21.2	19.2	59.6	26.3	80.8
		Suburban	37.1	3.2[j]	17.9	3.3	78.8	18.5	96.7
		Rural	9.9	0.9[j]	28.3	5.7	66.0	30.0	94.3
		Other developed	32.1	2.8[j]	4.2	31.4	64.4	6.2	68.6
		Total	552.1	47.7[j]	20.1	18.6	61.2	24.7	81.4
	Sussex								
		Urban	171.7	6.8[j]	13.9	13.7	72.4	16.1	86.3
		Suburban	13.3	0.5[j]	19.4	10.1	70.5	21.6	89.9
		Rural	26.7	1.1[j]	11.0	10.7	78.3	12.3	89.3
		Other developed	62.9	2.5[j]	4.5	28.2	67.3	6.2	71.8
		Total	274.6	10.8[j]	11.7	16.6	71.7	14.0	83.4
	State total								
		Urban	786.6	15.0[k]	18.3	16.8	65.0	22.0	83.3
		Suburban	81.1	1.5[k]	15.4	8.1	76.5	16.8	91.9
		Rural	58.4	1.1[k]	15.2	8.0	76.8	16.5	92.0
		Other developed	120.2	2.3[k]	4.4	27.9	67.7	6.1	72.1
		Total	1,046.4	19.9[k]	16.3	16.9	66.8	19.6	83.1
	Kent	County all total	1,551.5	29.6[k]	22.2	2.1	75.7	22.7	97.9
	New Castle	County all total	1,158.5	22.1[k]	21.7	9.1	69.2	23.9	90.9
	Sussex	County all total	2,535.2	48.3[k]	26.4	2.2	71.4	27.0	97.8
		State all total	5,245.1	100.0[k]	24.1	3.7	72.2	25.0	96.3

[e] Land area as determined by, [f] Impervious cover (that is, buildings, roads, sidewalks), [g] Non-tree, non-impervious cover (that is, grass/herbaceous, soil, water), [h] Percent of greenspace filled with tree cover, [i] Percent of area occupied by tree and other cover, [j] Percent of county total land area.

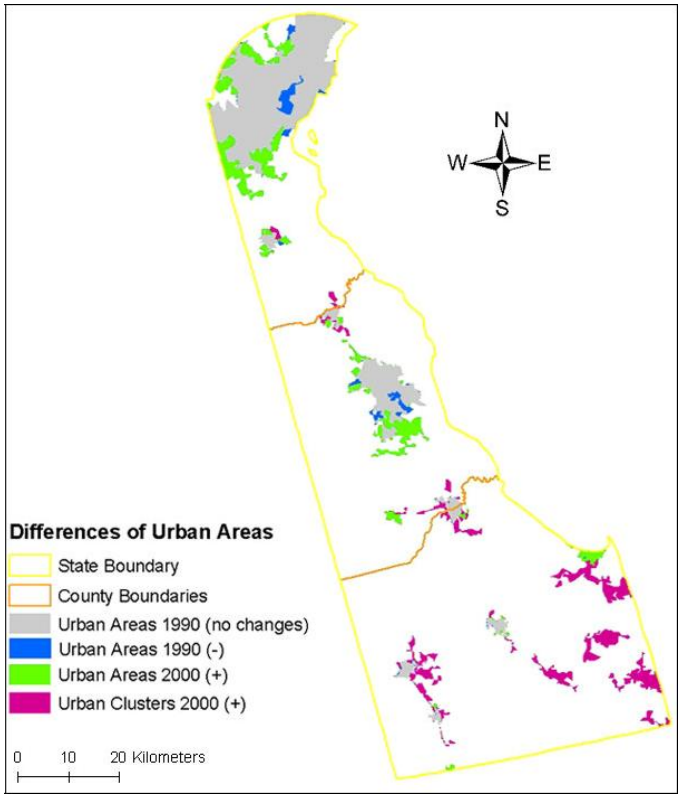

Figure 2. Differences between urban areas 1990 and 2000 in Delaware.

