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Urban Forest Assessment in Northern Delaware

David J. Nowak
Robert E. Hoehn
Jun Wang
Andy Lee
Vikram Krishnamurthy
Gary Schwetz

Abstract

An analysis of the urban forest of the Wilmington, Delaware, area was conducted for three areas: 1) a metropolitan corridor in New Castle County (NCC); 2) the city of Wilmington (within NCC); and 3) the Rattlesnake Run sewershed (within the city of Wilmington) using the Urban Forest Effects (UFORE) model. This analysis reveals that there are about 882,700 trees (19.3 percent tree cover) in the NCC metro corridor and about 136,000 trees (16.1 percent tree cover) in Wilmington. The three most common species in the NCC urban forest are red maple (22.8 percent), sweetgum (16.9 percent), and black cherry (3.9 percent). In Wilmington, most common species are Norway maple (16.4 percent), northern white cedar (15.0 percent), and tree-of-heaven (9.5 percent). These trees store and remove a significant amount of carbon, reduce building energy use, and annually remove large amounts of air pollution. The UFORE hydrologic analysis of the Rattlesnake Run sewershed reveals that existing tree cover reduced nonsanitary flow by 1.4 percent during an August-to-February simulation period. Increasing existing tree cover over pervious surfaces from 5 to 45 percent reduced outlet flow by 1.7 percent; increasing tree cover from 5 to 45 percent over impervious land reduced flow by 10.7 percent.

The Authors

DAVID J. NOWAK is a research forester and project leader, and ROBERT E. HOEHN is a biological sciences technician with the U.S. Forest Service, Northern Research Station, 5 Moon Library, SUNY-ESF, Syracuse, NY 13210.

JUN WANG is an adjunct assistant professor and Andy Lee is a research assistant with SUNY College of Environmental Science and Forestry, 5 Moon Library, Syracuse, NY 13210.

VIKRAM KRISHNAMURTHY is a stewardship manager with the Eastern Shore Land Conservancy, P.O. Box 169, Queenstown, MD 21658.

GARY SCHWETZ is a director of programs with Delaware Center for Horticulture, 1810 N. Dupont St., Wilmington, DE 19806.

Cover Photo

A north-facing view of Wilmington's West Center City on the edge of downtown. Photo used with permission by Gary Schwetz, Delaware Center for Horticulture

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EXECUTIVE SUMMARY

Urban trees and forests provide multiple services and benefits to society. These trees and forests are found among a mix of land use types throughout an area, ranging from forest land to heavily developed and populated urban sites. The varied structure and composition of trees among these multiple land uses combine to create the urban forest where many people live, work, and play. These trees and their consequent functions or services (e.g., air and water quality improvement, carbon sequestration, reduced air temperatures) are directly influenced by management decisions and actions that affect the forest structure (species composition, number and location of trees). Thus, proper urban forest management can increase the environmental benefits derived from the urban forest. A first step to improving urban forest management is to assess the current structure and benefits derived by the existing urban forest.

To help assess urban forest effects, a multi-tiered study was initiated in 2004 to sample the urban forest in northern Delaware using the Urban Forest Effects (UFORE) model.[1] The first study focused on a metropolitan corridor in New Castle County. After this initial assessment, an intensified sampling of the city of Wilmington within the New Castle County study area was conducted to specifically analyze this highly urbanized area and to model the effects of trees on the outlet flow from Rattlesnake Run (in Wilmington).

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The UFORE model assesses the structure of the urban forest (e.g., species composition, tree density, tree size, health of tree population) and several urban forest functions and values: carbon storage and sequestration, pollution removal, and tree effects on building energy use (Table 1).

This report highlights the findings of the UFORE analyses in New Castle County metro corridor (NCC), the city of Wilmington, and the Rattlesnake Run sewershed. More detailed information on methods and results are reported at http://nrs.fs.fed.us/units/urban/data

Table 1.—Wilmington area urban forest summary

Feature	Measure New Castle metro corridor	Measure City of Wilmington
Number of trees	882,700	136,000
Tree cover	19.3%	16.1%
Most common species	Red maple, sweetgum, black cherry	Norway maple, northern white cedar, tree-of-heaven
Percentage of tree <=6 inches diameter	47.6%	54.2%
Carbon storage	285,000 tons[a] ($5.9 million)	46,000 tons ($959,000)
Carbon sequestration	10,000 tons/yr ($207,000/yr)	1,300 tons/yr ($27,000/yr)
Pollution removal	295 tons/yr ($1.9 million/yr)	45 tons/yr ($291,000/yr)
Building energy savings	$403,000	$183,000
Avoided carbon emissions	1,020 tons/yr ($21,000/yr)	475 tons/yr ($9,800/yr)
Structural value	$1.2 billion	$166 million

[a]Ton—short ton (U.S.) (2,000 lbs)

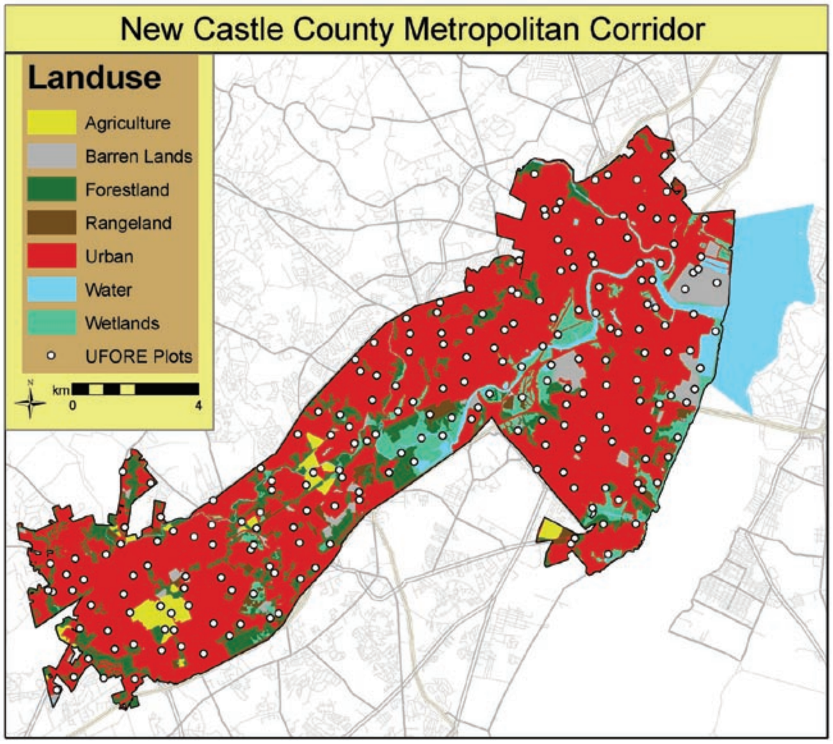

Figure 1.—Plot distribution within NCC.

UFORE METHODS

UFORE uses standardized data collected from randomly located plots and local hourly air pollution and meteorological data to quantify forest structure and effects, including:

- Urban forest structure (e.g., species composition, tree density, tree health, leaf area, leaf and tree biomass, species diversity, etc.)
- Amount of pollution removed hourly by the urban forest, and its associated percent air quality improvement throughout a year. Pollution removal is calculated for ozone, sulfur dioxide, nitrogen dioxide, carbon monoxide and particulate matter (<10 microns)
- Total carbon stored and net carbon annually sequestered by the urban forest
- Effects of trees on building energy use and consequent effects on carbon dioxide emissions from power plants
- Compensatory value of the forest, as well as the value of air pollution removal and carbon storage and sequestration
- Potential impacts of Asian longhorned beetle, emerald ash borer, gypsy moth, and Dutch elm disease

The assessment of northern Delaware's urban forest used a randomized grid-based sampling system for distributing one-tenth acre field plots throughout NCC (208 plots) (Fig. 1). The NCC boundaries were provided by the Delaware Center for Horticulture and were designed to include major urban areas in northern New Castle County between Wilmington and Newark, DE (between I-95 and Kirkwood Highway 2). Field data were collected by the Delaware Center for Horticulture and Delaware Forest Service. After data collection in the

NCC metro corridor (36,981 ac; 14,966 ha), additional plots were randomly distributed and measured in Wilmington (7,544 ac; 3,053 ha) and Rattlesnake Run (447 ac; 181 ha). The numbers of plots in these areas were 78 and 28, respectively.

Field plots were categorized into one of eight land uses based on the state of Delaware's 2002 land use map for New Castle County, provided by the Delaware Center for Horticulture (Table 2). Because of limited plots in Wilmington, urban boundary land-use categories were combined to ensure a minimum sample size.

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Data collection took place during the leaf-on season to properly assess tree canopies. Within each plot, data were collected on land use, ground and tree cover, shrub characteristics, and individual tree attributes of species, stem-diameter at breast height (d.b.h.; measured at 4.5 ft), tree height, height to base of live crown, crown width, percentage crown canopy missing and dieback, and distance and direction to residential buildings.[2]

To calculate current carbon storage, biomass for each tree was calculated using equations from the literature and measured tree data. Open-grown, maintained trees tend to have less biomass than predicted by forest-derived biomass equations.[3] To adjust for this difference, biomass results for open-grown urban trees are multiplied by 0.8.[3] No adjustment is made for trees found in natural stand conditions. Tree dry-weight biomass was converted to stored carbon by multiplying by 0.5.

Table 2.—Plot distribution (number of plots analyzed) in the each study area

Study Area	Land-use	Number of plots
NCC metro corridor	Residential	56
	Combined urban	41
	Commercial/industrial	34
	Forested	19
	Wetland/water	19
	Barren/open/agriculture	15
	Transportation	14
	Parks & recreation	10
	Total	208
Wilmington	Residential/parks[a]	11
	Combined urban	30
	Commercial/transportation[b]	23
	Open/water[c]	14
	Total	78

[a] includes forests
[b] includes industrial land
[c] includes barren, agriculture and wetlands

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To estimate the gross amount of carbon sequestered annually, average diameter growth from the appropriate genera and diameter class and tree condition was added to the existing tree diameter (year *x*) to estimate tree diameter and carbon storage in year *x*+1.

Air pollution removal estimates are derived from calculated hourly tree-canopy resistances for ozone, and sulfur and nitrogen dioxides based on a hybrid of big-leaf and multi-layer canopy deposition models.[4, 5] 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 measured values from the literature[6, 7] that were adjusted depending on leaf phenology and leaf area. Particulate removal incorporated a 50 percent resuspension rate of particles back into the atmosphere.[8]

Seasonal effects of trees on residential building energy use were calculated based on procedures described the literature[9] using distance and direction of trees from residential structures, tree height, and tree condition data.

Compensatory values were based on valuation procedures of the Council of Tree and Landscape Appraisers, which uses tree species, diameter, and condition and location information.[10]

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To learn more about UFORE methods[11] and see detailed study results visit: http://nrs.fs.fed.us/units/urban/data.

URBAN FOREST STRUCTURE

The structure of the urban forest determines the environmental services derived from the urban forest and its management needs. The focus of this analysis was predominately on the effects of trees within the various study areas. Though shrubs have an impact on various ecosystem services, shrub effects are relatively small compared to tree effects. Shrubs are, however, included in the assessment of urban forest effects on air pollution removal and hydrology, though only tree cover was varied in the hydrology assessment.

The NCC urban forest has an estimated 882,700 trees with a tree cover of 19.3 percent. Trees that have diameters less than or equal to 6 inches account for 47.6 percent of the population (Fig. 2). The three most common species in the urban forest are red maple (22.8 percent), sweetgum (16.9 percent), and black cherry (3.9 percent) (Fig. 3). The 10 most common species account for 64 percent of all trees. More species information is provided in Appendix 1.

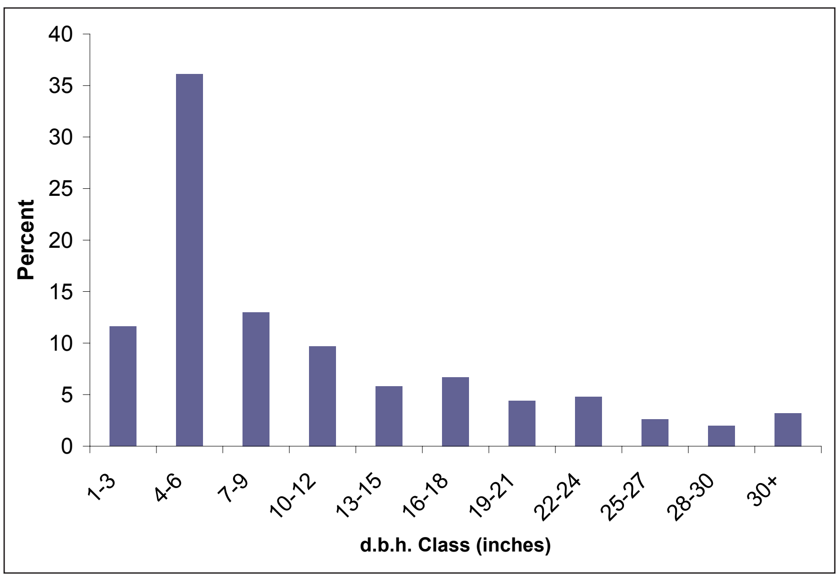

Figure 2.—Tree diameter distribution in NCC metro corridor.

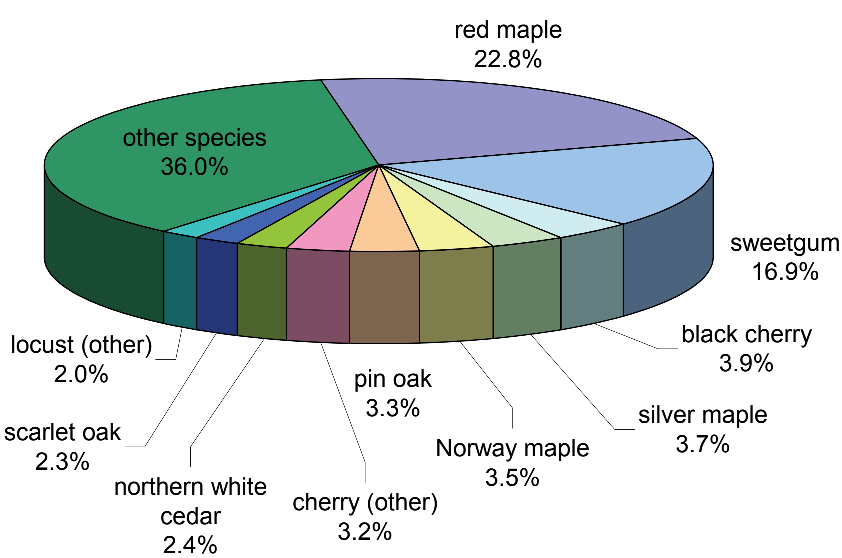

Figure 3.—Species composition in NCC metro corridor.

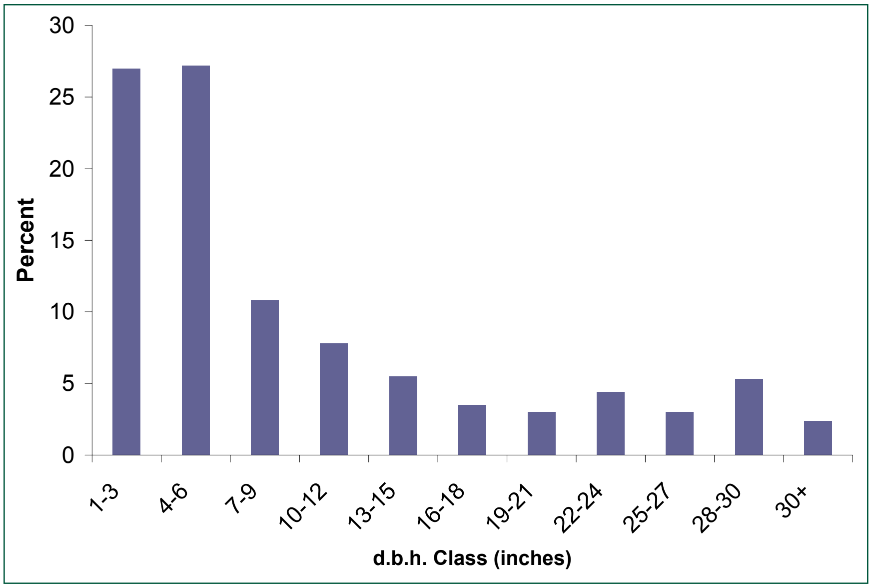

Figure 4.—Tree diameter distribution in Wilmington.

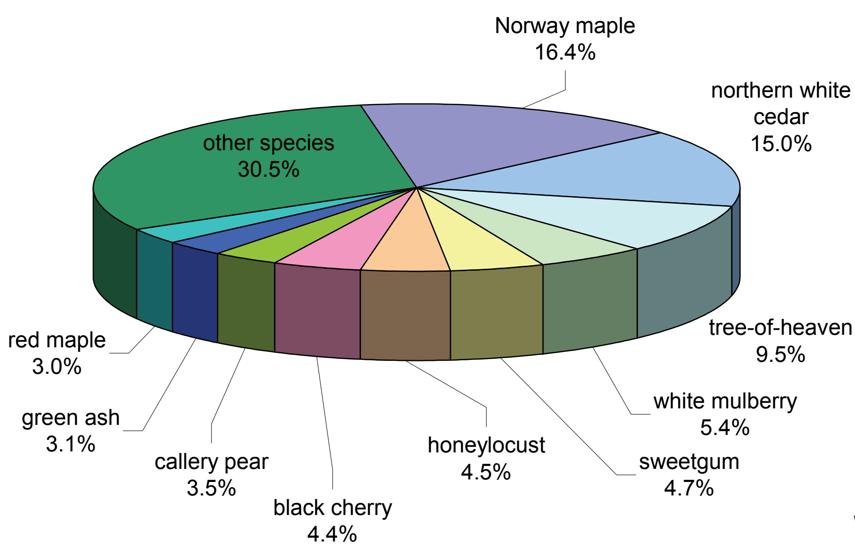

Figure 5.—Species composition in Wilmington.

Wilmington has an estimated 136,000 trees that cover 16.1 percent of the city. Smaller trees (diameters less than or equal to 6 inches) account for 54.2 percent of the population (Fig. 4). The three most common species in the urban forest are Norway maple (16.4 percent), northern white cedar (15.0 percent), and tree-of-heaven (9.5 percent) (Fig. 5). The 10 most common species account for 69.5 percent of all trees. More species information is given in Appendix 2.

