United States Department of Agriculture

Forest Service

Northern Research Station

Resource Bulletin NRS-7

Assessing Urban Forest Effects and Values

Philadelphia's Urban Forest

Northern Research Station
USDA Forest Service

UFORE
Urban Forest Effects Model

Abstract

An analysis of trees in Philadelphia reveals that this city has about 2.1 million trees with canopies that cover 15.7 percent of the area. The most common tree species are black cherry, crabapple, and tree of heaven. The urban forest currently stores about 530,000 tons of carbon valued at $9.8 million. In addition, these trees remove about 16,100 tons of carbon per year ($297,000 per year) and about 802 tons of air pollution per year ($3.9 million per year). The structural, or compensatory, value is estimated at $1.8 billion. Information on the structure and functions of the urban forest can be used to improve and augment support for urban forest management programs and to integrate urban forests within plans to improve environmental quality in the Philadelphia area.

The Authors

DAVID J. NOWAK is a research forester and project leader, ROBERT E. HOEHN III, is a biological sciences technician, DANIEL E. CRANE is an information technology specialist, JACK C. STEVENS is a forester, and JEFFREY T. WALTON is a research forester with the Forest Service's Northern Research Station at Syracuse, NY.

Photographs

Cover photo by Phillip Rodbell; pages 1, 3 (lower right), 5, 6, 7, 8, 9, 10, and 13 courtesy of the Pennsylvania Horticultural Society.

Acknowledgments

This study was funded in part by the National Urban and Community Forestry Advisory Council (NUCFAC).

Published by:
USDA FOREST SERVICE
11 CAMPUS BLVD SUITE 200
NEWTOWN SQUARE PA 19073-3294

February 2007

For additional copies:
USDA Forest Service
Publications Distribution
359 Main Road
Delaware, OH 43015-8640
Fax: (740)368-0152

Visit our homepage at: **http://www.nrs.fs.fed.us**

Urban forests provide numerous benefits to society, yet relatively little is known about this important resource.

In 1996, the UFORE model was used to survey and analyze Philadelphia's urban forest.

The calculated environmental benefits of the urban forest are significant, yet many environmental and social benefits still remain to be quantified.

Executive Summary

Trees in cities can contribute significantly to human health and environmental quality. Unfortunately, little is known about the urban forest resource and what it contributes to the local and regional society and economy. To better understand the urban forest resource and its numerous values, the USDA Forest Service, Northern Research Station, developed the Urban Forest Effects (UFORE) model. Results from this model are used to advance the understanding of the urban forest resource, improve urban forest policies, planning and management, provide data for potential inclusion of trees within environmental regulations, and determine how trees affect the environment and consequently enhance human health and environmental quality in urban areas.

Forest structure is a measure of various physical attributes of the vegetation, such as tree species composition, number of trees, tree density, tree health, leaf area, biomass, and species diversity. Forest functions, which are determined by forest structure, include a wide range of environmental and ecosystem services such as air pollution removal and cooler air temperatures. Forest values are an estimate of the economic worth of the various forest functions.

To help determine the vegetation structure, functions, and values of the urban forest in Philadelphia, a vegetation assessment was conducted during the summer of 1996. For this assessment, one-tenth acre field plots were sampled and analyzed using the UFORE model. This report summarizes results and values of:

- Forest structure
- Potential risk to forest from insects or diseases
- Air pollution removal
- Carbon storage
- Annual carbon removal (sequestration)
- Changes in building energy use

Philadephia Urban Forest Summary

Feature	Measure
Number of trees	2.1 million
Tree cover	15.7%
Most common species	black cherry, crabapple, tree of heaven
Percentage of trees < 6-inches diameter	57.5%
Pollution removal	802 tons/year ($3.9 million/year)
Carbon storage	530,000 tons ($9.8 million)
Carbon sequestration	16,100 tons/year ($297,000/year)
Building energy reduction	$1,178,000/year
Avoided carbon emissions	$14,400/year
Structural value	$1.8 billion