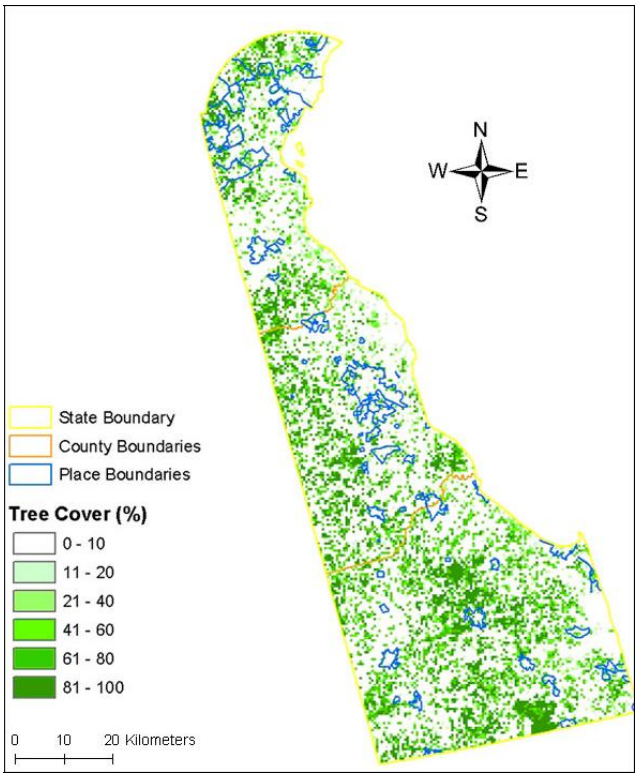

Figure 3. Tree cover and place boundaries in Delaware.

ii. 16.8% impervious cover (Table 4, Figure 4).

Urban tree cover was greatest in New Castle County (21.2%), followed by Sussex (13.9%) and Kent County (13.8%). Average percent urban greenspace in Delaware was 83.3%, with a stocking level of 22% (Table 4). Average tree cover per capita in urban, suburban and rural places is 336 m^2 per capita, with 268 m^2 per capita in urban/suburban places (places with population greater than 2,500) and 541 m^2 per capita in rural places (population < 2,500).

Tree cover averaged 16.3% in urban/suburban places and 15.4% in rural places. Even though the tree cover average was comparable between urban/suburban and rural places, the distribution of tree cover in each of these areas differed (Figure 5). Urban/suburban and rural places were dominated by places with less than 20% tree cover. However, rural had more places with less than 10% tree cover and had more diversity in the amount of cover, with some rural places having greater than 40% tree cover. Both urban/suburban and rural places displayed a considerable diversity in percent tree cover within Delaware (Figure 5).

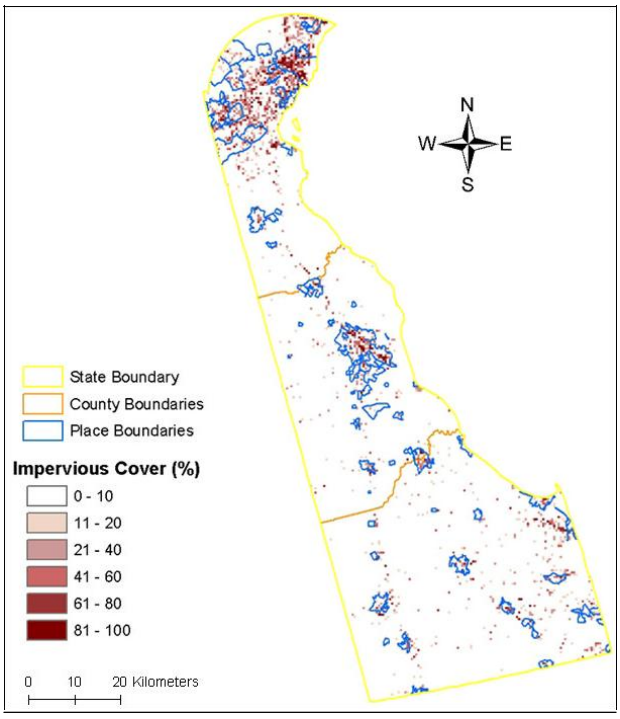

Figure 4. Impervious cover and place boundaries in Delaware.