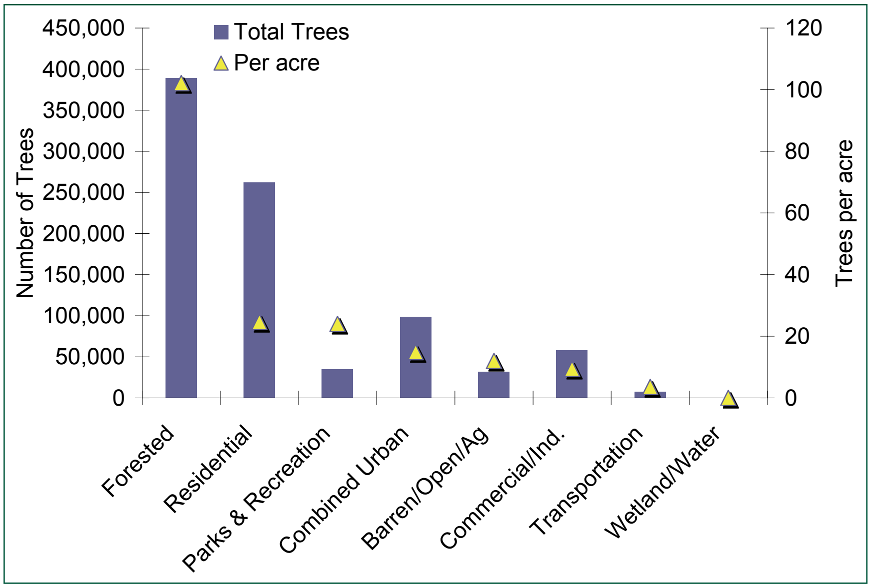

Figure 6.—Tree population and density by land use in NCC metro corridor.

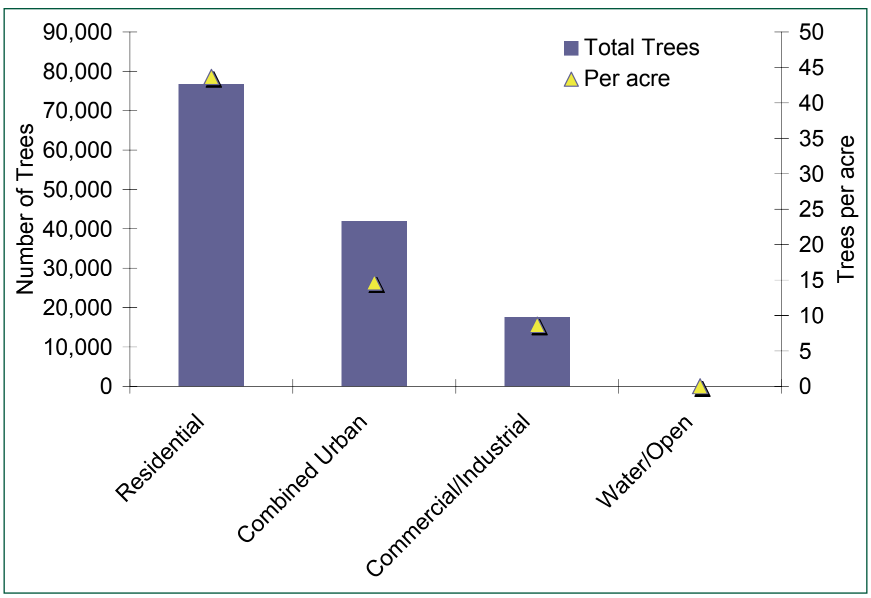

Figure 7.—Tree population and density by land use in Wilmington.

The highest density of trees in NCC occurs in the forested land use (102.1 trees/acre), followed by the residential (24.6 trees/acre) and the parks and recreation (24.0 trees/acre). The overall tree density in NCC is 23.9 trees/acre (Fig. 6).

The highest density of trees in Wilmington occurs in the residential (43.6 trees/acre), followed by the combined urban (14.6 trees/acre) and the commercial/industrial (8.7 trees/acre). There were no trees sampled in the water/open land use. The overall tree density in Wilmington is 18.0 trees/acre (Fig. 7).

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Native Range of Tree Species

Urban forests are a mix of native tree species that existed prior to the development of the city and exotic species that were introduced by residents or by other means. Thus, urban forests often have a tree diversity that is higher than surrounding native landscapes. Increased tree diversity can minimize the overall impact or destruction by a species-specific insect or disease, but the increase in the number of exotic plants can also pose a risk to native plants if some of the exotics species are invasive plants that can potentially out-compete and displace native species.

In the NCC metro corridor, about 70 percent of the trees are species native to Delaware. Trees with a native origin outside of North America are mostly from North America+* and Eurasia (7 and 6 percent of the species, respectively).

Thirty-one percent of Wilmington's trees were native to Delaware. Trees with a native origin outside of North America are mostly from Asia and Eurasia (22 and 18 percent of the species respectively).

Leaf area and biomass

Many tree benefits are linked directly to the amount of healthy leaf surface area. Trees that dominate in terms of leaf area in the NCC are red maple, silver maple, and sweetgum (Fig. 10). In Wilmington, tree species with the most leaf area are Norway maple, sweetgum, and red maple (Fig. 11).

Relatively large trees will contribute more leaf area than small trees. Leaf area directly impacts the ecosystem services that the individual trees produce. We define large trees as

*Native to North America and one other continent not including South America.

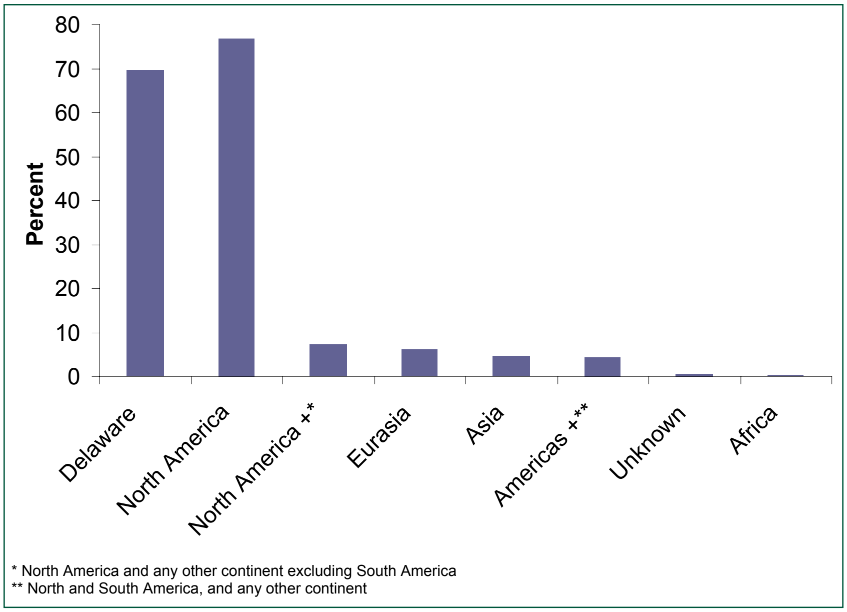

Figure 8.—Native origin of species in the NCC metro corridor.

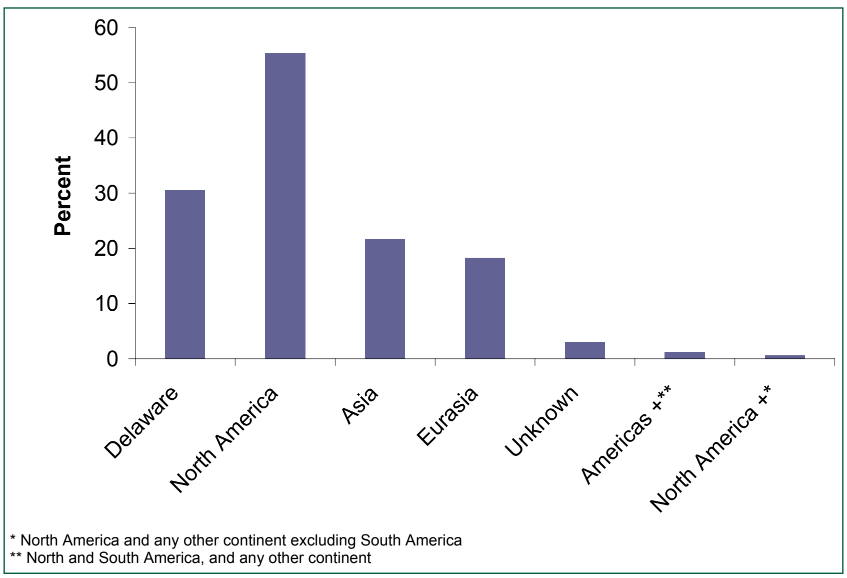

Figure 9.—Native origin of tree species in the city of Wilmington.

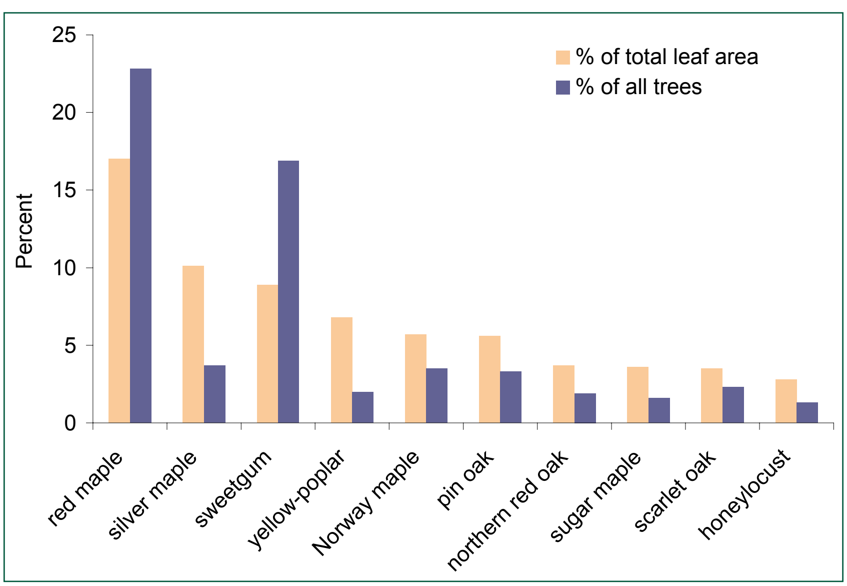

Figure 10.—Percent of tree population and leaf area for 10 most common tree species in NCC metro corridor.

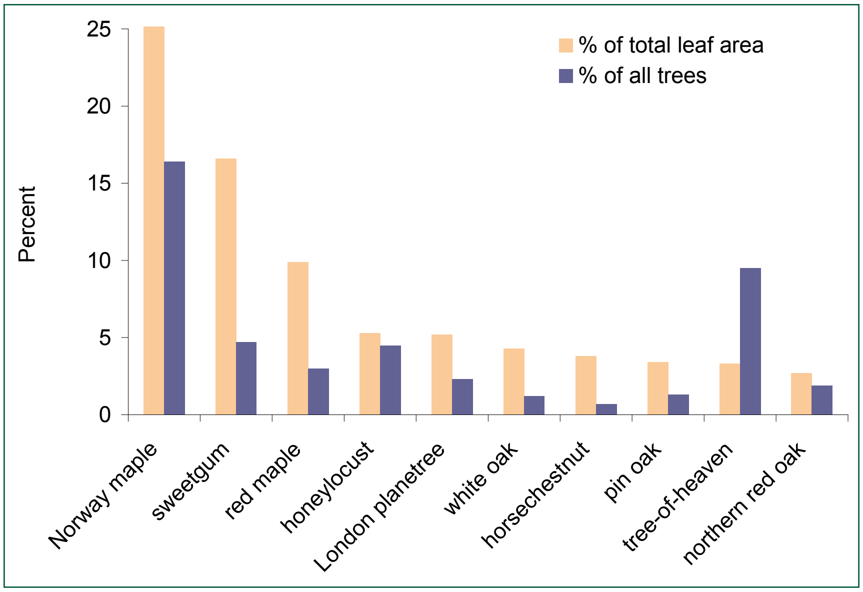

Figure 11.—Percent of tree population and leaf area for 10 most common tree species in Wilmington.

species with percentage of leaf area much greater than percentage of total population, and the opposite goes for smaller trees (species with percentage of leaf area much less than percentage of total population). In the NCC corridor, tree species with relatively large individuals contributing leaf area to the population are yellow-poplar, silver maple, and sugar maple. Smaller trees in the population are black willow, northern white cedar, and sassafras. A species must also constitute at least 1 percent of the population to be considered as relatively large or small trees in the population. In Wilmington, the species contributing the most leaf area per tree were horse chestnut, white oak, and sweetgum. The smaller trees in the population were white spruce, northern white cedar, and Japanese maple.

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Ground covers

In addition to trees and shrubs, various other types of materials and vegetation constitute the urban environment. Some of these additional cover types (e.g., grass) can affect the local environment (pollution removal, transpirational cooling), but information on all ground cover types can be used to determine how much ground space may be available for additional tree or shrub cover. In NCC, herbaceous plants (e.g., grass, gardens, ivy) cover approximately 46 percent of the ground, followed by impervious surfaces (excluding buildings) at 25 percent, and building cover at 14 percent (Fig. 12). In Wilmington, impervious surfaces (excluding buildings) dominate at 34 percent, followed by herbaceous plants (28 percent), and buildings (18 percent) (Fig. 13).

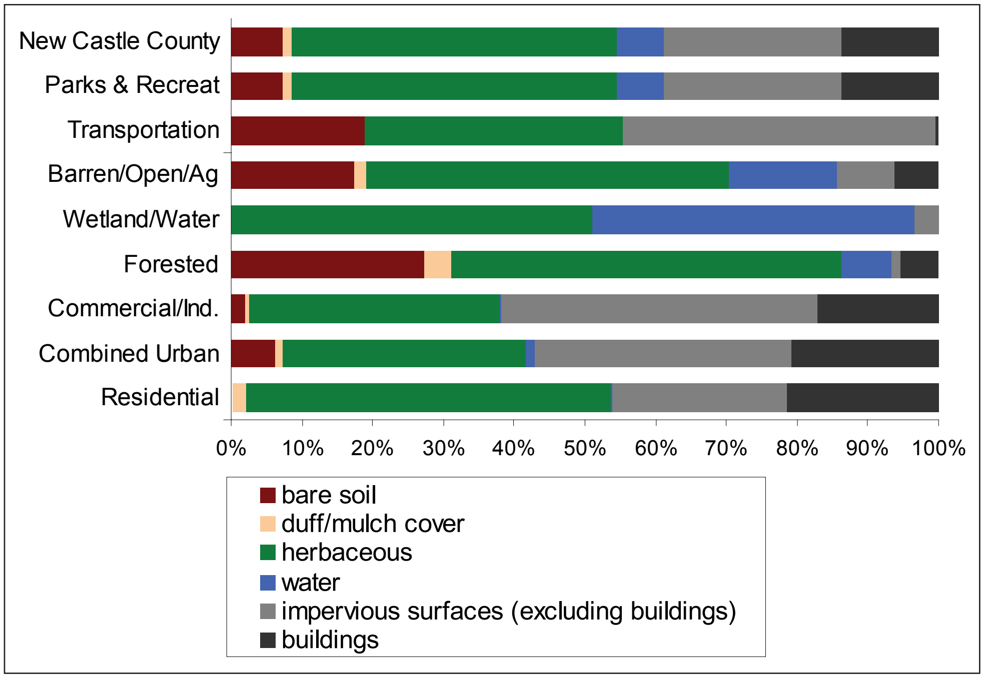

Figure 12.—Ground-cover distribution by land-cover type in NCC metro corridor.

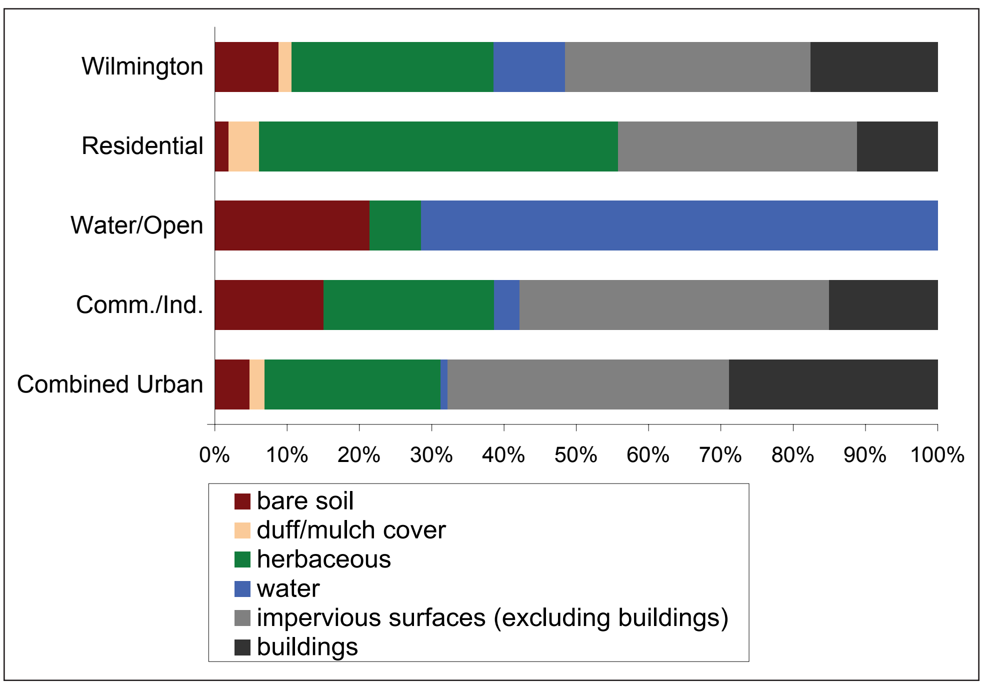

Figure 13.—Ground-cover distribution by land-cover type in Wilmington.

Structural and Ecosystem Services Values

Urban forests have a structural value based on the tree itself (e.g., the cost of having to replace the tree with a similar tree). The structural value[10] of the urban forest in NCC is about $1.2 billion; in Wilmington it is about $166 million. The structural value of an urban forest tends to increase with a rise in the number and size of healthy trees.

Urban forests also have functional values (either positive or negative) based on the functions the tree performs (ecosystem services). These benefits include reducing energy costs to homeowners, carbon sequestration, and removal of air pollutants. Annual functional values tend to increase with increased number and size of healthy trees and are usually on the order of several million dollars per year. There are many other functional values of the urban forest, though they are not quantified here (e.g., reduction in air temperatures and ultra-violet radiation, improvements in water quality). Through proper management, urban forest values can be increased. However, the values and benefits also can decrease as the amount of healthy tree cover declines.

Carbon Storage and Sequestration

Climate change is an issue of global concern. Trees can mitigate climate change by sequestering and storing atmospheric carbon (from carbon dioxide) in vegetative tissue. Carbon storage and sequestration depend on the size and health of the tree. Larger and healthier trees tend to store and sequester more carbon than smaller trees.

Carbon storage by trees is a way that trees can influence global climate change. As trees grow, they store more carbon by holding it in their accumulated tissue. As trees die and decay, they release much of the stored carbon back into the atmosphere. Thus, carbon storage is an indication of the amount of carbon that can be lost if trees are allowed to die and decompose.

The carbon stored in NCC is estimated at 285,000 tons with a value of $5.9 million; in Wilmington trees store 46,000 tons of carbon ($959,000 value).

Trees also reduce the amount of carbon in the atmosphere by sequestering carbon in new growth every year. The amount of carbon sequestered depends on the size and health of the tree. Larger, healthier trees will sequester more carbon then their smaller counterparts.