Ton – short ton (U.S.) (2,000 lbs)

Benefits ascribed to urban trees include:

- Air pollution removal
- Air temperature reduction
- Reduced building energy use
- Absorption of ultraviolet radiation
- Improved water quality
- Reduced noise
- Improved human comfort
- Increased property value
- Improved physiological & psychological well-being
- Aesthetics
- Community cohesion

Urban Forest Effects Model and Field Measurements

Though urban forests have many functions and values, currently only a few of these attributes can be assessed. To help assess the city's urban forest, data from 210 field plots located throughout the city were analyzed using the Forest Service's Urban Forest Effects (UFORE) model.[1]

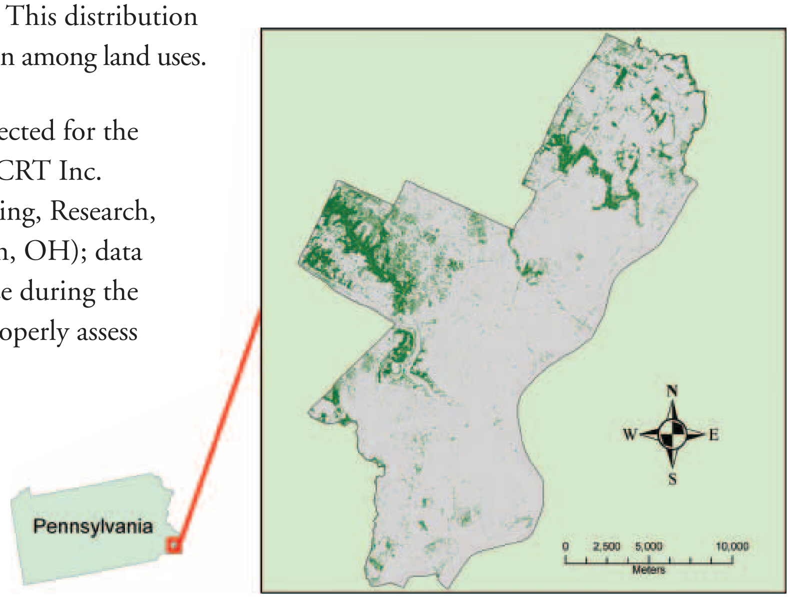
UFORE is designed to use standardized field data from randomly located plots and local hourly air pollution and meteorological data to quantify urban forest structure and its numerous effects, including:

- 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 impact of infestations by Asian longhorned beetles, emerald ash borers, gypsy moth, and Dutch elm disease.

For more information go to http://www.ufore.org

In the field, one-tenth acre plots were randomly located in the different land use strata of Philadelphia. These land uses were used to divide the analysis into smaller zones. The plots were divided among the following land uses: Commercial/Industrial (10 plots), Institutional (11 plots), Multi-Family Residential (35 plots), Park (19 plots), Single Family Residental (30 plots), Transportation (10 plots), Vacant (15 plots), and Wooded (80 plots). This distribution allows for comparison among land uses.

Field data were collected for the Forest Service by ACRT Inc. (Appraisal, Consulting, Research, and Training, Akron, OH); data collection took place during the leaf-on season to properly assess



Field Survey Data

Plot Information

- Land use type
- Percent tree cover
- Percent shrub cover
- Percent plantable
- Percent ground cover types
- Shrub species/ dimensions

Tree parameters

- Species
- Stem diameter
- Total height
- Height to crown base
- Crown width
- Percent foliage missing
- Percent dieback
- Crown light exposure
- Distance and direction to buildings from trees

tree canopies. Within each plot, data included 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.