Urban tree benefits

Given a median tree density of 476.9 trees per hectare of tree cover in urban areas based on field data from se-

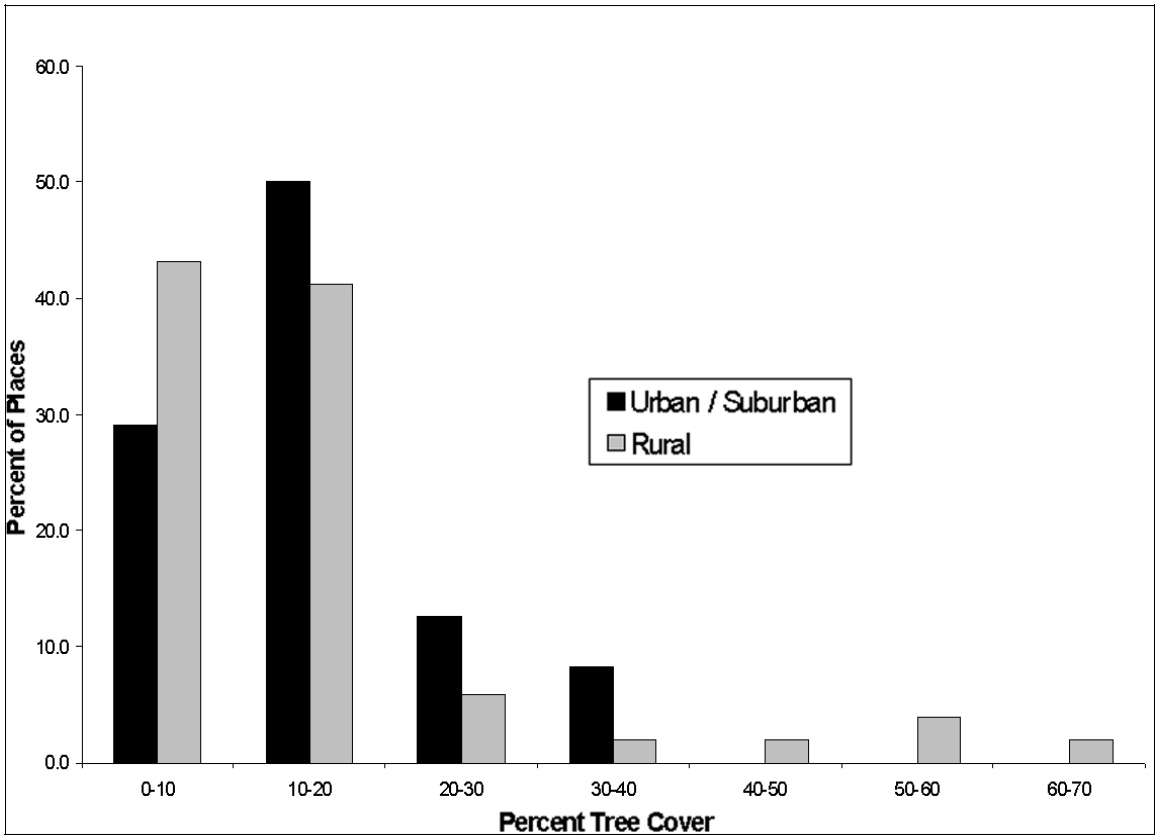

Figure 5. Percent of total number of urban/suburban and rural places within 10% tree cover categories.

veral U.S. cities (Table 5), the number of urban trees in Delaware is estimated at 7.1 million trees.

Carbon storage

Given a median carbon storage density of 9.1 kgC/m^2 of tree cover and an annual gross carbon sequestration rate of 0.3 kgC/m^2 cover/year, based on data from several U.S. cities (Nowak and Crane, 2002), the total amount of carbon stored and annually sequestered in Delaware is estimated at 1.3 million metric tons of carbon and the trees annually remove about 44,000 metric tons of carbon and 1,430 metric tons of air pollution.

Air pollution removal

Pollution removal by urban trees in Delaware was estimated using the Urban Forest Effects (UFORE) model (e.g., Nowak et al., 1998; Nowak and Crane, 2000; Nowak et al., 2001a; Nowak et al., 2002) using year 2000 hourly pollution concentration data from 15 monitors (6 ozone; 4 sulfur dioxide; 2 particulate matter less than 10 microns; 2 carbon monoxide; 1 nitrogen dioxide) and weather data from 3 stations throughout Delaware. As urban forest field data have not been available for Delaware during the preparation of the study, urban/ suburban tree cover was assumed to have a leaf area index of 6 and to be 10% evergreen (Nowak and Crane, 2000). To estimate total pollution removal by Delaware's urban forest, all hourly pollution concentration data were combined with each weather station's hourly data and the average of the annual pollution removal output from each weather station was computed. As special information, concentration data for nitrogen dioxide were unavailable for 8 months, therefore average concen- tration data from the existing 4 months data were used to estimate the missing concentrations. Annual urban forest pollution removal in Delaware, 2000, has been estimated at (metric ton = t):

1. Carbon monoxide (CO) removal: 26 t.
2. Nitrogen dioxide (NO_2) removal: 47 t.
3. Ozone (O_3) removal: 725 t.
4. Sulfur dioxide (SO_2) removal: 152 t.
5. Particulate matter less than 10 microns (PM_{10}): 480 t.
6. Total (5 pollutants): 1,430 t.