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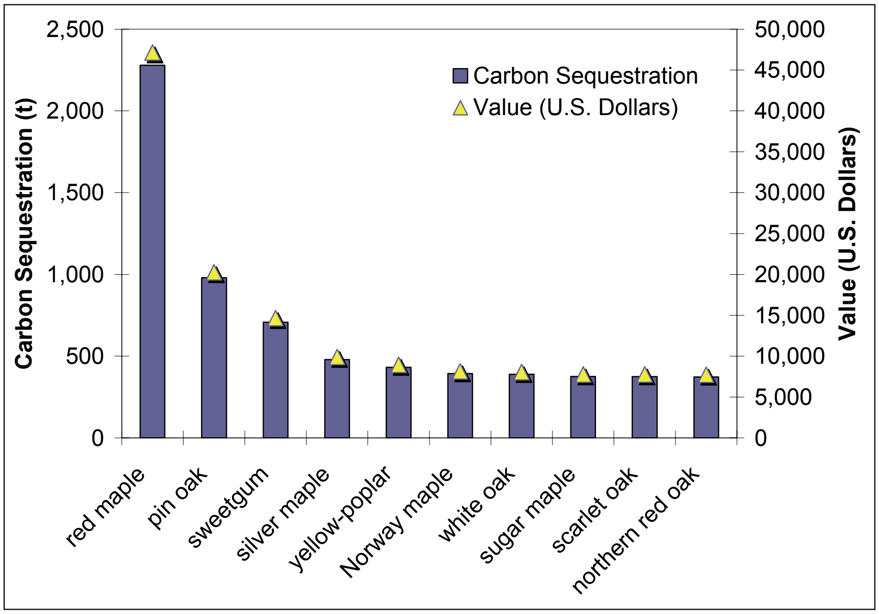

Figure 14.—Annual carbon sequestration and value for 10 most common tree species in NCC metro corridor.

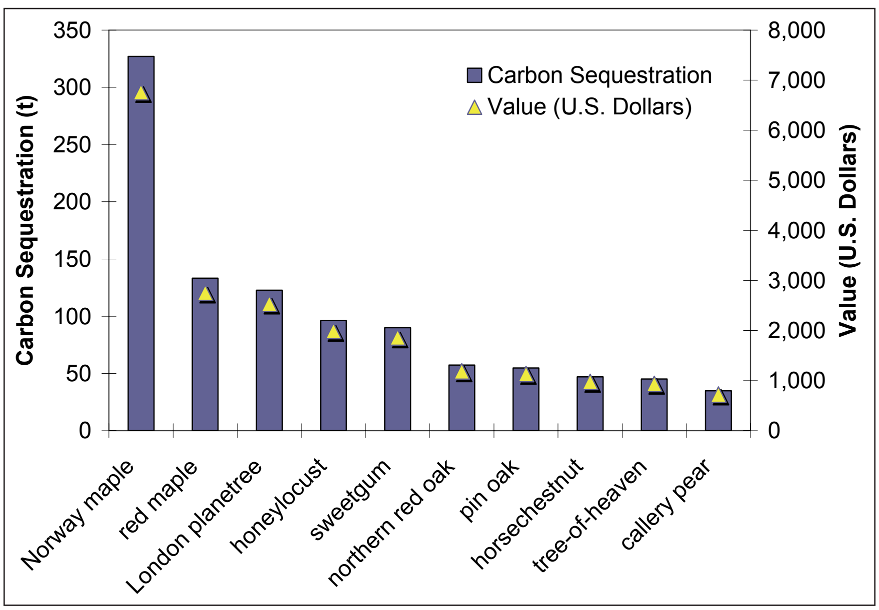

Figure 15.—Annual carbon sequestration and value for 10 most common tree species in Wilmington.

In NCC, trees sequester 10,000 tons of carbon per year with a value of $207,000. The land uses with the highest carbon sequestered per acre are forest (1,900 lbsC/ac/yr), parks and recreation (980 lbsC/ac/yr), and residential (760 lbsC/ac/yr). The lowest rates of sequestration are in water/wetland (0 lbsC/ac/yr), transportation (70 lbsC/ac/yr), and barren/open/agriculture (120 lbsC/ac/yr). The tree species that sequester the most carbon in NCC are red maple, pin oak and sweetgum (Fig. 14).

Wilmington's urban forest sequestered 1,300 tons of carbon with an associated value of $27,000. Trees in residential areas sequester the most carbon per acre (680 lbsC/ac/yr), followed by combined urban (270 lbsC/ac/yr) and commercial/industrial (100 lbsC/ac/yr). The species that sequester the most carbon are Norway maple, red maple and London planetree (Fig. 15).

Energy Savings

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Trees affect energy consumption by shading buildings, providing evaporative cooling, and blocking winter winds. Generally, trees tend to reduce energy use in the summer months and can either increase or decrease consumption in the winter months. When trees reduce the energy consumption of the building, it reduces the amount of energy needed to be produced by power plants. This subsequent reduction is reflected in the tons of carbon avoided. The location of the trees, distance and direction from the building, and size of the tree affect energy use. Trees are considered to interact with buildings if they are greater than 20 feet tall and are within 60 feet of a space-conditioned building.[9]

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It is estimated trees in NCC save approximately $403,000/year in residential building energy costs (Table 3). The reduction of energy use also lessens the amount of carbon released into the atmosphere from power plants by about 1,020 tons/year ($21,000/year) (Table 4).

This trend is mirrored in Wilmington where study results show trees reduce energy costs by $183,000, and carbon from power plants by 475 tons/year ($9,800/year) (Tables 5-6).

Table 3.—Annual savings ($) in residential energy expenditures during heating and cooling seasons in the NCC metro corridor. Note: negative numbers indicate an increase in energy use.

	Heating	Cooling	Total
MBTU†	-45,000	n/a	-45,000
MWH††	-8,000	456,000	448,000
Total	-53,000	456,000	403,000

†One Million British Thermal Units
††Megawatt-hour

Table 4.—Annual energy savings due to trees near residential buildings in the NCC metro corridor. Note: negative numbers indicate an increase in energy use or carbon emissions.

	Heating	Cooling	Total
MBTU†	-5,300	n/a	-5,300
MWH††	-100	4,500	4,400
Carbon avoided (t)	-100	1,120	1,020

†One Million British Thermal Units
††Megawatt-hour

Table 5.—Annual savings ($) in residential energy expenditures during heating and cooling seasons in Wilmington. Note: negative numbers indicate an increase in energy use.

	Heating	Cooling	Total
MBTU[†]	-43,000	n/a	-43,000
MWH[††]	-8,000	234,000	226,000
Total	-51,000	234,000	183,000

[†]One million british thermal units

[††]Megawatt-hour

Table 6.—Annual energy savings due to trees near residential buildings in Wilmington. Note: negative numbers indicate an increase in energy use or carbon emissions.

	Heating	Cooling	Total
MBTU[†]	-5,100	n/a	-5,100
MWH[††]	-100	2300	2,200
Carbon avoided (t)	-100	575	475

[†]One million british thermal units

[††]Megawatt-hour

Air Pollution Removal

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Poor air quality exists in many urban areas. Poor air quality can lead to human health problems, damage to landscape materials and ecosystem processes, and reduced visibility. The urban forest can improve air quality by reducing air temperature, directly removing pollutants from the air, and reducing energy consumption in buildings, which consequently reduce air pollutant emissions from the power plants.

In this study, pollution removal was calculated for both trees and shrubs. Commonly, shrubs remove less pollution than trees. This difference was most pronounced in Wilmington, where trees remove 5.2 times more pollution than shrubs. In NCC, trees remove 1.6 times more pollution than shrubs. This difference is most likely due to the percent shrub cover and associated leaf area in each study. In Wilmington, the shrub cover is 3 percent, where the shrub cover in NCC is 7 percent.

Total pollution removal by tree and shrubs in NCC is 295 tons/year with an associated value of $1.9 million/year. Shrubs remove approximately one-third of that total removal (112 tons/year). Pollution removal was greatest for ozone (O_3), followed by particulate matter less than 10 microns (PM_{10}), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and finally carbon monoxide (CO) (Fig. 16).

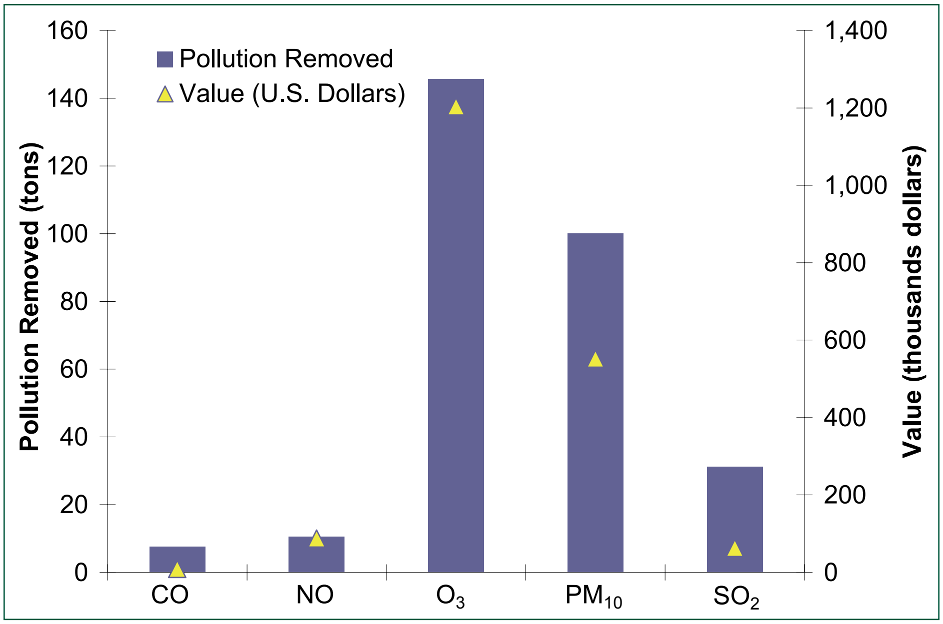

Figure 16.—Pollution removal by trees and shrubs in the NCC metro corridor.

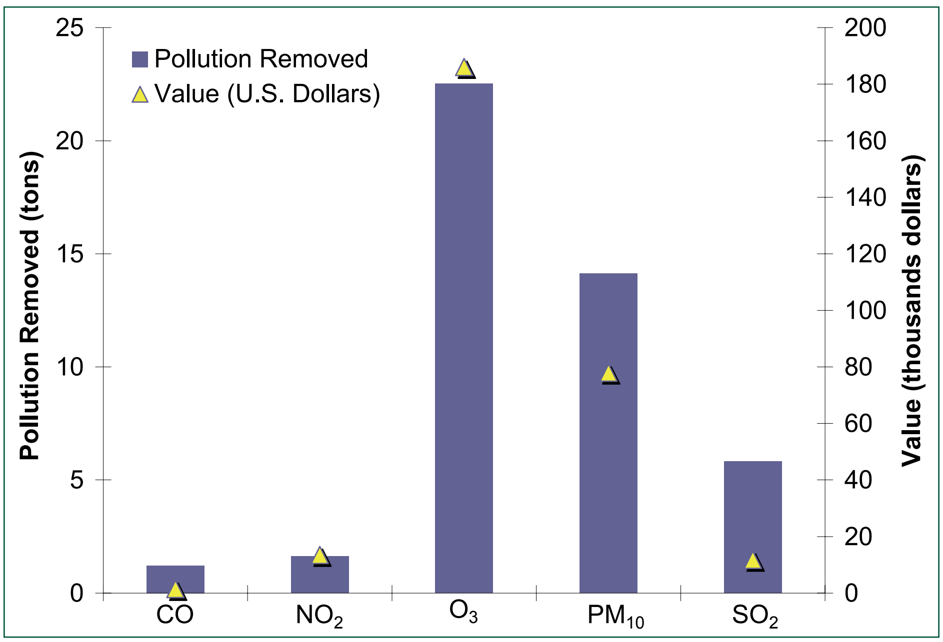

Figure 17.—Pollution removal by trees and shrubs in Wilmington.

Wilmington trees and shrubs remove 45 tons of pollution per year ($291,000/year) with a similar removal pattern as in NCC (Fig. 17). The shrub layer in Wilmington removes only about 7 tons of pollution per year.

The value assigned to pollution removal is calculated using the median externality costs associated with each pollutant[12] adjusted to 2006 values based on the producer's price index.[13] General recommendations for air quality improvement with trees are provided in Appendix 3. Relative tree effects are also provided in Appendix 4.

POTENTIAL PEST IMPACT

Various insects and diseases can infest urban forests, potentially killing trees and reducing the health, value and sustainability of the urban forest. As various pests have differing tree hosts, the potential damage or risk of each pest will differ. Four exotic pests were analyzed for their potential impact: Asian longhorned beetle, gypsy moth, emerald ash borer, and Dutch elm disease (Figs. 18 and 19).

The Asian longhorned beetle (ALB)[14] is an insect that bores into and kills a wide range of hardwood species. ALB represents a potential loss to the NCC urban forest of $515.8 million in structural value, 51.0 percent of the tree population. In Wilmington, $81.5 million of structural value is at risk, approximately 39.2 percent of the population.

Gypsy moth[15] is a defoliator that feeds on many species causing widespread defoliation and tree death if the outbreak conditions last several years. The pest could potentially result in damage to or loss of $442.6 million in the NCC, and 30.6 percent of the tree population. In Wilmington it represents a potential loss of $53.3 million in structural value and 9.1 percent of the population.

Emerald ash borer (EAB)[16] has killed thousands of ash tree in Michigan, Ohio, and Indiana. In the NCC metro corridor, EAB has the potential to affect 1.5 percent of the population with a structural value of $13.9 million. In Wilmington there is a potential to affect 3.1 percent of the population with a structural value of $1.4 million.

American elm, one of the most important street trees in the 20th century, has been devastated by Dutch elm disease.[17] Since first reported in the 1930s, the disease has killed more than 50 percent of the native elm population in the United States. In both of the studies, no known susceptible elm trees were tallied, thus there is no reported risk to Dutch elm disease.


Donald Duerr, U.S. Forest Service, Bugwood.org, 1124042

Asian longhorned beetle.


Thomas B. Denholm, New Jersey Department of Agriculture, Bugwood.org, 1124042

Asian longhorned beetle damage.


USDA, APHIS PPQ, Bugwood.org 2652084

Gypsy moth.


Joseph O'Brien, U.S. Forest Service, Bugwood.org 5037070

Dutch elm disease.


David Cappaert, Michigan State University, Bugwood.org 9000019

Emerald ash borer.

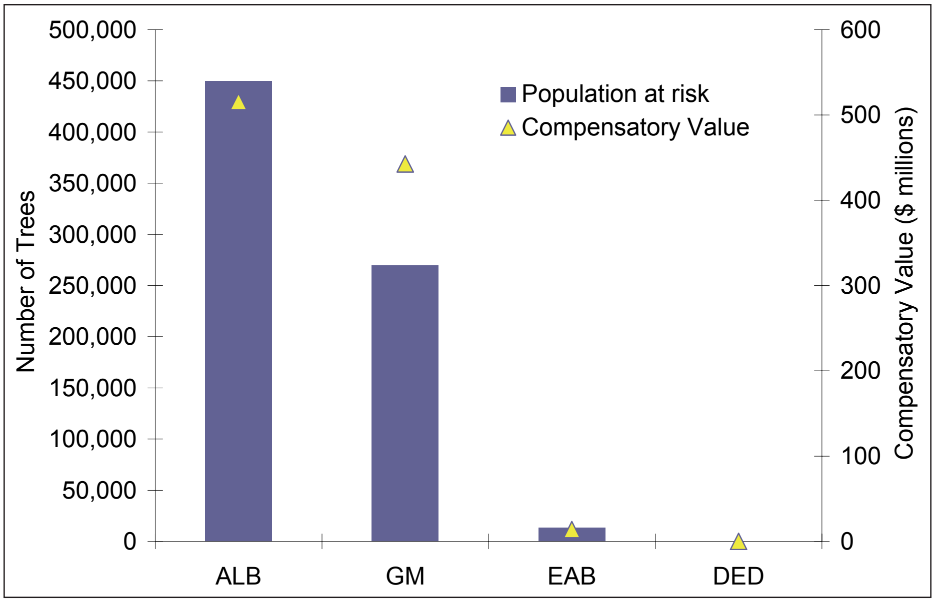

Figure 18.—Total number and structural value of trees susceptible to the Asian longhorned beetle (ALB), gypsy moth (GM), emerald ash borer (EAB), and Dutch elm disease (DED) in the NCC metro corridor.

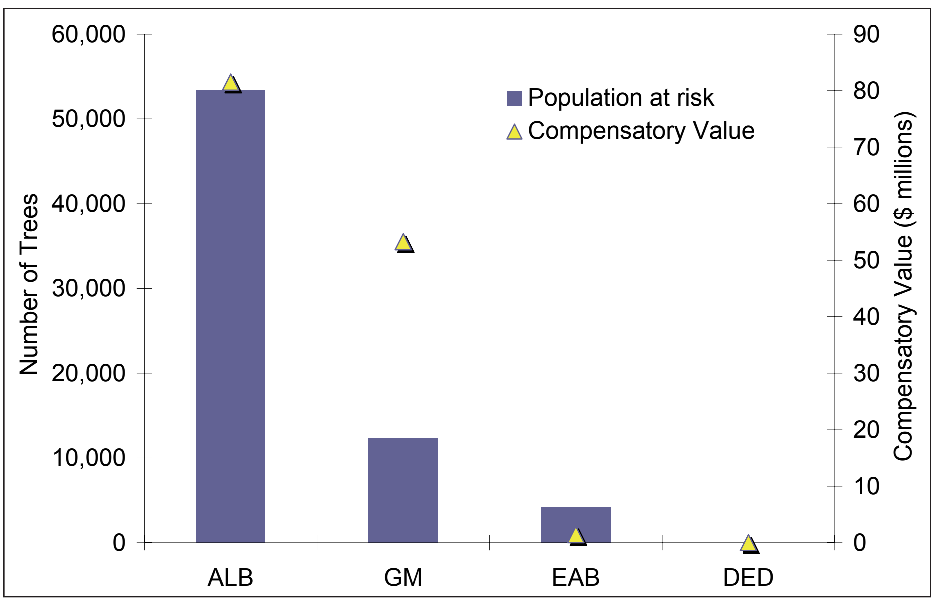

Figure 19.—Number and compensatory value of trees susceptible to the Asian longhorned beetle (ALB), gypsy moth (GM), emerald ash borer (EAB), and Dutch elm disease (DED) in Wilmington.

PRIORITY PLANTING INDEX

To determine the best locations to plant trees, tree canopy and impervious cover maps from National Land Cover Data[18] (Figs. 20-23) were used in conjunction with 2000 U.S. Census data to produce an index of priority planting areas (Figs. 24-25). Index values were produced for each census block group with the higher the index value, the higher the priority of the area for tree planting. This index is a type of "environmental equity" index with areas with higher human population density and lower tree cover tending to get the higher index value. The criteria used to make the index were:

- Population density: the greater the population density, the greater the priority for tree planting
- Tree stocking levels: the lower the tree stocking level (the percent of available greenspace (tree, grass, and soil cover areas) that is occupied by tree canopies), the greater the priority for tree planting
- Tree cover per capita: the lower the amount of tree canopy cover per capita (m2/capita), the greater the priority for tree planting

Each criteria was standardized[19] on a scale of 0 to 1 with 1 representing the census block with the highest value in relation to priority of tree planting (i.e., the census block with highest population density, lowest stocking density or lowest tree cover per capita were standardized to a rating of 1). Individual scores were combined and standardized based on the following formula to produce an overall priority index value between 0 and 100:

$$I = (PD * 40) + (TS * 30) + (TPC * 30)$$

Where I = index value, PD is standardized population density, TS is standardized tree stocking, and TPC is standardized tree cover per capita.