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 to 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, condition and location information.[10]

To learn more about UFORE methods[11] visit:
http://www.nrs.fs.fed.us/UFORE/data/ or www.ufore.org

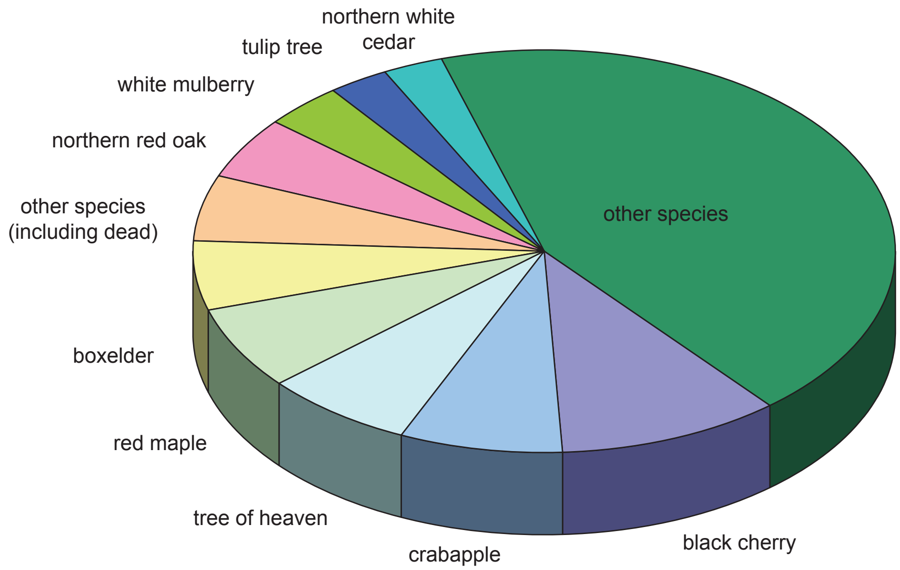
There are an estimated 2.1 million trees in Philadelphia with canopies that cover 15.7 percent of the city.

The 10 most common species account for 56.5 percent of the total number of trees.

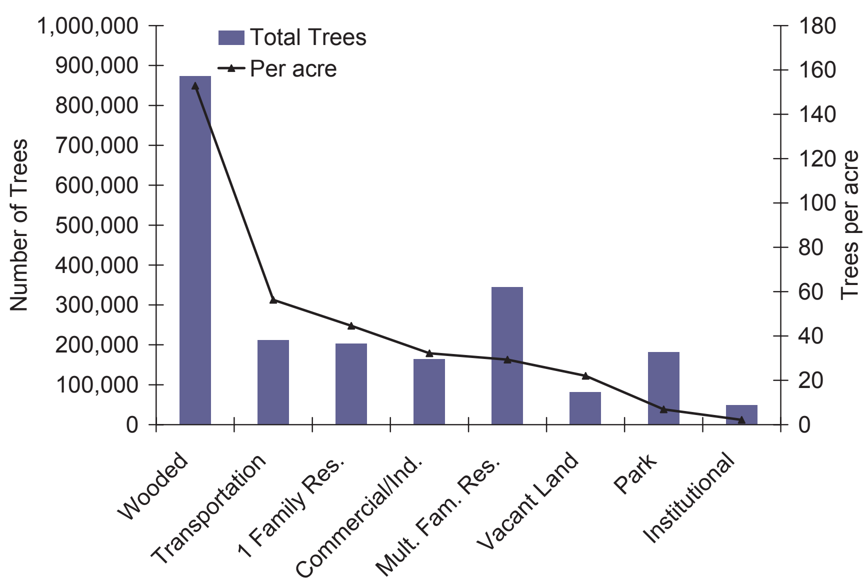
Tree density is highest in the Wooded land use, and lowest in the Institutional land use.