DISCUSSION

The data presented in this study are the assessment of

Table 5. Average number of trees, carbon storage and annual carbon sequestration rates per unit of canopy cover for several U.S. cities.

City	Trees	Carbon		Reference
	Trees/ha cover	Storage (kg C/m^2 cover)	Annual Sequestration (kg C/m^2 cover)	
Atlanta, GA	751.5	9.7	0.3	Nowak and Crane, 2000.
Baltimore, MD	598.1	12.3	0.3	Nowak and Crane, 2000.
Boston, MA	371.7	9.1	0.3	Nowak and Crane, 2000.
Casper, WY	252.8	7	0.2	Nowak et al., 2006a.
Chicago, IL	618	12.9	N/A	Nowak, 1994.
Freehold, NJ	275	10.4	0.3	Nowak and Crane, 2000.
Jersey City, NJ	308.7	4.4	0.2	Nowak and Crane, 2000.
Minneapolis, MN	245.5	5.7	0.2	Nowak et al., 2006b.
Moorestown, NJ	547.9	9.9	0.3	Nowak and Crane, 2000.
Morgantown, VW	829.6	10.6	0.3	Nowak and Crane, 2000.
New York, NY	312	7.3	0.2	Nowak et al., 2007b.
Oakland, CA	570	5.2	N/A	Nowak and Crane, 2002.
Philadelphia, PA	394.3	9	0.3	Nowak et al., 2007c.
San Francisco, CA	468.1	12.3	0.3	Nowak et al., 2007d.
Syracuse, NY	583.1	10.5	0.3	Nowak et al., 2001b.
Washington, DC	423.4	10.4	0.3	Nowak et al., 2006c.
Woodbridge, NJ	557.3	8.2	0.3	Nowak and Crane, 2000.
Median	476.9	9.1	0.3	

urban and community forests in Delaware and provide baseline data for assessing future changes in urban forest cover. Cover information in this report was based on higher resolution data than used in the original urban forests assessment (1991 AVHRR data).

Though the data used in this study are based on wall-to-wall coverage of cover characteristics in the state, there are some data limitations, particularly at the local scale (e.g., block level). Individual pixel prediction errors averaged 8.4% (average error for misclassification of any one pixel). However, aggregating the pixels into larger groups reduces the overall error in cover esti-mates. It is likely that the cover estimates for individual places, counties and the state are less than 1%.

While preparing this study, no urban forest field data existed in Delaware (exclusive of some street tree inventtory data), median data from other urban forests were used to estimate the number of urban trees and carbon storage by urban trees in Delaware. Urban field data are needed in Delaware to help improve these estimates, as well as to estimate other urban forest effects (e.g., building energy conservation). Long-term monitoring of urban forest field data used in conjunction with satellite-based cover maps will provide essential information to assess urban forest health and change and to improve urban forest management.

Delaware is one of the most urbanized states in the nation (ranked 6th among lower 48 states) and continues to urbanize at a relative high rate (2.6% increase between 1990 and 2000; ranked 9th among lower 48 states). The urban/suburban growth rate is likely to increase in the future because as urban/suburban areas increase, the rate of urban growth also tends to increase. According to Nowak et al. (2005), data indicate that urban growth rates tend to increase as percent of state land classified as urban/suburban increases. This increa-sing growth rates occurs up until around 80% of the state is urbanized, at which point percent urban growth declines as the land base for expansion is reduced.

The data presented in this study provide the understanding of Delaware's urban forest. These data establish a baseline to assess change and can be used to understand:

i. Extent of the urban forest resource
ii. Variations in the resource across the state
iii. Magnitude and value of the urban forest resource
iv. Urban development in Delaware
v. Implication of policy decisions related to urban sprawl and urban forest management

In addition, the cover maps themselves can be integrated in local Geographic Information Systems (GIS) to assist in local policy, design and management decisions throughout the state. This urban forest information and data sets can be used to mend decisions to improve en-

vironmental quality and human health throughout Delaware.

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