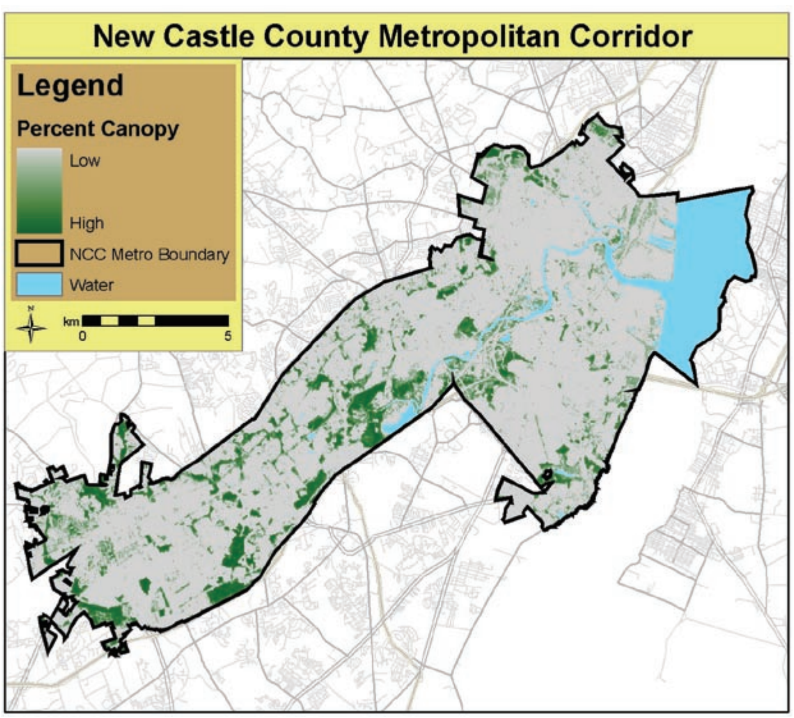

Figure 20.—Existing canopy cover for the NCC metro corridor.

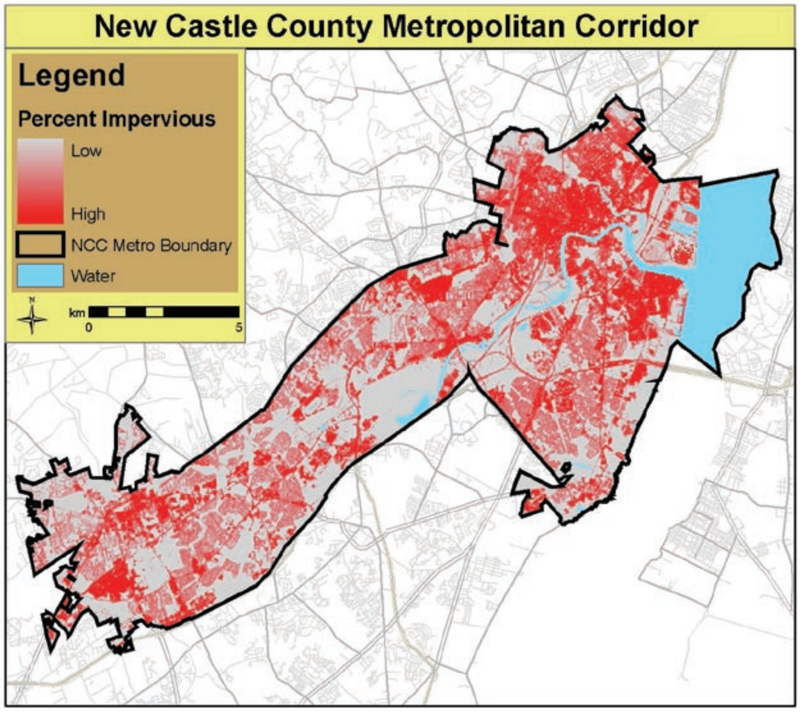

Figure 21.—Impervious cover in the NCC metro corridor.

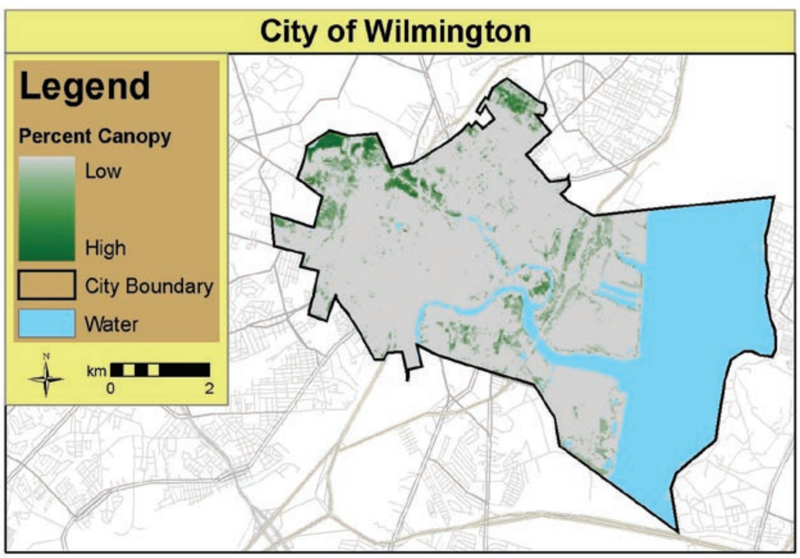

Figure 22.—Existing canopy cover for Wilmington.

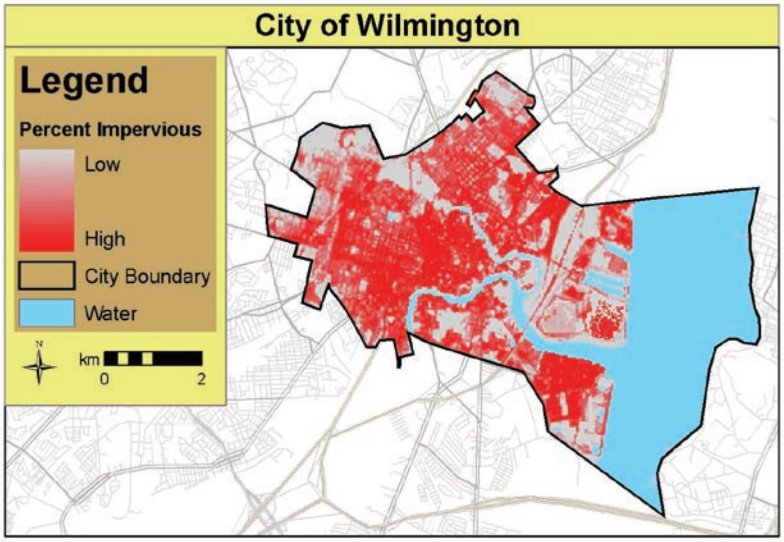

Figure 23.—Impervious cover in Wilmington.

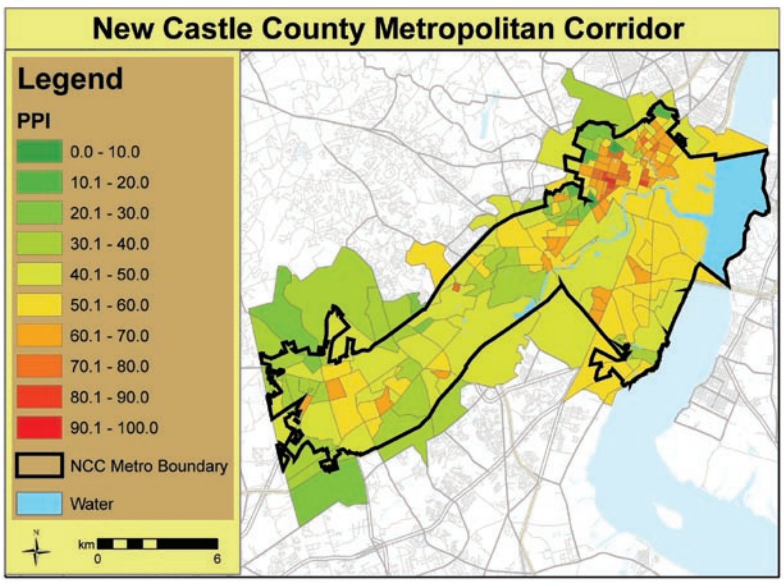

Figure 24.—Priority planting areas for the NCC metro corridor. The higher the index value, the higher the priority.

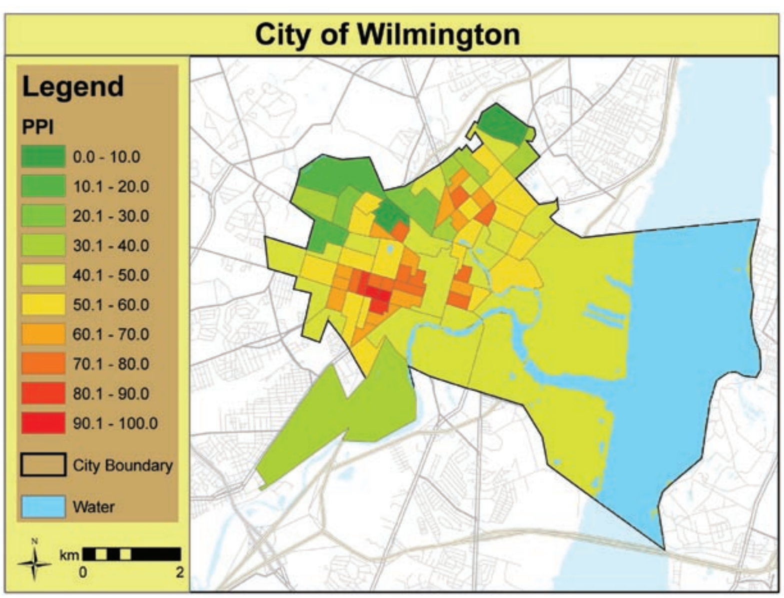

Figure 25.—Priority planting areas for Wilmington. The higher the index value, the higher the priority.

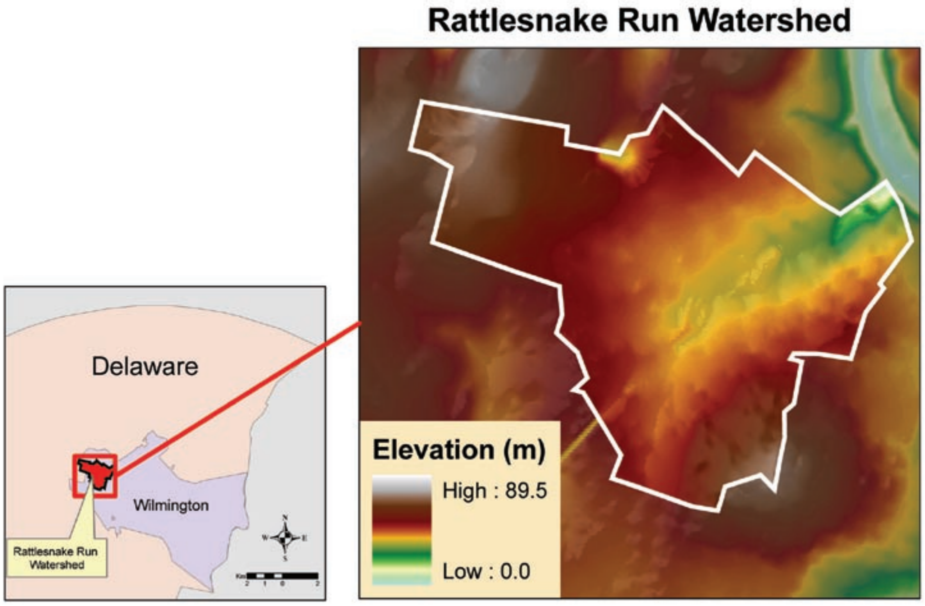

Figure 26.—Location of Rattlesnake Run sewershed.

RATTLESNAKE RUN SEWERSHED ANALYSIS

The sewershed of Rattlesnake Run in the city of Wilmington (Fig. 26) was analyzed using the UFORE-Hydro model[20], which was modified to meet the conditions of a sewershed.[21] The goal of this analysis was to determine the potential effect of changes in tree cover in this heavily impervious sewershed on pipe discharge.

The UFORE-Hydro model creates a pipe-flow hydrograph using hourly precipitation data along with a digital elevation model and cover parameters derived from UFORE and National Land Cover Data (NLCD).[18] Some of the base model parameters were:

- Impervious cover with no tree cover = 50.9 percent
- Impervious connectivity to pipes = 100 percent
- Tree cover = 8.9 percent
  - Over pervious surfaces = 5.7 percent
  - Over impervious surfaces = 3.2 percent
- Shrub cover = 7.8 percent
- Grass cover = 25 percent
- Leaf area index = 4.7

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Table 7.—Summary of flow partitioning in Rattlesnake Run during simulation period

	Height (mm)	Volume (m^3)	Height (in)	Volume (ft^3)
Sanitary flow type	427.7	774,094	16.84	27,336,880
Impervious flow	150.7	272,752	5.93	9,632,143
Subsurface flow	34.4	62,261	1.35	2,198,712
Pervious runoff flow	0.03	54	0.001	1,917
Total observed flow	**612.83**	**1,109,161**	**24.12**	**39,169,652**
Total rainfall	317	573,738	12.48	20,261,377

The model was calibrated using hourly sewer flow data collected at the Brandywine Park gauge from August 8, 2001 to February 10, 2002 (Table 7; Fig. 27). Model calibration indicated a reasonable fit to the measured flow data (Fig. 28). One issue of the model calibration was that the model used a repeating daily curve for anthropogenic flows (showers, toilets), thus could not account for random variations in water use. This pattern affected the base flow calibration coefficient. The calibration coefficients of the model were (1.0 = perfect fit):

- Peak flow weighted = 0.62
- Base flow weighted = 0.32
- Balance flow (peak and base) = 0.67

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After calibration, the model was run by varying the amount of tree cover to estimate the effect of changes in canopy cover on sewershed flow during the model simulation period. As tree cover in the sewershed totaled 8.9 percent, simulations were run in 5 percent increments using 10 percent tree cover as the current base case. For the base run, 5 percent tree cover was modeled over pervious cover and 5 percent over impervious cover (10 percent total tree cover). For simulations of changes in tree cover over

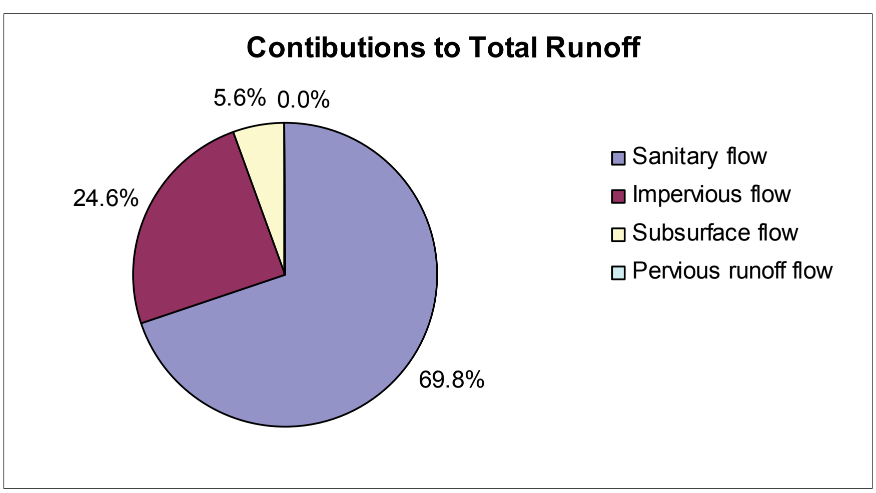

Figure 27.—Percent contribution of sources of flow to total observed flow in Rattlesnake Run sewershed during simulation period.

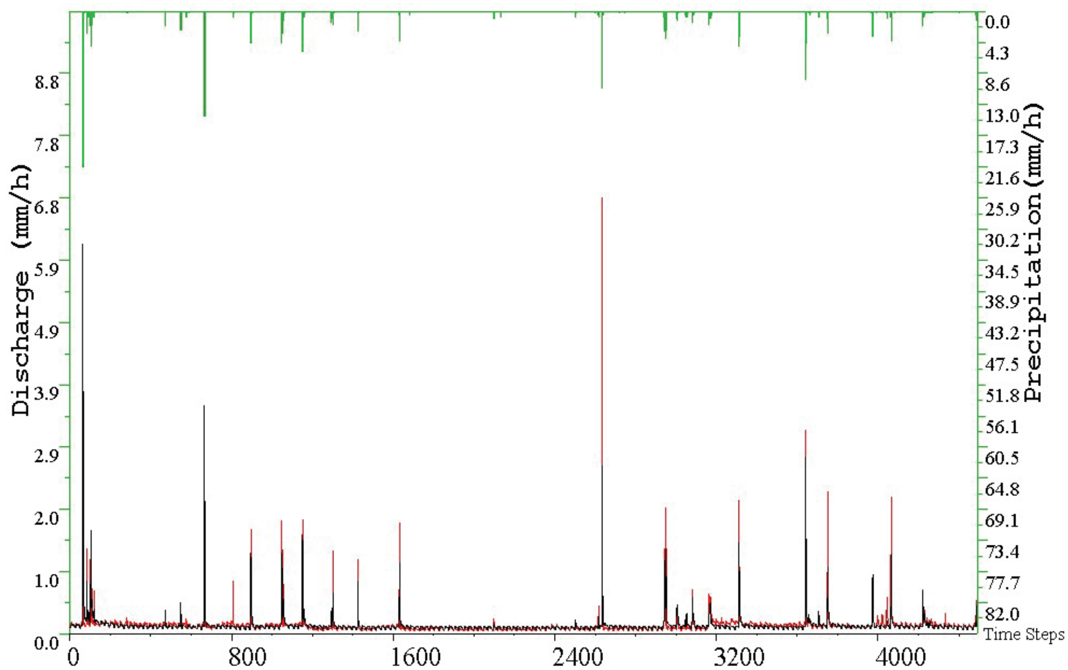

Figure 28.—Actual flow data versus predicted flow data for Rattlesnake Run during modeling period (8/8/01 to 2/10/02). Green bars indicate precipitation amounts; red lines indicate observed discharge data; black lines indicate model simulated discharge data.

pervious land, tree cover over impervious was held at 5 percent and tree cover over pervious land was changed in 5 percent increments from 0 to 45 percent tree cover. Similarly, for simulations of changes in tree cover over impervious land, tree cover over pervious was held at 5 percent and tree cover over impervious land was changed in 5 percent increments from 0 to 45 percent tree cover. One additional run of 0 percent tree cover was run to estimate the effect of no trees. Outputs of total flow during the simulation period were contrasted for the pervious and impervious tree cover changes to illustrate the potential impact of tree cover changes on sewershed flow in Rattlesnake Run.

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In addition, 10 storm events were simulated to estimate the effect of increased tree cover on peak flow during the rain event. One storm event was also simulated with trees leaf-on (August 27 storm event) and trees leaf-off (November 20 storm event). During leaf-off period, deciduous trees and shrubs would drop their leaves, but evergreen trees (33.5 percent of the tree population) and evergreen shrubs (72.5 percent of the shrub population) would retain their leaves, as would grass ground-cover types. During these simulations, tree cover was increased by 25 percent over impervious surfaces (total tree cover = 33.9 percent; impervious tree cover = 30.7 percent; pervious tree cover = 3.2 percent), and by 50 percent over impervious cover (total tree cover = 58.9 percent; impervious tree cover = 55.7 percent; pervious tree cover = 3.2 percent).