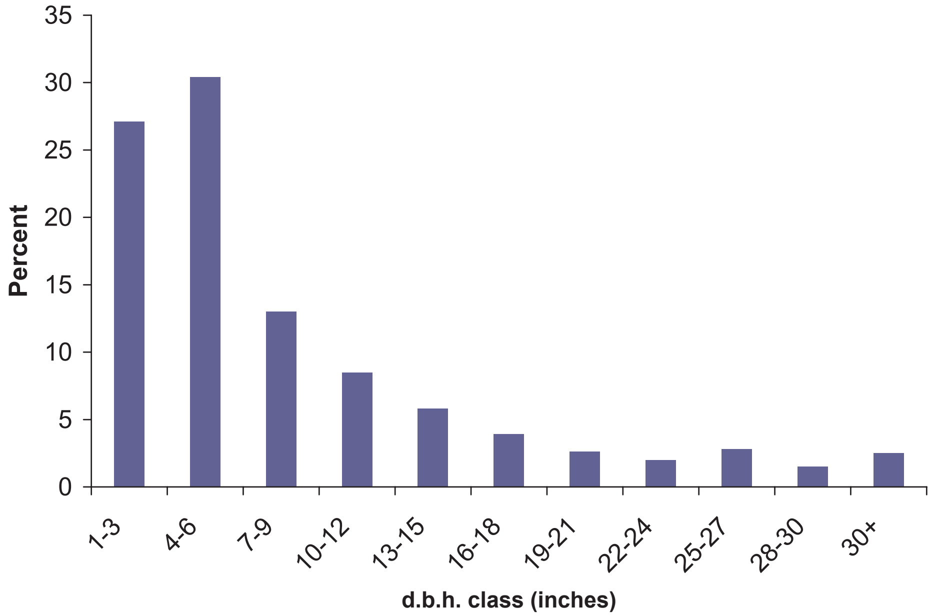
Tree Characteristics of the Urban Forest

The urban forest of Philadelphia has an estimated 2.1 million trees with a tree cover of 15.7 percent. Trees that have diameters less than 6 inches account for 57.5 percent of the population. The three most common species in the urban forest are black cherry (10.2 percent), crabapple (7.5 percent), and tree of heaven (7.1 percent). The 10 most common species account for 56.5 percent of all trees; their relative abundance is illustrated below.



The highest density of trees occurs in the Wooded (152.9 trees/acre), followed by the Transportation (56.3 trees/acre) and the single Family Residential (44.6 trees/acre). The overall tree density in Philadelphia is 25.1 trees/acre, which is comparable to other city tree densities (Appendix I), of 14.4 to 119.2 trees/acre.

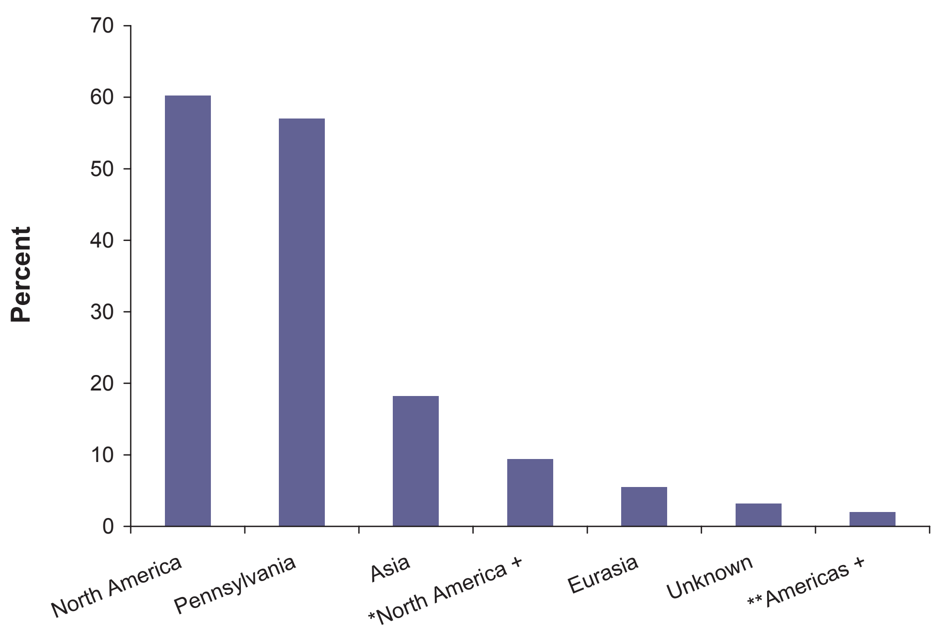




Nearly 57 percent of the tree species in Philadelphia are native to Pennsylvania.