Under the simulation of an addition 50 percent tree cover, nearly the entire impervious cover of Rattlesnake Run is covered by trees (only 0.9 percent of the sewershed would have noncovered impervious surfaces). This simulation is not realistic in terms of canopy cover, but illustrates the near potential maximum effect of additional canopy cover over impervious surfaces.

Overall Simulation Period Effects

Assuming 10 percent tree cover as a starting case (5 percent tree cover over pervious cover and 5 percent over impervious cover), the total nonsanitary sewershed flow during the simulation period was 11,772,000 ft^3 (333,356 m^3). Increasing tree cover to 45 percent of pervious areas (with 5 percent tree cover impervious land for a total of 50 percent tree cover) reduced total nonsanitary flow to 11,572,000 ft^3 (327,686 m^3) (1.7 percent reduction), while increasing tree cover to 45 percent over impervious areas (with 5 percent tree cover pervious land for a total of 50 percent tree cover) reduced total nonsanitary flow to 10,637,000 ft^3 (301,198 m^3) (10.7 percent reduction) (Fig. 29; Table 8).

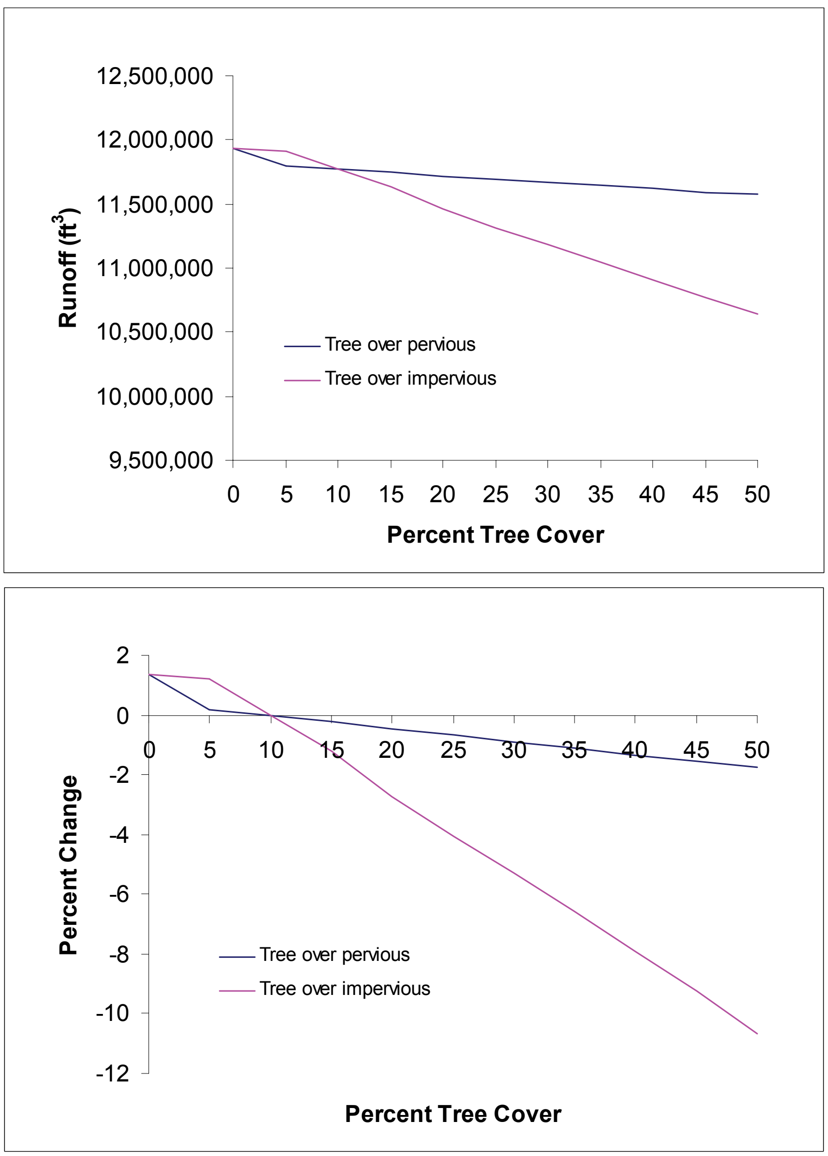

Figure 29.—Simulated effect of changes in tree cover over pervious cover versus effect of changes in tree cover over impervious cover on total runoff (cubic feet and percent) in Rattlesnake Run during the simulation period (8/8/01 to 2/10/02). Exclusive of 0 percent tree cover run, all simulations held tree cover over one class (pervious or impervious) constant at 5 percent while varying the other class in 5 percent increments (see Table 8). Base case run was 10 percent tree cover.

Table 8.—Percent tree cover over pervious and impervious areas for tree cover simulations of trees over pervious areas and trees over impervious areas (Fig. 29)

Tree over pervious			Tree over impervious		
	Tree cover over:			Tree cover over:	
Tree Cover	Pervious	Impervious	Tree cover	Pervious	Impervious
0	0	0	0	0	0
5	0	5	5	5	0
10	5	5	10	5	5
15	10	5	15	5	10
20	15	5	20	5	15
25	20	5	25	5	20
30	25	5	30	5	25
35	30	5	35	5	30
40	35	5	40	5	35
45	40	5	45	5	40
50	45	5	50	5	45

The greatest effect on nonsanitary flow was by tree cover over impervious areas as impervious area flow contributes to over 80 percent of the nonsanitary flow (Table 7). Trees over pervious areas had a relatively minor effect on nonsanitary flow, with most of the effect being on reducing subsurface groundwater flow, but also a minor reduction in runoff from pervious areas. Overall, existing vegetation cover in the sewershed is estimated to reduce nonsanitary flow by 1.4 percent during the simulation period. As much of the simulation period (August 8, 2001 to February 10, 2002) occurred during the leaf-off season (though evergreen and ground cover leaves still exist during that period), the existing vegetation effect would be expected to be higher if the simulation period was entirely during a leaf-on season.

Leaf-on versus Leaf-off Effects

To illustrate differences in leaf-on vs. leaf-off effects, an identical storm was simulated on two different dates. The storm of August 27, 2001 (0.08 inch, 1-hour event at 5 p.m.) was also simulated on November 20, 2001 (5 a.m.) by changing the rain event on this day to a 1-hour period (precipitation amount on November 20 was the same as on August 27, but fell over a 4-hour period). During the leaf-on simulation, peak flow was reduced by 48 percent by increasing cover by 25 percent (all over impervious surfaces), and reduced by 95 percent by increasing cover by 50 percent (all over impervious surfaces) (Fig. 30; Appendix 5). During the leaf-off simulation, peak flow was reduced by 26 percent by

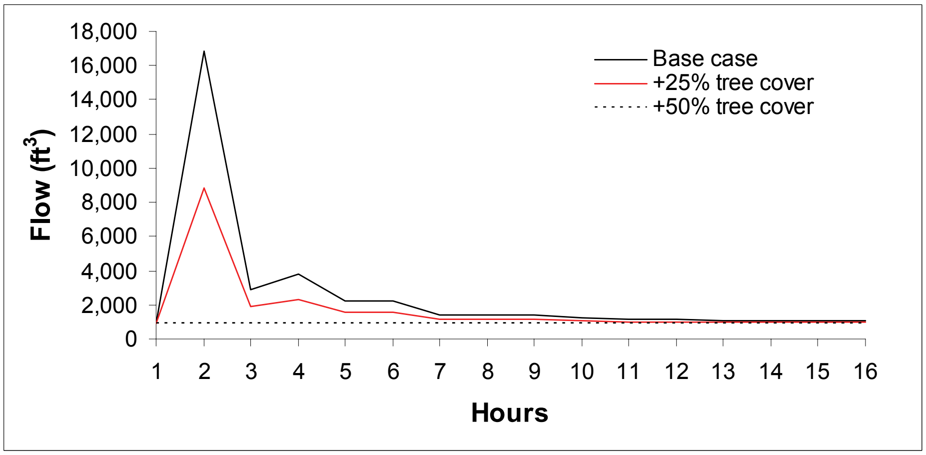

Figure 30.—Simulated effect of increasing tree cover over impervious surfaces on nonsanitary outlet flow during a 1-hour, 0.08-inch, leaf-on rain event on August 30, 2001.

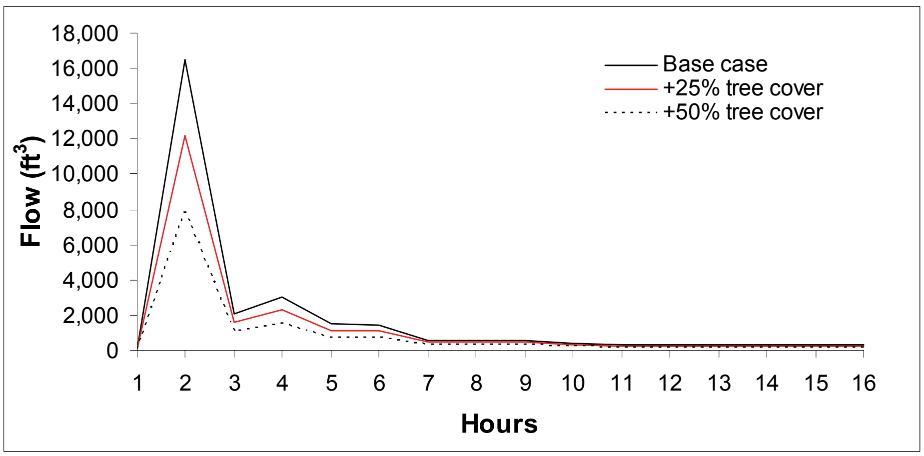

Figure 31.—Simulated effect of increasing tree cover over impervious surfaces on nonsanitary outlet flow during a simulated 1-hour, 0.08-inch, leaf-off rain event on November 20, 2001.

increasing cover by 25 percent (all over impervious surfaces), and reduced by 52 percent by increasing cover by 50 percent (all over impervious surfaces) (Fig. 31; Appendix 5). The leaf-off effect is mostly due the effects of bark surfaces and evergreen vegetation on intercepting rainfall. The percent effect for both simulations is relatively high as percent effect tends to increase as precipitation during the storm event decreases. Thus, as can be seen in the following storm simulations, trees have the greatest relative effect on runoff during smaller storm events.

Peak Storm Effects

To illustrate the effect of increased tree cover over impervious surfaces on peak flow, the first 10 storm events of the simulation period are presented. Similar to the leaf-off – leaf-on simulation, tree cover was increased by 25 and 50 percent over impervious surfaces. Reductions in peak flow varied from 1.1 to 47.6 percent for a 25 percent canopy increase (all over impervious surfaces), and from 2.2 to 94.6 percent for a 50 percent canopy increase (all over impervious surfaces). Percent reduction in flow tended to decrease as storm precipitation increased (Table 9; Figs. 32-41).

Table 9.—Percent peak flow reduction for 10 storm events due to increasing tree cover by 25 and 50 percent over impervious surfaces.

Simulation			Duration	Total rainfall		Peak flow reduction (%)	
Storm No.	Date	Start time	hrs	mm	in	25% tree cover	50% tree cover
1	8/10/2001	3 pm	3	36.32	1.43	1.1	2.2
2	8/27/2001	5 pm	1	2.03	0.08	47.6	94.6
3	8/30/2001	9 pm	1	2.54	0.10	29.6	59.3
4	9/4/2001	6 pm	2	14.73	0.58	3.3	6.5
5	9/14/2001	6 am	9	12.70	0.50	4.2	8.4
6	9/20/2001	2 pm	16	18.03	0.71	5.1	17.4
7	9/24/2001	7 pm	16	16.76	0.66	4.7	12.6
8	9/30/2001	9 pm	18	8.38	0.33	3.5	7.0
9	10/6/2001	9 am	4	4.57	0.18	33.6	58.3
10	10/14/2001	10 pm	5	9.14	0.36	1.9	3.8

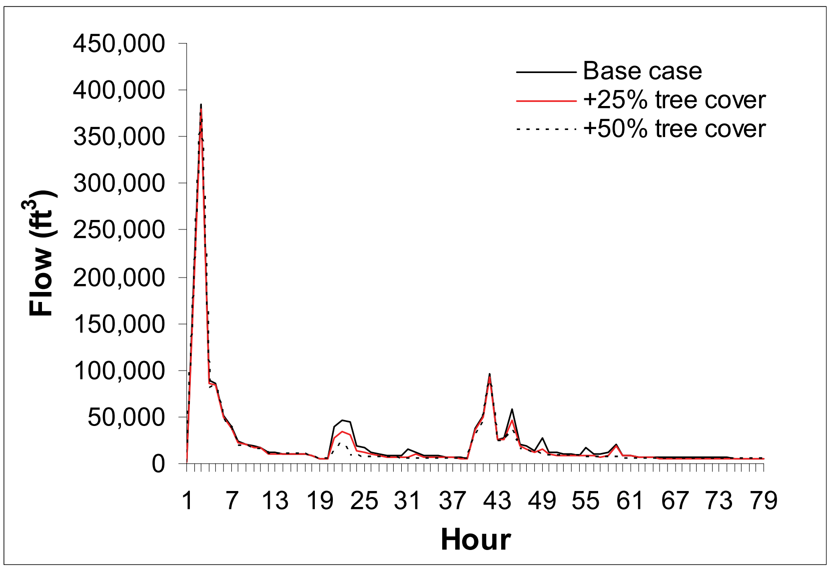

Figure 32.—Simulated effect of increasing tree cover over impervious surfaces on nonsanitary outlet flow during a 2.5-day intermittent, 1.43-inch rain event (Storm 1) on August 10, 2001 (see Appendix 6).

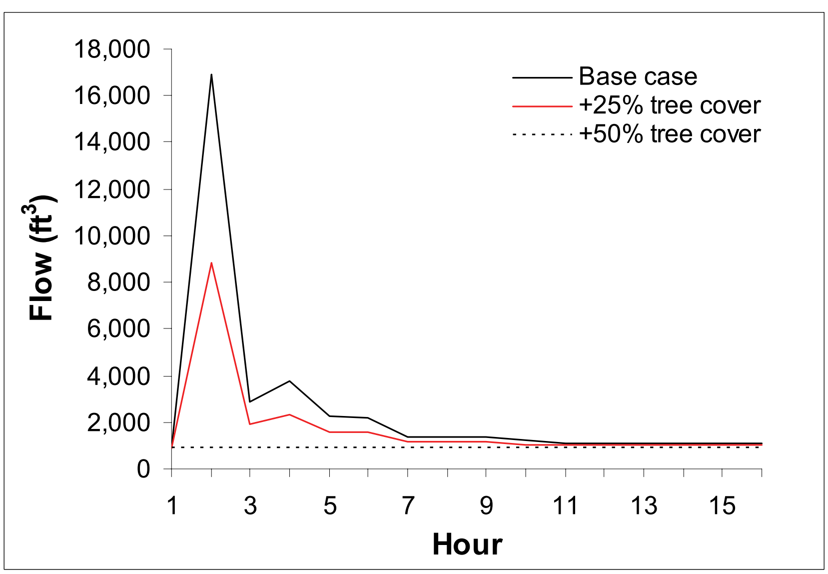

Figure 33.—Simulated effect of increasing tree cover over impervious surfaces on nonsanitary outlet flow during a 1-hour, 0.08-inch rain event (Storm 2) on August 27, 2001 (see Appendix 6).

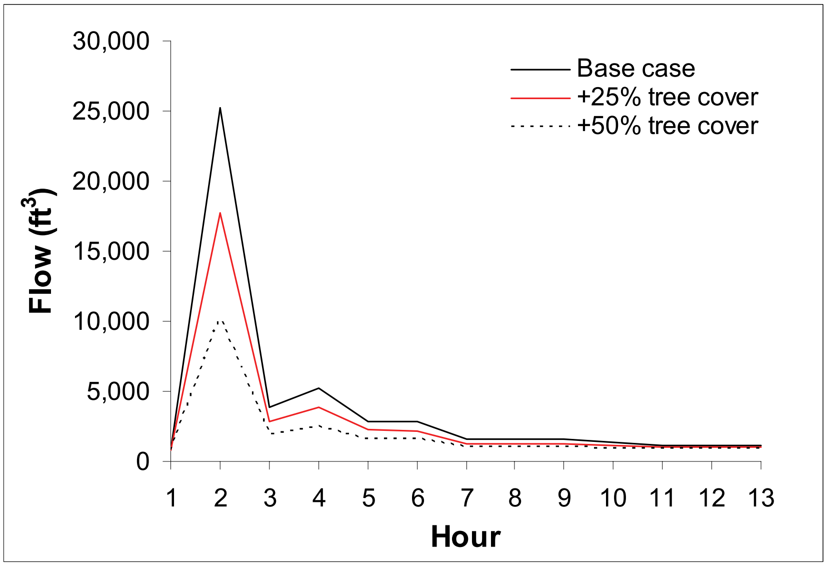

Figure 34.—Simulated effect of increasing tree cover over impervious surfaces on nonsanitary outlet flow during a 1-hour, 0.10-inch rain event (Storm 3) on August 30, 2001 (see Appendix 6).

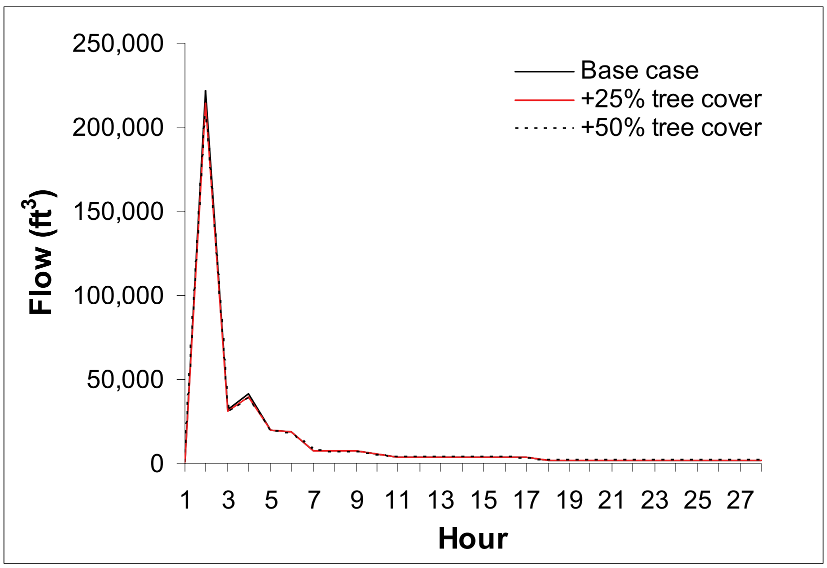

Figure 35.—Simulated effect of increasing tree cover over impervious surfaces on nonsanitary outlet flow during a 2-hour, 0.58-inch rain event (Storm 4) on September 4, 2001 (see Appendix 6).

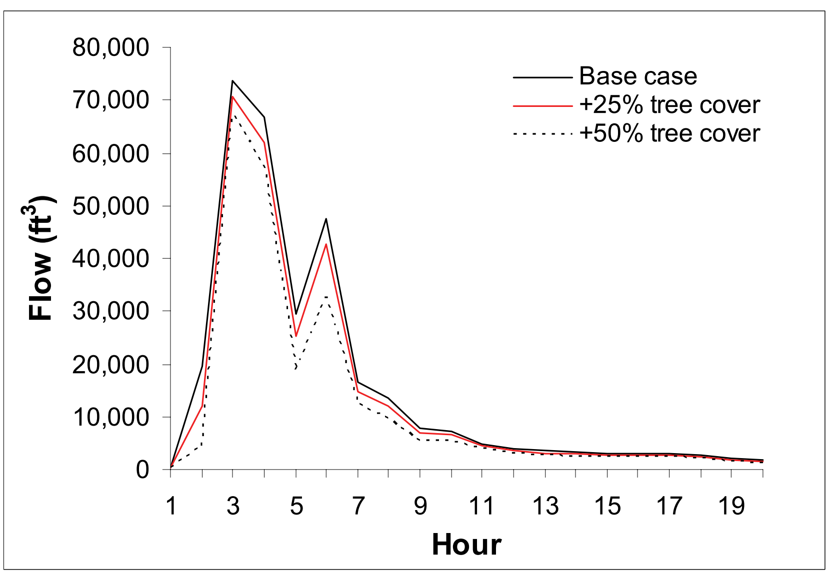

Figure 36.—Simulated effect of increasing tree cover over impervious surfaces on non-sanitary outlet flow during a 9-hour, 0.50-inch rain event (Storm 5) that started on September 14, 2001 (see Appendix 6).

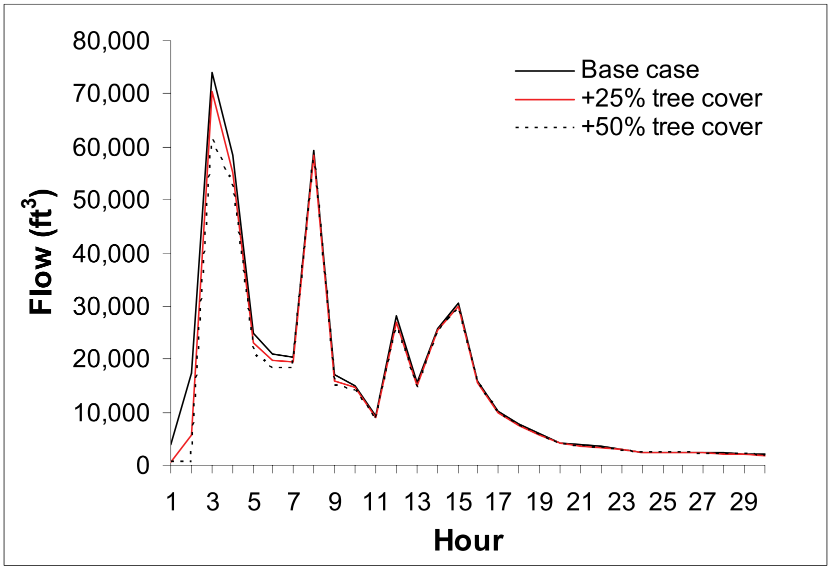

Figure 37.—Simulated effect of increasing tree cover over impervious surfaces on nonsanitary outlet flow during a 16-hour, 0.71-inch rain event (Storm 6) that started on September 20, 2001 (see Appendix 6).

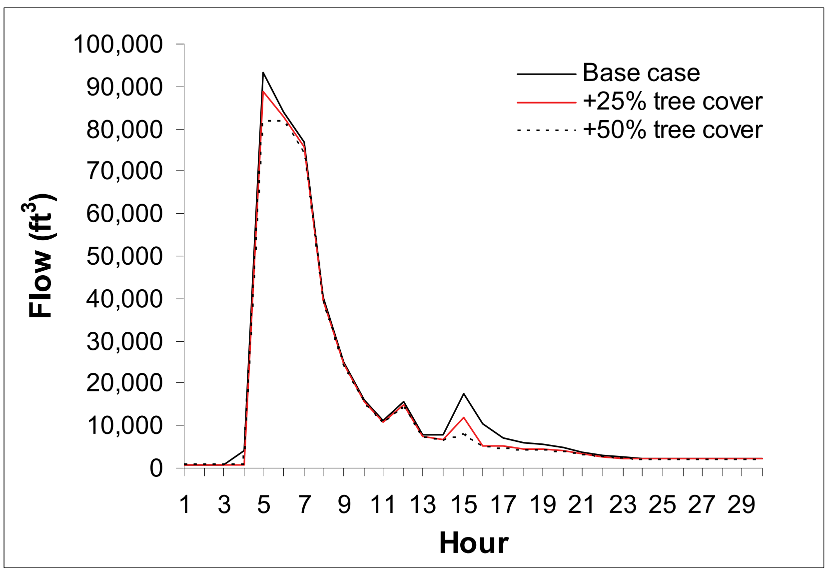

Figure 38.—Simulated effect of increasing tree cover over impervious surfaces on nonsanitary outlet flow during a 16-hour intermittent, 0.66-inch rain event (Storm 7) that started on September 24, 2001 (see Appendix 6).

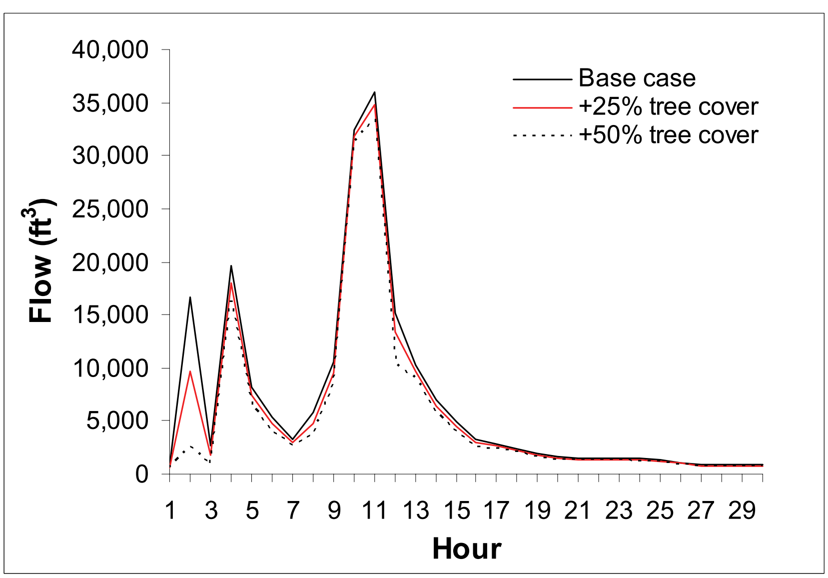

Figure 39.—Simulated Effect of increasing tree cover over impervious surfaces on nonsanitary outlet flow during an 18-hour intermittent, 0.33-inch rain event (Storm 8) that started on September 30, 2001 (see Appendix 6).

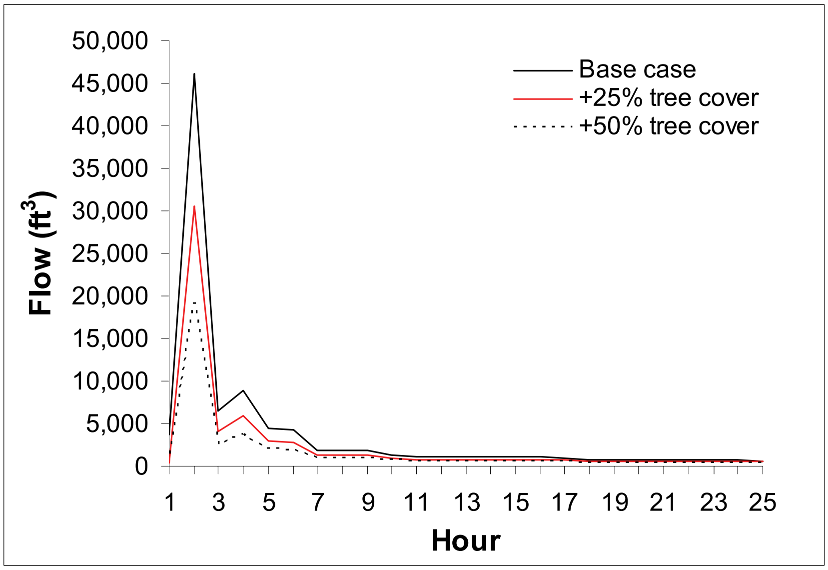

Figure 40.—Simulated effect of increasing tree cover over impervious surfaces on nonsanitary outlet flow during a 4-hour, 0.18-inch rain event (Storm 9) on October 6, 2001 (see Appendix 6).

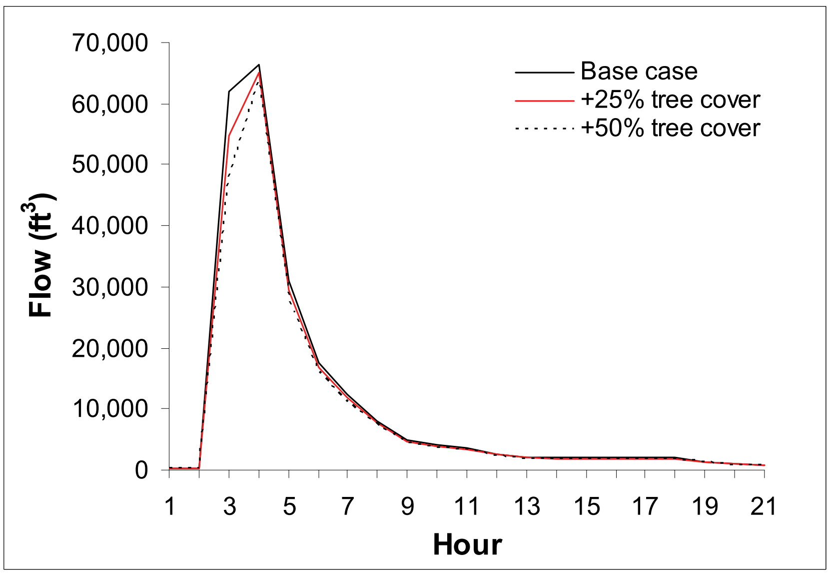

Figure 41.—Simulated effect of increasing tree cover over impervious surfaces on nonsanitary outlet flow during a 5-hour, 0.36-inch rain event (Storm 10) on October 14, 2001 (see Appendix 6).

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15 Northeastern Area State and Private Forestry. 2005. **Gypsy moth digest.** Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Area State and Private Forestry. http://www.na.fs.fed.us/fhp/gm/ Last accessed July 2007.

16 Northeastern Area State and Private Forestry. 2005. **Forest health protection emerald ash borer home.** Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Area State and Private Forestry. http://www.na.fs.fed.us/fhp/eab (July 2007).

17 Stack, R.W.; McBride, D.K.; Lamey, H.A. 1996. **Dutch elm disease.** PP-324 (revised). Fargo, ND: North Dakota State University, Cooperative Extension Service. http://www.ext.nodak.edu/extpubs/plantsci/trees/pp324w.htm (July 2007).

18 National Land Cover Data 2001 www.epa.gov/mrlc/nlcd.html. (July 2007).

19 Standardized value for population density was calculated as: PD = (n – m) / r where: PD is the value (0-1), n is the value for the census block (population / km^2), m is the minimum value for all census blocks, and r is the range of values among all census blocks (maximum value – minimum value). Standardized value for tree stocking was calculated as: TS = (1 – (T/(T+G)) where: TS is the value (0-1), T is percent tree cover, and G is percent grass cover. Standardized value for tree cover per capita was calculated as: TPC = 1 – [(n – m) / r], where: TPC is the value (0-1), n is the value for the census block (m^2/capita), m is the minimum value

for all census blocks, and r is the range of values among all census blocks (maximum value – minimum value).

20 Wang, J.; Endreny, T.A.; Nowak, D.J. 2008. **Mechanistic simulation of urban tree effects in an urban water balance model.** Journal of American Water Resource Association. 44(1): 75-85.

21 Trees' interception of rainfall is the major factor in this sewershed analysis. For the interception routine in UFORE-Hydro, precipitation is distributed onto the surface of the watershed with a percentage intercepted by either tree canopy or shrub/ground cover canopy, and then the remainder reaching the lower impervious or pervious cover.

The UFORE-Hydro interception algorithm is deterministic and provides a unique adjustment and combination of existing physically based subroutines by Rutter et al.[22, 23] rather than the empirical methods based on gross precipitation.[24] The interception routine is based on the Rutter model, but considers sparse vegetation[25], keeps a running water balance of the canopy and vegetative stem (i.e., branch and trunk), and simulates influence of precipitation intensity, duration, and a changing tree canopy. Testing of the Rutter model has occurred in numerous forest types around the world.[26-30] The Rutter interception theory has been advanced to consider throughfall in sparse vegetation[25,31], providing insights useful for the tree structure common in the urban forest.

UFORE-Hydro modified the Rutter model by incorporating a seasonally varying leaf area index (LAI) interception storage term, included simulation of sparse vegetation, and reduced model parameters by constraining canopy drip until storage is filled. Interception of precipitation by the canopy is controlled both by weather dynamics of precipitation intensity and duration, and tree characteristics of leaf area, storage capacity, and initial storage. The interception equation in UFORE-Hydro is

$$\Delta C/\Delta t = P - R - E \qquad (1)$$

where C (m) is the depth of water on the unit canopy at time t, P is above-canopy precipitation in meters/second (m/s), R (m/s) is the below canopy throughflow precipitation reaching the ground, diminished from P by interception, E (m/s) is the evaporation rate from the wet canopy, and Δt is the simulation time interval (s in this example). As explained below, UFORE-Hydro simplifies the explicit simulation of canopy drainage performed in the Rutter model to reduce model parameter requirements. Similar to the sparse vegetation simulation[25], UFORE-Hydro assigns P as the open-sky precipitation for the entire fractional area not covered directly by canopy. UFORE-Hydro uses Pw as the weighted sum of open-sky precipitation, P, and below-canopy throughflow, R, to represent the watershed average depth of precipitation.

In the canopy fraction of the watershed and at the first stage of interception, which is from the start of precipitation until the canopy storage capacity (S) is filled and equal to Cmax, the forest canopy intercepts most of the precipitation. Simulation allows a small amount of precipitation to fall through the canopy as free throughfall (Pf) without contact, and while interception is active (i.e., prior to S reaching Cmax) R is equal to Pf. S is defined as the water retained on the canopy that would not drain to the ground under normal conditions. The UFORE-Hydro model allows no water to drip from the canopy before S is filled in the first stage. The second stage starts when stored rain equals S with no further interception and all subsequent precipitation reaches the ground, either as Pf or canopy drip. Thirdly, the drying stage starts when precipitation has stopped. Evaporation is permitted to occur in each of the three stages to recover the interception storage, creating a dynamic process. Eq (1) regulates canopy storage using throughflow rates, precipitation rates, and evaporation rates — the latter two representing meteorological controls. More detailed information on standard UFORE-Hydro methods is given in Wang et al.[20]

The time series (hourly) sanitary flow rate was obtained from the time series observed discharge data under dry-flow periods and was modified during the model calibration process to consider the contribution of local groundwater.

There are several aspects of the sewershed model that are different from the published UFORE-Hydro:

A. Sanitary flow dominates (70 percent) the total runoff (observed discharge). During the simulation period:

- Total rainfall: 12.48 in (317 mm)
- Total observed runoff: 39,169,652 ft^3 (1,109,161 m^3), in which
  - sanitary flow: 27,336,880 ft^3 (774,094 m^3)
  - impervious flow: 39,169,652 ft^3 (272,752 m^3) (~ 50 percent of rainfall)
  - subsurface groundwater flow : 2,198,712 ft^3 (62,261 m^3)
  - runoff from pervious area flow : 1,917 ft^3 (54 m^3)

B. The tree simulation focused on the impact of nonsanitary flow. Estimated sanitary flow was subtracted from the observed discharge data as sanitary flow in the model is not affected by tree hydrological processes and routing to the outlet.

A sewershed analysis is different from a typical watershed analysis. Therefore, the following assumptions about Rattlesnake Run were made to use UFORE-Hydro:

A. All runoff generated from impervious area (impervious runoff) flows into the sewer lines.
B. A small part of local groundwater (subsurface flow) and runoff from pervious area (pervious runoff) drains into the sewer lines.
C. All sanitary flow goes to the sewer lines.
D. The observed discharge at the Brandywine Park gauge/Rattlesnake Run combined sewer outlet is the sum of the impervious runoff, sanitary flow, and the small part of the groundwater and pervious runoff.

22 Rutter, A.J.; Kershaw, K.A.; Robins, P.C.; Morton, A.J. 1971. **A predictive model of rainfall interception in forests. I. A derivative of the model from observations in a plantation of Corsican pine**. Agricultural Meteorology. 9: 367-384.

23 Rutter, A.J.; Morton, A.J.; Robins, P.C. 1975. **A predictive model of rainfall interception in forests. II. Generalization of the model and comparison with observations in some coniferous and hardwood stands**. Journal of Applied Ecology. 12: 367-380.

24 Jackson, I.J., 1975. **Relationships between rainfall parameters and interception by tropical forests**. Journal of Hydrology. 24: 215-238.

25 Valente, F.; David, J.S.; Gash, J.H.C. 1997. **Modeling interception loss for two sparse eucalypt and pine forests in Central Portugal using reformulated Rutter and Gash analytical models.** Journal of Hydrology. 190: 141-162.

26 Gash, J.H.C.; Morton, A.J. 1978. **An application of the Rutter model to the estimation of the interception loss from the Thetford Forest**. Journal of Hydrology. 38: 49-58.

27 Calder, I.R., 1986. **A stochastic model of rainfall interception**. Journal of Hydrology. 89: 65-71.

28 Hutjes, R.W.A.; Wierda, A.; Veen, A.W.L. 1990. **Rainfall interception in the Tay´ forest, Ivory Coast: application of two simulation models to a humid tropical system**. Journal of Hydrology. 114: 259-275.

29 Eltahir, E.A.; Bras, R.L. 1993. **A description of rainfall interception over large areas**. Journal of Climate. 6: 1002-1008.

30 Jetten, V.G., 1996. **Interception of tropical rain forest – performance of a canopy water balance model**. Hydrological Processes. 10: 671-685.

31 Gash, J.H.C.; Lloyd, C.R.; Lachaud, G. 1995. **Estimating sparse rainfall interception with an analytical mode**. Journal of Hydrology. 170: 79-86.

Explanation of Calculations of Appendix 4

32 Total city carbon emissions were based on 2003 U.S. per capita carbon emissions, calculated as total U.S. carbon emissions (Energy Information Administration, 2003, Emissions of Greenhouse Gases in the United States 2003. http://www.eia.doe.gov/oiaf/1605/1605aold.html) divided by 2003 total U.S. population (www.census.gov). Per capita emissions were multiplied by Minneapolis population to estimate total city carbon emissions.

33 Average passenger automobile emissions per mile were based on dividing total 2002 pollutant emissions from light-duty gas vehicles (National Emission Trends http://www.epa.gov/ttn/chief/trends/index.html) by total miles driven in 2002 by passenger cars (National Transportation Statistics http://www.bts.gov/publications/national_transportation_statistics/2004/).