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 other means.

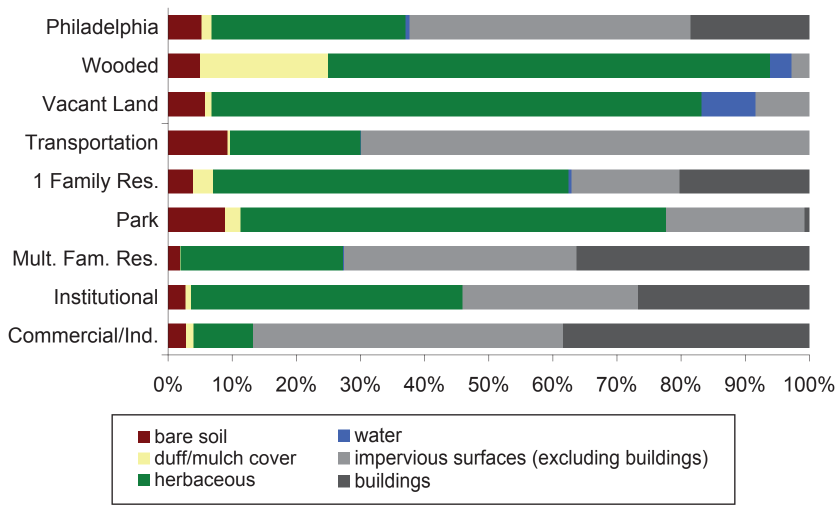
Urban forests are a mix of native tree species that existed prior to the development of the city and exotic species that were introduced by residents or other means. Thus, urban forests often have a tree diversity that is higher than surrounding native landscapes. An increased tree diversity can minimize 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 exotic species are invasive plants that can potentially out-compete and displace native species. In Philadelphia, about 57 percent of the trees are from species native to Pennsylvania. Trees with a native origin outside of North America are mostly from Asia (18.2 percent of the species).



*North America + refers to tree species that are native to North America and one other continent.
**Americas + refers to tree species that are native to North and South America and one other continent.

Urban Forest Cover and Leaf Area

Trees cover about 15.7 percent of Philadelphia; shrubs cover 5.9 percent of the city. Dominant ground cover types include impervious surfaces (excluding buildings) (e.g., driveways, sidewalks, parking lots) (41.2 percent), herbaceous (e.g., grass, gardens) (28.4 percent), and buildings (17.4 percent).



Healthy leaf area equates directly to tree benefits provided to the community.

Black cherry has the greatest importance to the Philadelphia urban forest based on relative leaf area and relative population.

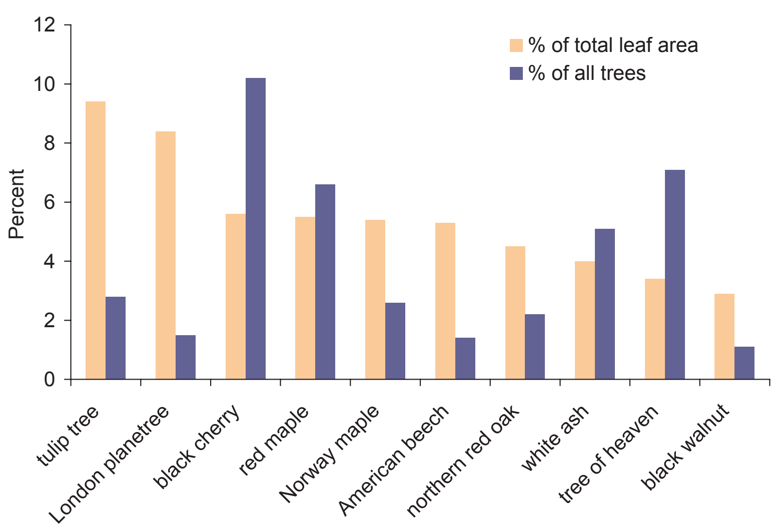
Many tree benefits are linked directly to the amount of healthy leaf surface area of the plant. In Philadelphia, trees that dominate in terms of leaf area are tulip tree, London planetree, and black cherry.

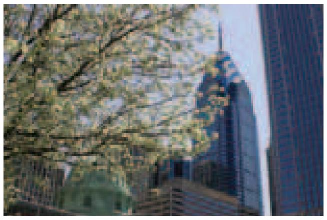
Tree species with relatively large individuals contributing leaf area to the population (species with percent of leaf area much greater than percent of total population) are London planetree, American beech, and tulip tree. Smaller trees in the population are Austrian pine, crabapple, and boxelder (species with percent of leaf area much less than percent of total population). A species must also constitute at least 1 percent of the total population to be considered as relatively large or small trees in the population.

The importance values (IV) are calculated using a formula that takes into account the relative leaf area and relative abundance. The most important species in the urban forest, according to calculated IVs, are black cherry, tulip tree, and red maple.

Common Name	% Pop[a]	% LA[b]	IV[c]
black cherry	10.2	5.6	15.8
tulip tree	2.8	9.4	12.2
red maple	6.6	5.5	12.1
tree of heaven	7.1	3.4	10.5
crabapple	7.5	2.4	9.9
London planetree	1.5	8.4	9.9
white ash	5.1	4.0	9.1
Norway maple	2.6	5.4	8.0
boxelder	5.6	1.8	7.4
northern red oak	2.2	4.5	6.7

[a] percent of population
[b] percent of leaf area
[c] Percent Pop + Percent LA





The urban forest of Philadelphia removes approximately 802 tons of pollutants each year, with a societal value of $3.9 million/year.

General urban forest management recommendations to improve air quality are given in Appendix II.

Air Pollution Removal by Urban Trees

Poor air quality is a common problem in many urban areas. It can lead to human health problems, damage to landscape materials and ecosystem processes, and reduced visibility. The urban forest can help 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. Trees also emit volatile organic compounds that can contribute to ozone formation. However, integrative studies have revealed that an increase in tree cover leads to reduced ozone formation.[12]

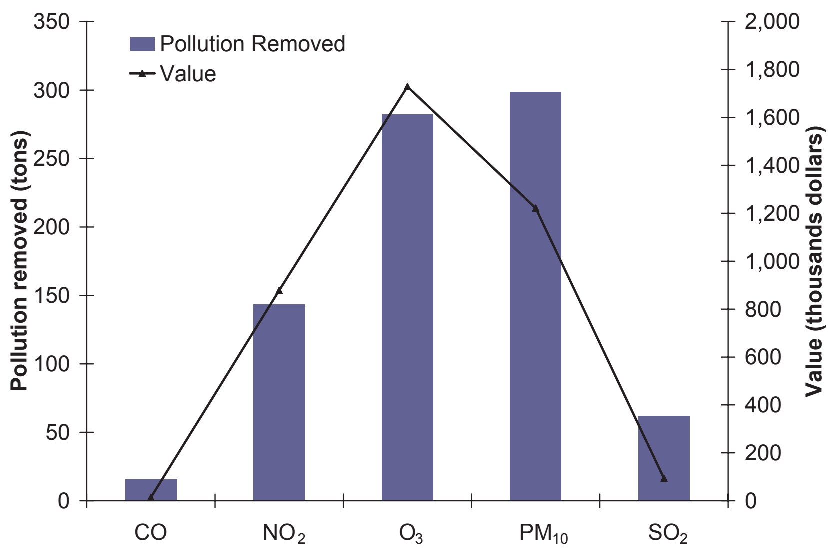
Pollution removal by trees and shrubs in Philadelphia was estimated using the UFORE model in conjunction with field data and hourly pollution and weather data for the year 2000. Pollution removal was greatest for particulate matter less than 10 microns (PM_{10}), followed by ozone (O_3), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and carbon monoxide (CO). It is estimated that trees and shrubs remove 802 tons of air pollution (CO, NO_2, O_3, PM_{10}, SO_2) per year with an associated value of $3.9 million (based on estimated national median externality costs associated with pollutants[13]). Trees remove about 2.5 times more air pollution than shrubs in Philadelphia.