Average annual passenger automobile emissions per vehicle were based on dividing total 2002 pollutant emissions from light-duty gas vehicles by total number of passenger cars in 2002 (National Transportation Statistics http://www.bts.gov/publications/national_transportation_statistics/2004/).

Carbon dioxide emissions from automobiles assumed 6 pounds of carbon per gallon of gasoline with energy costs of refinement and transportation included (Graham, R.L.; Wright, L.L.; Turhollow, A.F. 1992. The potential for short-rotation woody crops to reduce U.S. CO_2 emissions. Climatic Change. 22: 223-238.)

34 Average household emissions based on average electricity kWh usage, natural gas Btu usage, fuel oil Btu usage, kerosene Btu usage, LPG Btu usage, and wood Btu usage per household from: Energy Information Administration. Total Energy Consumption in U.S. Households by Type of Housing Unit, 2001. www.eia.doe.gov/emeu/recs/recs2001/detailcetbls.html.

CO_2, SO_2, and NOx power plant emission per KWh from: U.S. Environmental Protection Agency. U.S. power plant emissions total by year. www.epa.gov/cleanenergy/egrid/samples.htm.

CO emission per kWh assumes one-third of 1 percent of C emissions is in the form of CO based on: Energy Information Administration. 1994. Energy use and carbon emissions: non-OECD countries. DOE/EIA-0579(94). Washington, DC: Department of Energy, Energy Information Administration. http://tonto.eia.doe.gov/bookshelf

PM_{10} emission per kWh from: Layton, M. 2004. 2005 Electricity environmental performance report: electricity generation and air emissions. Sacramento, CA: California Energy Commission. http://www.energy.ca.gov/2005_energypolicy/documents/2004-11-15_workshop/2004-11-15_03- A_LAYTON.PDF

CO_2, NOx, SO_2, PM_{10}, and CO emission per Btu for natural gas, propane and butane (average used to represent LPG), Fuel #4 and #6 (average used to represent fuel oil and kerosene) from: Abraxas energy consulting. http://www.abraxasenergy.com/emissions/

CO_2 and fine particle emissions per Btu of wood from: Houck, J.E.; Tiegs, P.E.; McCrillis, R.C.; Keithley, C.; Crouch, J. 1998. Air emissions from residential heating: the wood heating option put into environmental perspective. In: Proceedings of U.S. EPA and Air and Waste Management Association conference: living in a global environment, V.1: 373-384.

CO, NOx and SOx emission per Btu of wood based on total emissions from wood burning (tonnes) from: Residential Wood Burning Emissions in British Columbia. 2005. http://www.env.gov.bc.ca/air/airquality/pdfs/wood_emissions.pdf.

Emissions per dry tonne of wood converted to emissions per Btu based on average dry weight per cord of wood and average Btu per cord from: Kuhns, M.; Schmidt, T. 1988. Heating with wood: species characteristics and volumes I. NebGuide G-88-881-A. Lincoln, NE: University of Nebraska, Institute of Agriculture and Natural Resources, Cooperative Extension.

APPENDIX 1. TREE SPECIES SAMPLED IN THE NCC METRO CORRIDOR

Genus	Species	Common name	% Pop[a]	% LA[b]	IV[c]	Potential Pest[d]			
						ALB	GM	EAB	DED
Abies	spp	fir	0.2	0.0	0.2				
Acer	*negundo*	boxelder	1.4	0.7	2.1	✓			
Acer	*palmatum*	Japanese maple	0.2	0.0	0.2	✓			
Acer	*pensylvanicum*	striped maple	0.2	0.4	0.6	✓			
Acer	*platanoides*	Norway maple	3.5	5.7	9.2	✓			
Acer	*rubrum*	red maple	22.8	17.0	39.8	✓			
Acer	*saccharinum*	silver maple	3.7	10.1	13.8	✓			
Acer	*saccharum*	sugar maple	1.6	3.6	5.2	✓			
Ailanthus	*altissima*	tree-of-heaven	1.5	1.7	3.2				
Carya	*ovata*	shagbark hickory	0.2	0.2	0.4				
Carya	spp	hickory	1.5	1.1	2.6				
Carya	*tomentosa*	mockernut hickory	0.2	0.1	0.3				
Cedrus	*atlantica*	Atlas cedar	0.2	0.8	1.0				
Chamaecyparis	*lawsoniana*	Port Orford cedar	0.2	0.5	0.7				
Cornus	*florida*	flowering dogwood	0.6	1.0	1.6				
Cornus	spp	dogwood	1.0	1.2	2.2				
Cryptomeria	*japonica*	Japanese red cedar	0.2	0.3	0.5				
Elaeagnus	spp	elaeagnus	0.2	0.5	0.7				
Fagus	spp	beech	0.2	0.1	0.3				
Fraxinus	*pennsylvanica*	green ash	1.5	1.4	2.9	✓		✓	
Gleditsia	*triacanthos*	honeylocust	1.3	2.8	4.1				
Ilex	spp	holly	1.1	0.7	1.8				
Juglans	*nigra*	black walnut	0.4	1.1	1.5				
Juniperus	*virginiana*	eastern red cedar	0.6	1.3	1.9				
Liquidambar	*styraciflua*	sweetgum	16.9	8.9	25.8		✓		
Liriodendron	*chinense*	ncn - liriodendron chinense	0.2	0.3	0.5				
Liriodendron	*tulipifera*	yellow-poplar	2.0	6.8	8.8				
Magnolia	*x soulangeana*	saucer magnolia	0.2	0.2	0.4				
Malus	spp	crabapple	1.5	1.2	2.7	✓	✓		
Morus	*alba*	white mulberry	0.2	0.6	0.8				
Morus	spp	mulberry	0.4	0.9	1.3				
Ostrya	*virginiana*	eastern hophornbeam	0.2	0.0	0.2		✓		
Other	spp	other species	0.6	0.1	0.7				
Picea	*pungens*	blue spruce	0.6	0.8	1.4				
Picea	spp	spruce	1.7	1.2	2.9				
Pinus	*nigra*	Austrian pine	0.6	0.8	1.4				
Pinus	spp	pine	0.9	0.2	1.1				
Pinus	*strobus*	eastern white pine	0.4	1.5	1.9				
Pinus	*thunbergii*	Japanese black pine	0.2	0.0	0.2				
Platanus	*occidentalis*	American sycamore	0.2	0.2	0.4	✓			
Populus	*alba*	white poplar	0.4	0.2	0.6	✓			

continued

Genus	Species	Common name	% Pop[a]	% LA[b]	IV[c]	Potential Pest[d]			
						ALB	GM	EAB	DED
Prunus	*serotina*	black cherry	3.9	2.0	5.9	✓			
Prunus	*serrulata*	Kwanzan cherry	0.8	0.9	1.7	✓			
Prunus	spp	cherry (other)	3.2	1.2	4.4	✓			
Pyrus	*calleryana*	callery pear	0.4	0.0	0.4	✓			
Pyrus	spp	pear	0.4	0.1	0.5				
Quercus	*alba*	white oak	1.4	1.6	3.0		✓		
Quercus	*coccinea*	scarlet oak	2.3	3.5	5.8		✓		
Quercus	*palustris*	pin oak	3.3	5.6	8.9		✓		
Quercus	*phellos*	willow oak	0.6	0.2	0.8		✓		
Quercus	*rubra*	northern red oak	1.9	3.7	5.6		✓		
Quercus	*velutina*	black oak	0.2	0.2	0.4		✓		
Robinia	*pseudoacacia*	black locust	0.6	0.9	1.5	✓			
Robinia	spp	locust (other)	2.0	1.0	3.0	✓			
Salix	*nigra*	black willow	1.5	0.0	1.5	✓	✓		
Sassafras	*albidum*	sassafras	1.8	0.4	2.2				
Thuja	*occidentalis*	northern white cedar	2.4	0.2	2.6				
Tilia	*americana*	American basswood	0.8	0.7	1.5	✓	✓		
Ulmus	*pumila*	Siberian elm	0.2	0.1	0.3	✓			
Zelkova	*serrata*	Japanese zelkova	0.4	1.3	1.7				

[a] Percent population
[b] Percent leaf area
[c] IV = importance value (% population + % leaf area)
[d] ALB = Asian longhorned beetle; GM = gypsy moth; EAB = emerald ash borer; DED = Dutch elm disease

APPENDIX 2. TREE SPECIES SAMPLED IN WILMINGTON

Genus	Species	Common Name	% Pop.[a]	% LA[b]	IV[c]	Potential Pest[d]			
						ALB	GM	EAB	DED
Abies	spp	fir	0.6	0.1	0.7				
Acer	*negundo*	boxelder	2.6	0.5	3.1	✓			
Acer	*palmatum*	Japanese maple	1.2	0.1	1.3	✓			
Acer	*platanoides*	Norway maple	16.4	27.5	43.9	✓			
Acer	*pseudoplatanus*	sycamore maple	1.2	1.6	2.8	✓			
Acer	*rubrum*	red maple	3.0	9.9	12.9	✓			
Aesculus	*hippocastanum*	horsechestnut	0.7	3.8	4.5	✓			
Ailanthus	*altissima*	tree-of-heaven	9.5	3.3	12.8				
Chamaecyparis	*lawsoniana*	Port Orford cedar	0.7	1.2	1.9				
Cornus	*florida*	flowering dogwood	2.8	0.9	3.7				
Cupressocyparis	*x leylandii*	Leyland cypress	1.4	0.5	1.9				
Fagus	*grandifolia*	American beech	0.7	0.1	0.8				
Fraxinus	*pennsylvanica*	green ash	3.1	2.3	5.4	✓		✓	
Gleditsia	*triacanthos*	honeylocust	4.5	5.3	9.8				
Ilex	*opaca*	American holly	2.3	1.5	3.8				
Ilex	spp	holly	1.2	0.1	1.3				
Liquidambar	*styraciflua*	sweetgum	4.7	16.6	21.3		✓		
Magnolia	*grandiflora*	southern magnolia	1.2	0.1	1.3				
Morus	*alba*	white mulberry	5.4	0.5	5.9				
Other	spp	other species	0.6	0.1	0.7				
Picea	*glauca*	white spruce	1.4	0.0	1.4				
Picea	*pungens*	blue spruce	0.7	0.1	0.8				
Pinus	*strobus*	eastern white pine	2.3	2.4	4.7				
Pinus	*thunbergii*	Japanese black pine	0.7	0.1	0.8				
Platanus	*acerifolia*	London planetree	2.3	5.2	7.5	✓			
Prunus	*serotina*	black cherry	4.4	1.1	5.5	✓			
Prunus	*serrulata*	Kwanzan cherry	0.7	1.7	2.4	✓			
Pyrus	*calleryana*	callery pear	3.5	1.7	5.2	✓			
Quercus	*alba*	white oak	1.2	4.3	5.5		✓		
Quercus	*palustris*	pin oak	1.3	3.4	4.7		✓		
Quercus	*rubra*	northern red oak	1.9	2.7	4.6		✓		
Thuja	*occidentalis*	northern white cedar	15.0	0.5	15.5				
Zelkova	*serrata*	Japanese zelkova	0.6	0.9	1.5				

[a] Percent population
[b] Percent leaf area
[c] IV = importance value (% population + % leaf area)
[d] ALB = Asian longhorned beetle; GM = gypsy moth; EAB = emerald ash borer; DED = Dutch elm disease

APPENDIX 3. GENERAL RECOMMENDATIONS FOR AIR QUALITY IMPROVEMENT

Urban vegetation can directly and indirectly affect local and regional air quality by altering the urban atmospheric environment. Four main ways that urban trees affect air quality are:

Temperature reduction and other microclimatic effects
Removal of air pollutants
Emission of volatile organic compounds (VOC) and tree maintenance emissions
Energy conservation on buildings and consequent power plant emissions

The cumulative and interactive effects of trees on climate, pollution removal, and VOC and power plant emissions determine the overall impact of trees on air pollution. Cumulative studies involving urban tree impacts on ozone have revealed that increased urban canopy cover, particularly with low VOC emitting species, leads to reduced ozone concentrations in cities. Local urban forest management decisions also can help improve air quality.

Urban forest management strategies to help improve air quality include:

Strategy	Reason
Increase the number of healthy trees	Increase pollution removal
Sustain existing tree cover	Maintain pollution removal levels
Maximize use of low VOC-emitting trees	Reduces ozone and carbon monoxide formation
Sustain large, healthy trees	Large trees have greatest per-tree effects
Use long-lived trees	Reduce long-term pollutant emissions from planting and removal
Use low maintenance trees	Reduce pollutants emissions from maintenance activities
Reduce fossil fuel use in maintaining vegetation	Reduce pollutant emissions
Plant trees in energy conserving locations	Reduce pollutant emissions from power plants
Plant trees to shade parked cars	Reduce vehicular VOC emissions
Supply ample water to vegetation	Enhance pollution removal and temperature reduction
Plant trees in polluted or heavily populated areas	Maximizes tree air quality benefits
Avoid pollutant-sensitive species	Improve tree health
Utilize evergreen trees for particulate matter	Year-round removal of particles

APPENDIX 4. RELATIVE TREE EFFECTS FOR TREES IN WILMINGTON

The urban forest in Wilmington provides benefits that include carbon storage and sequestration, and air pollutant removal. To estimate a relative value of these benefits, tree benefits were compared to estimates of average carbon emissions in the city[32], average passenger automobile emissions[33], and average household emissions.[34]

General tree information:

Average tree diameter (d.b.h.) = 9.5 in.
Median tree diameter (d.b.h.) = 5.5 in.
Average number of trees per person = 1.9
Number of trees sampled = 112
Number of species sampled = 33

D.b.h.	Carbon storage			Carbon sequestration			Pollution removal	
Class (in)	(lbs)	($)	(miles) [a]	(lbs/yr)	($/yr)	(miles) [a]	(lbs)	($)
1-3	7	0.06	30	2.1	0.02	8	0.0	0.24
3-6	41	0.37	150	7.2	0.07	26	0.2	1.01
6-9	141	1.29	510	14.8	0.14	54	0.3	2.06
9-12	288	2.65	1,050	18.5	0.17	68	0.5	3.16
12-15	455	4.19	1,670	25.5	0.23	93	0.7	4.38
15-18	835	7.69	3,060	34.5	0.32	126	1.2	7.47
18-21	1,218	11.22	4,460	42.8	0.39	157	1.3	7.93
21-24	1,848	17.02	6,770	51.0	0.47	187	1.3	8.32
24-27	2,489	22.92	9,110	59.8	0.55	219	1.8	11.16
27-30	3,151	29.02	11,540	69.7	0.64	255	2.5	15.90
30+	9,019	83.07	33,030	76.2	0.70	279	2.5	15.85

[a] miles = number of automobile miles driven that produces emissions equivalent to tree effect

The city of Wilmington trees provide:

Carbon storage equivalent to:
Amount of carbon (C) emitted in city in 38 days or
Annual C emissions from 28,000 automobiles or
Annual C emissions from 14,000 single family houses

Annual C sequestration equivalent to:
Amount of C emitted in city in 1.1 days or
Annual C emissions from 800 automobiles or
Annual C emissions from 400 single family homes

Carbon monoxide removal equivalent to:
Annual carbon monoxide emissions from <10 automobiles or
Annual carbon monoxide emissions from 20 single family houses

Nitrogen dioxide removal equivalent to:
Annual nitrogen dioxide emissions from 90 automobiles or
Annual nitrogen dioxide emissions from 60 single family houses

Sulfur dioxide removal equivalent to:
Annual sulfur dioxide emissions from 7,100 automobiles or
Annual sulfur dioxide emissions from 100 single family houses

Particulate matter less than 10 micron (PM_{10}) removal equivalent to:
Annual PM_{10} emissions from 31,200 automobiles or
Annual PM_{10} emissions from 3,000 single family houses

APPENDIX 5. HOURLY FLOW DATA FOR LEAF-ON — LEAF-OFF SIMULATION

The following table provides the simulated values behind Figures 30 and 31, based on simulations of increasing tree cover by 25 and 50 percent over impervious surfaces compared to the base case of 8.9 percent tree cover (5.7 percent tree cover pervious surfaces and 3.2 percent tree cover impervious surfaces). Leaf-on simulation was for August 27, 2001 starting at 5 p.m.; leaf-off simulation was for November 20, 2001 starting at 4 a.m.

Leaf-on Simulation

		Tree cover			Tree cover		
Hour	Rain (in)	Base	+25%	+50%	Base	+25%	+50%
		Cubic meters			Cubic feet		
1	0	26	26	26	913	913	913
2	0.08	478	250	26	16,873	8,839	911
3	0	81	53	26	2,872	1,884	909
4	0	108	66	26	3,797	2,342	906
5	0	64	45	26	2,262	1,579	904
6	0	63	44	26	2,219	1,556	902
7	0	39	32	25	1,385	1,141	900
8	0	39	32	25	1,383	1,139	898
9	0	39	32	25	1,381	1,137	896
10	0	35	30	25	1,226	1,059	894
11	0	32	28	25	1,118	1,004	892
12	0	32	28	25	1,116	1,002	890
13	0	32	28	25	1,114	1,000	888
14	0	31	28	25	1,112	998	886
15	0	31	28	25	1,110	996	884
16	0	31	28	25	1,108	994	882

Leaf-off Simulation

		Tree cover			Tree cover		
Hour	Rain (in)	Base	+25%	+50%	Base	+25%	+50%
		Cubic meters			Cubic feet		
1	0	2	2	2	80	80	80
2	0.08	468	345	223	16,523	12,193	7,864
3	0	60	44	29	2,103	1,570	1,038
4	0	87	64	42	3,058	2,274	1,490
5	0	42	31	21	1,479	1,111	742
6	0	41	31	20	1,436	1,079	722
7	0	16	13	9	580	448	317
8	0	16	13	9	580	448	317
9	0	16	13	9	580	448	317
10	0	12	9	7	422	332	242
11	0	9	7	5	313	252	190
12	0	9	7	5	313	252	190
13	0	9	7	5	313	252	190
14	0	9	7	5	313	252	190
15	0	9	7	5	313	251	190
16	0	9	7	5	313	251	190

APPENDIX 6. HOURLY FLOW DATA FOR 10 STORM SIMULATIONS

The following table provides the simulated values behind Figures 32-41, based on simulations of increasing tree cover by 25 and 50 percent over impervious surfaces compared to the base case of 8.9 percent tree cover (5.7 percent tree cover pervious surfaces and 3.2 percent tree cover impervious surfaces).

Storm 1 - Start time 3 pm (8/10/2001)

		Tree cover			Tree cover		
Hour	Rain (in)	Base	+25%	+50%	Base	+25%	+50%
		----------*Cubic meters*-------------			--------------*Cubic feet*--------------		
1	0	52	52	52	1,839	1,839	1,839
2	0.57	6,295	5,945	5,596	222,296	209,959	197,621
3	0.85	10,886	10,766	10,645	384,448	380,189	375,930
4	0.01	2,550	2,424	2,292	90,039	85,610	80,952
5	0	2,437	2,386	2,335	86,050	84,276	82,473
6	0	1,460	1,415	1,369	51,568	49,981	48,352
7	0	1,098	1,077	1,055	38,777	38,018	37,240
8	0.01	680	617	538	24,012	21,796	18,993
9	0	580	560	538	20,487	19,775	18,986
10	0	526	507	484	18,591	17,904	17,107
11	0.01	489	474	456	17,286	16,736	16,101
12	0	324	313	300	11,443	11,043	10,587
13	0	324	315	306	11,441	11,129	10,792
14	0	313	305	295	11,057	10,757	10,435
15	0	313	304	295	11,040	10,741	10,418
16	0	306	298	289	10,792	10,514	10,221
17	0	295	288	280	10,409	10,162	9,902
18	0	234	230	225	8,270	8,114	7,947
19	0	161	157	153	5,693	5,561	5,418
20	0	159	156	152	5,630	5,512	5,385
21	0.12	1,120	757	393	39,563	26,729	13,885
22	0.09	1,309	990	670	46,220	34,948	23,667
23	0.07	1,253	864	257	44,261	30,528	9,077
24	0	525	407	262	18,545	14,377	9,255
25	0	469	362	214	16,576	12,772	7,568
26	0.01	340	279	200	12,012	9,869	7,066
27	0	283	238	174	10,005	8,389	6,132
28	0	242	211	173	8,538	7,450	6,123
29	0	232	205	171	8,205	7,238	6,033
30	0.03	228	193	164	8,058	6,832	5,803
31	0.02	435	193	161	15,351	6,820	5,680
32	0.01	345	297	161	12,173	10,496	5,672
33	0	253	196	160	8,936	6,907	5,663
34	0	237	201	160	8,382	7,104	5,655
35	0	225	190	160	7,929	6,700	5,646
36	0	210	188	159	7,423	6,623	5,619
37	0	191	172	153	6,756	6,073	5,395
38	0	176	160	143	6,228	5,635	5,055
39	0	168	156	143	5,937	5,496	5,047
40	0.08	1,075	1,029	871	37,946	36,354	30,756
41	0.1	1,456	1,390	1,311	51,403	49,099	46,312
42	0.19	2,724	2,637	2,529	96,212	93,123	89,320

continued

Storm 1 - continued

43	0	745	714	674	26,304	25,215	23,797
44	0.01	759	730	691	26,818	25,771	24,403
45	0.12	1,640	1,331	1,018	57,929	46,995	35,948
46	0	569	516	458	20,106	18,207	16,179
47	0	517	451	381	18,250	15,934	13,443
48	0	397	359	319	14,012	12,684	11,249
49	0.07	789	415	302	27,862	14,666	10,650
50	0.01	338	276	244	11,920	9,741	8,620
51	0	346	265	230	12,229	9,373	8,112
52	0	306	258	229	10,818	9,107	8,101
53	0	294	249	224	10,383	8,799	7,897
54	0	265	239	220	9,343	8,448	7,753
55	0.03	467	245	218	16,491	8,667	7,701
56	0	279	230	211	9,841	8,115	7,441
57	0	274	217	199	9,665	7,673	7,031
58	0.01	336	261	179	11,858	9,202	6,314
59	0.03	581	541	214	20,505	19,105	7,573
60	0	251	221	157	8,862	7,798	5,553
61	0	253	229	156	8,927	8,072	5,504
62	0	218	194	151	7,702	6,855	5,320
63	0	209	189	150	7,394	6,689	5,306
64	0	188	170	147	6,655	6,019	5,201
65	0	185	170	147	6,537	5,987	5,191
66	0	184	169	147	6,486	5,955	5,181
67	0	179	164	146	6,324	5,804	5,151
68	0	176	162	145	6,227	5,706	5,124
69	0	176	161	145	6,217	5,696	5,115
70	0	175	161	145	6,196	5,686	5,105
71	0	174	161	144	6,135	5,674	5,095
72	0	173	160	144	6,125	5,665	5,085
73	0	173	160	144	6,109	5,651	5,076
74	0	171	159	143	6,052	5,604	5,062
75	0	168	155	142	5,933	5,486	5,023
76	0	167	154	141	5,896	5,451	4,989
77	0	164	152	140	5,809	5,376	4,927
78	0	162	151	139	5,728	5,319	4,893
79	0	160	149	138	5,652	5,262	4,863

Storm 2 - Start time 5 pm (8/27/2001)

		Tree cover			Tree cover		
Hour	Rain (in)	Base	+25%	+50%	Base	+25%	+50%
		Cubic meters			*Cubic feet*		
1	0	26	26	26	913	913	913
2	0.08	478	250	26	16,873	8,839	911
3	0	81	53	26	2,872	1,884	909
4	0	108	66	26	3,797	2,342	906
5	0	64	45	26	2,262	1,579	904
6	0	63	44	26	2,219	1,556	902
7	0	39	32	25	1,385	1,141	900
8	0	39	32	25	1,383	1,139	898
9	0	39	32	25	1,381	1,137	896
10	0	35	30	25	1,226	1,059	894
11	0	32	28	25	1,118	1,004	892
12	0	32	28	25	1,116	1,002	890

continued

Storm 2 - continued

13	0	32	28	25	1,114	1,000	888
14	0	31	28	25	1,112	998	886
15	0	31	28	25	1,110	996	884
16	0	31	28	25	1,108	994	882

Storm 3 - Start time 9 pm (8/30/2001)

		Tree cover			Tree cover		
Hour	Rain (in)	Base	+25%	+50%	Base	+25%	+50%
		------------*Cubic meters*-----------			-------------*Cubic feet*-------------		
1	0	23	22	22	815	792	770
2	0.1	714	503	291	25,221	17,747	10,273
3	0	108	81	55	3,814	2,875	1,936
4	0	148	109	70	5,230	3,858	2,486
5	0	82	63	45	2,885	2,228	1,572
6	0	80	62	44	2,820	2,183	1,546
7	0	44	37	30	1,547	1,298	1,049
8	0	44	37	30	1,545	1,296	1,047
9	0	44	37	30	1,544	1,294	1,046
10	0	37	32	27	1,309	1,131	953
11	0	32	29	25	1,145	1,017	888
12	0	32	29	25	1,143	1,015	887
13	0	32	29	25	1,142	1,013	885

Storm 4 - Start time 6 pm (9/4/2001)

		Tree cover			Tree cover		
Hour	Rain (in)	Base	+25%	+50%	Base	+25%	+50%
		-----------*Cubic meters*-----------			-------------*Cubic feet*-------------		
1	0	18	18	18	649	637	624
2	0.57	6,280	6,075	5,870	221,775	214,543	207,311
3	0.01	907	879	851	32,019	31,039	30,058
4	0	1,167	1,129	1,091	41,200	39,870	38,541
5	0	572	554	536	20,210	19,569	18,927
6	0	545	527	510	19,238	18,623	18,008
7	0	218	211	205	7,704	7,466	7,227
8	0	212	205	199	7,486	7,251	7,017
9	0	212	205	199	7,485	7,250	7,016
10	0	152	147	143	5,368	5,203	5,038
11	0	109	106	103	3,860	3,743	3,626
12	0	108	105	102	3,831	3,715	3,598
13	0	108	105	102	3,830	3,714	3,597
14	0	108	105	102	3,829	3,712	3,596
15	0	108	105	102	3,827	3,711	3,595
16	0	108	105	102	3,826	3,710	3,594
17	0	98	95	92	3,474	3,369	3,264
18	0	54	52	51	1,896	1,843	1,790
19	0	53	51	50	1,865	1,813	1,760
20	0	53	51	50	1,864	1,812	1,759
21	0	53	51	50	1,863	1,810	1,758
22	0	53	51	50	1,862	1,809	1,757
23	0	53	51	50	1,861	1,808	1,756
24	0	53	51	50	1,860	1,807	1,754
25	0	53	51	50	1,859	1,806	1,753

continued

Storm 4 - continued

26	0	53	51	50	1,858	1,805	1,752
27	0	53	51	50	1,857	1,804	1,751
28	0	53	51	50	1,856	1,803	1,750

Storm 5 - Start time 6 am (9/14/2001)

		Tree cover			Tree cover		
Hour	Rain (in)	Base	+25%	+50%	Base	+25%	+50%
		-----------*Cubic meters*-----------			-------------*Cubic feet*-------------		
1	0.03	12	12	12	410	410	410
2	0.06	558	344	130	19,694	12,134	4,574
3	0.17	2,085	1,998	1,911	73,644	70,557	67,470
4	0.13	1,886	1,752	1,618	66,617	61,879	57,141
5	0.02	836	713	529	29,515	25,196	18,691
6	0.07	1,349	1,206	931	47,648	42,583	32,884
7	0	465	420	348	16,428	14,820	12,279
8	0.01	382	343	275	13,505	12,102	9,723
9	0.01	224	198	156	7,898	6,985	5,521
10	0	205	185	154	7,223	6,542	5,434
11	0	139	127	109	4,912	4,476	3,841
12	0	111	100	83	3,925	3,533	2,942
13	0	99	89	74	3,489	3,146	2,624
14	0	89	81	69	3,160	2,867	2,453
15	0	84	76	66	2,967	2,697	2,334
16	0	84	76	66	2,967	2,696	2,333
17	0	83	76	66	2,935	2,677	2,326
18	0	76	70	62	2,685	2,484	2,190
19	0	59	54	46	2,096	1,915	1,641
20	0	48	44	37	1,699	1,545	1,301

Storm 6 - Start time 2 pm (9/20/2001)

		Tree cover			Tree cover		
Hour	Rain (in)	Base	+25%	+50%	Base	+25%	+50%
		-----------*Cubic meters*-----------			-------------*Cubic feet*-------------		
1	0.05	110	17	16	3,880	603	559
2	0.04	492	162	16	17,375	5,713	559
3	0.17	2,100	1,993	1,735	74,146	70,380	61,278
4	0.11	1,657	1,564	1,486	58,530	55,236	52,495
5	0.01	706	655	591	24,915	23,116	20,887
6	0.01	594	556	519	20,974	19,632	18,315
7	0.02	576	549	513	20,341	19,373	18,127
8	0.12	1,677	1,653	1,631	59,235	58,375	57,590
9	0.01	480	452	426	16,951	15,965	15,030
10	0	426	412	398	15,036	14,556	14,047
11	0	267	256	245	9,430	9,043	8,650
12	0.05	793	767	742	28,019	27,090	26,200
13	0.02	438	425	413	15,463	14,999	14,574
14	0.04	730	719	709	25,778	25,383	25,027
15	0.05	862	852	844	30,434	30,096	29,797
16	0.01	449	440	432	15,845	15,527	15,242
17	0	291	284	277	10,273	10,034	9,795
18	0	220	216	211	7,772	7,623	7,441
19	0	166	162	159	5,867	5,731	5,611
20	0	120	116	113	4,237	4,113	4,004

continued

Storm 6 - continued

21	0	107	103	100	3,766	3,648	3,545
22	0	99	96	93	3,507	3,390	3,288
23	0	87	83	80	3,057	2,942	2,843
24	0	71	68	65	2,515	2,402	2,305
25	0	70	66	64	2,457	2,348	2,253
26	0	70	66	64	2,457	2,347	2,253
27	0	69	66	63	2,424	2,315	2,222
28	0	64	61	59	2,265	2,161	2,072
29	0	62	59	56	2,178	2,075	1,987
30	0	57	54	52	2,026	1,923	1,835

Storm 7 - Start time 7 pm (9/24/2001)

		Tree cover			Tree cover		
Hour	Rain (in)	Base	+25%	+50%	Base	+25%	+50%
		-----------*Cubic meters*-----------			-------------*Cubic feet*-------------		
1	0.01	24	23	22	842	809	780
2	0	24	23	22	839	806	778
3	0.01	24	23	22	838	805	777
4	0.03	117	23	22	4,119	796	768
5	0.22	2,641	2,516	2,310	93,283	88,868	81,573
6	0.17	2,374	2,340	2,312	83,849	82,651	81,649
7	0.12	2,172	2,140	2,100	76,687	75,586	74,174
8	0.03	1,145	1,121	1,097	40,449	39,602	38,751
9	0	712	698	679	25,134	24,634	23,967
10	0	455	446	438	16,060	15,762	15,469
11	0	312	304	297	11,020	10,745	10,474
12	0.02	449	426	403	15,853	15,055	14,230
13	0	218	211	204	7,708	7,469	7,212
14	0.01	224	187	180	7,926	6,608	6,368
15	0.03	498	336	222	17,572	11,873	7,845
16	0.01	293	152	133	10,353	5,366	4,711
17	0	199	151	127	7,028	5,321	4,473
18	0	172	132	118	6,076	4,660	4,181
19	0	159	131	118	5,605	4,642	4,173
20	0	133	115	108	4,714	4,076	3,824
21	0	105	93	88	3,691	3,291	3,095
22	0	88	77	71	3,096	2,707	2,511
23	0	73	64	60	2,594	2,265	2,107
24	0	68	60	57	2,386	2,131	2,000
25	0	67	60	57	2,360	2,131	1,999
26	0	67	60	57	2,359	2,130	1,999
27	0	66	60	56	2,347	2,119	1,988
28	0	65	59	55	2,293	2,069	1,943
29	0	65	59	55	2,291	2,069	1,942
30	0	64	58	55	2,264	2,058	1,937

Storm 8 - Start time 9 pm (9/30/2001)

		Tree cover			Tree cover		
Hour	Rain (in)	Base	+25%	+50%	Base	+25%	+50%
		-----------*Cubic meters*-----------			-------------*Cubic feet*-------------		
1	0.02	19	18	18	670	639	618
2	0.06	473	273	73	16,692	9,636	2,591
3	0	75	49	24	2,640	1,745	860

continued

Storm 8 - continued

4	0.04	555	509	464	19,591	17,977	16,374
5	0.01	231	209	187	8,171	7,374	6,589
6	0	153	134	115	5,404	4,721	4,049
7	0	93	84	76	3,273	2,978	2,694
8	0.01	164	134	104	5,803	4,728	3,664
9	0.02	301	270	239	10,625	9,523	8,433
10	0.07	919	901	884	32,441	31,832	31,234
11	0.07	1,020	984	949	36,036	34,762	33,500
12	0.01	430	379	294	15,197	13,390	10,375
13	0	290	274	254	10,241	9,672	8,959
14	0.01	198	183	163	6,981	6,465	5,739
15	0	138	128	114	4,875	4,504	4,042
16	0	91	83	71	3,230	2,918	2,517
17	0	81	75	68	2,875	2,660	2,419
18	0.01	69	64	59	2,426	2,268	2,083
19	0	55	50	45	1,927	1,779	1,605
20	0	45	41	37	1,575	1,448	1,307
21	0	43	39	36	1,505	1,390	1,268
22	0	43	39	36	1,505	1,390	1,268
23	0	42	39	36	1,498	1,386	1,265
24	0	41	38	35	1,443	1,346	1,239
25	0	38	35	32	1,331	1,246	1,145
26	0	30	28	25	1,076	995	896
27	0	24	22	20	862	790	701
28	0	24	22	20	834	771	701
29	0	24	22	20	833	770	701
30	0	24	22	20	833	770	701

Storm 9 - Start time 9 am (10/6/2001)

		Tree cover			Tree cover		
Hour	Rain (in)	Base	+25%	+50%	Base	+25%	+50%
		-----------*Cubic meters*-----------			-------------*Cubic feet*-------------		
1	0.05	103	11	10	3,636	372	350
2	0.11	1,306	867	544	46,129	30,617	19,215
3	0.01	186	116	76	6,555	4,092	2,670
4	0.01	251	166	107	8,877	5,848	3,766
5	0	128	83	55	4,515	2,944	1,954
6	0	120	81	54	4,229	2,866	1,905
7	0	53	37	26	1,866	1,290	922
8	0	53	37	26	1,866	1,289	922
9	0	52	37	26	1,835	1,289	922
10	0	39	28	21	1,379	1,000	741
11	0	31	23	17	1,078	799	616
12	0	31	23	17	1,078	798	615
13	0	31	23	17	1,078	798	615
14	0	31	23	17	1,077	798	615
15	0	31	23	17	1,077	798	615
16	0	30	23	17	1,072	797	615
17	0	28	21	17	977	749	584
18	0	19	15	13	654	534	450
19	0	19	15	13	654	534	450
20	0	19	15	13	654	534	450
21	0	19	15	13	654	534	450
22	0	19	15	13	654	533	449

continued

Storm 9 - continued

23	0	18	15	13	653	533	449
24	0	18	15	13	653	533	449
25	0	18	15	13	626	517	445

Storm 10 - Start time 10 pm (10/14/2001)

		Tree cover			Tree cover		
Hour	Rain (in)	Base	+25%	+50%	Base	+25%	+50%
		-----------*Cubic meters*-----------			-------------*Cubic feet*-------------		
1	0.01	5	5	5	165	165	165
2	0.02	5	5	5	165	165	165
3	0.16	1,755	1,554	1,354	61,962	54,889	47,816
4	0.14	1,878	1,842	1,806	66,304	65,046	63,789
5	0.03	880	834	788	31,071	29,446	27,820
6	0	497	477	457	17,560	16,852	16,144
7	0	354	335	316	12,507	11,837	11,167
8	0	225	217	209	7,934	7,662	7,390
9	0	137	130	123	4,852	4,601	4,350
10	0	119	112	106	4,199	3,964	3,728
11	0	102	97	93	3,608	3,440	3,272
12	0	75	71	68	2,638	2,521	2,403
13	0	60	57	54	2,130	2,018	1,906
14	0	58	55	52	2,046	1,936	1,826
15	0	58	55	52	2,046	1,936	1,826
16	0	58	55	52	2,046	1,936	1,826
17	0	58	55	52	2,046	1,936	1,826
18	0	55	52	50	1,948	1,849	1,750
19	0	40	39	37	1,416	1,368	1,320
20	0	28	26	25	980	935	891
21	0	25	24	23	891	848	806

Nowak, David J.; Hoehn, Robert E.; Wang, Jun; Lee, Andy; Krishnamurthy,Vikram; Schwetz, Gary. 2009. **Urban forest assessment in northern Delaware.** Resour. Bull. NRS-33. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 50 p.

Presents results of an analysis of the urban forest of the Wilmington, Delaware, the metropolitan corridor in New Castle County (NCC), and Rattlesnake Run sewershed in the city of Wilmington using the Urban Forest Effects (UFORE) model. This analysis reveals that there are about 882,700 trees (19.3 percent tree cover) in the NCC metro corridor and about 136,000 trees (16.1 percent tree cover) in Wilmington. The three most common species in the NCC urban forest are red maple (22.8 percent), sweetgum (16.9 percent), and black cherry (3.9 percent). In Wilmington, most common species are Norway maple (16.4 percent), northern white cedar (15.0 percent), and tree-of-heaven (9.5 percent). These trees store and remove a significant amount of carbon, reduce building energy use, and annually remove large amounts of air pollution. The UFORE hydrologic analysis of the Rattlesnake Run sewershed reveals that existing tree cover reduced nonsanitary flow by 1.4 percent during an August-to-February simulation period. Increasing existing tree cover over pervious surfaces from 5 to 45 percent reduced outlet flow by 1.7 percent; increasing tree cover from 5 to 45 percent over impervious land reduced flow by 10.7 percent.

KEY WORDS: Wilmington, Delaware, urban forestry, urban ecosystem services, urban hydrology, Urban Forest Effects (UFORE) Model

Capitalizing on the strengths of existing science capacity in the Northeast and Midwest to attain a more integrated, cohesive, landscape-scale research program

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