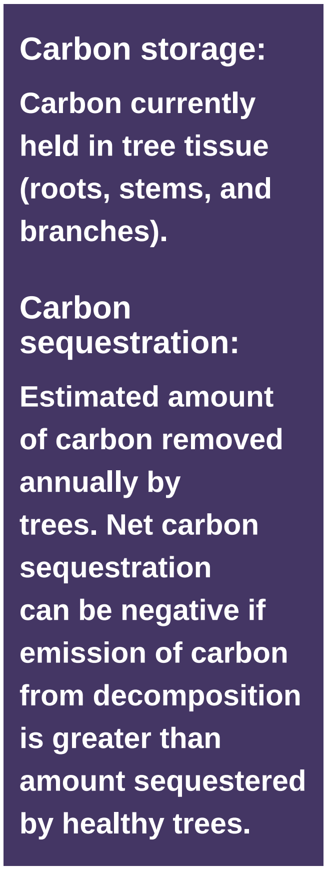
The average percentage of air pollution removal during the daytime, in-leaf season was estimated to be:

- O_3 0.33%
- SO_2 0.32%
- CO 0.001%
- PM_{10} 0.38%
- NO_2 0.22%

Peak 1-hour air quality improvements during the in-leaf season for heavily-treed areas were estimated to be:

- O_3 9.4%
- SO_2 9.6%
- CO 0.05%
- PM_{10} 12.2%
- NO_2 5.3%

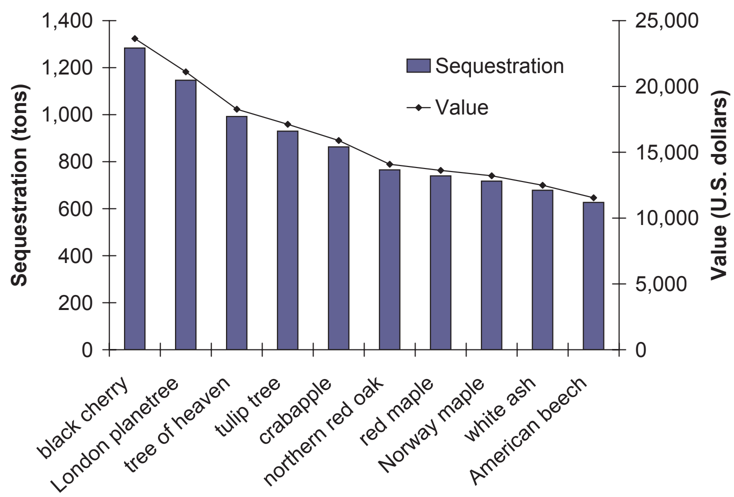




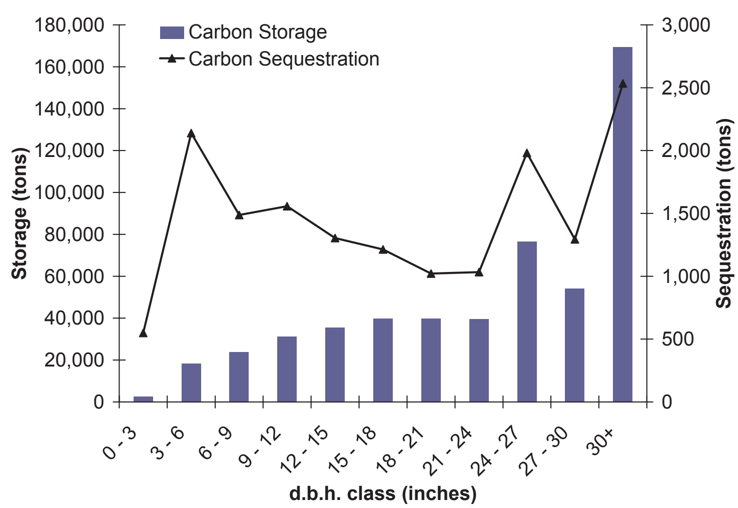
Carbon Storage and Sequestration

Climate change is an issue of global concern. Urban trees can help mitigate climate change by sequestering atmospheric carbon (from carbon dioxide) in tissue and by reducing energy use in buildings, and consequently reducing carbon dioxide emissions from fossil-fuel based power plants.[14]

Trees reduce the amount of carbon in the atmosphere by sequestering carbon in new tissue growth every year. The amount of carbon annually sequestered is increased with healthier trees and larger diameter trees. Gross sequestration by trees in Philadelphia is about 16,100 tons of carbon per year with an associated value of $297,000. Net carbon sequestration in the Philadelphia urban forest is about 11,800 tons.



Carbon storage by trees is another way 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 to 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. Trees in Philadelphia are estimated to store 530,000 tons of carbon ($9.8 million). Of all the species sampled, tulip tree stores the most carbon (approximately 10.5 percent of the total carbon stored), while black cherry is estimated to sequester the most carbon annually (8.0 percent of all sequestered carbon).



Trees affect energy consumption by shading buildings, providing evaporative cooling, and blocking winter winds.

Interactions between buildings and trees save an estimated $1.18 million in heating and cooling costs.

Lower energy use in residential buildings reduced carbon emissions from power plants by 770 tons ($14,400).

Trees Affect Energy Use in Buildings

Trees affect energy consumption by shading buildings, providing evaporative cooling, and blocking winter winds. Trees tend to reduce building energy consumption in the summer months and can either increase or decrease building energy use in the winter months, depending on the location of trees around the building. Estimates of tree effects on energy use are based on field measurements of tree distance and direction to space-conditioned residential buildings.[9]

Based on average energy costs in 2002 dollars, trees in Philadelphia are estimated to reduce energy costs from residential buildings by $1.18 million annually. Trees also provide an additional $14,400 in value per year by reducing the amount of carbon released by fossil-fuel based power plants (a reduction of 770 tons of carbon emissions).

Annual energy savings due to trees near residential buildings

	Heating	Cooling	Total
MBTU[a]	-251,300	n/a	-251,300
MWH[b]	-3,700	32,300	28,600
Carbon avoided (t)	-4,850	5,620	770

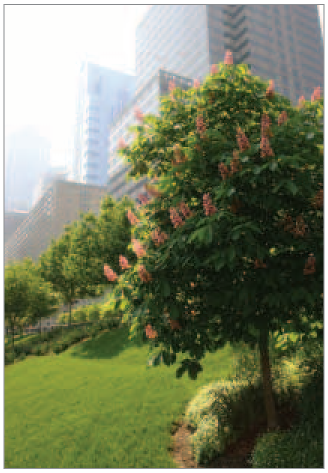
[a]Million British Thermal Units
[b]Megawatt-hour

Annual savings[c] (U.S. $) in residential energy expenditures during heating and cooling seasons

	Heating	Cooling	Total
MBTU[a]	-1,996,000	n/a	-1,996,000
MWH[b]	-414,000	3,588,000	3,174,000
Carbon avoided (t)	-90,000	104,300	14,400

[a]Million British Thermal Units
[b]Megawatt-hour
[c]Based on state-wide energy costs

Structural and Functional 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 Philadelphia is about $1.8 billion. 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. Annual functional values also 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.

Urban forests have a structural value based on the tree itself.

Urban forests also have functional values based on the functions the tree performs.

Large, healthy, long-lived trees provide the greatest structural and functional values.

A map of priority planting locations for Philadelphia is in Appendix IV.

A list of tree species found in Philadelphia is in Appendix V.

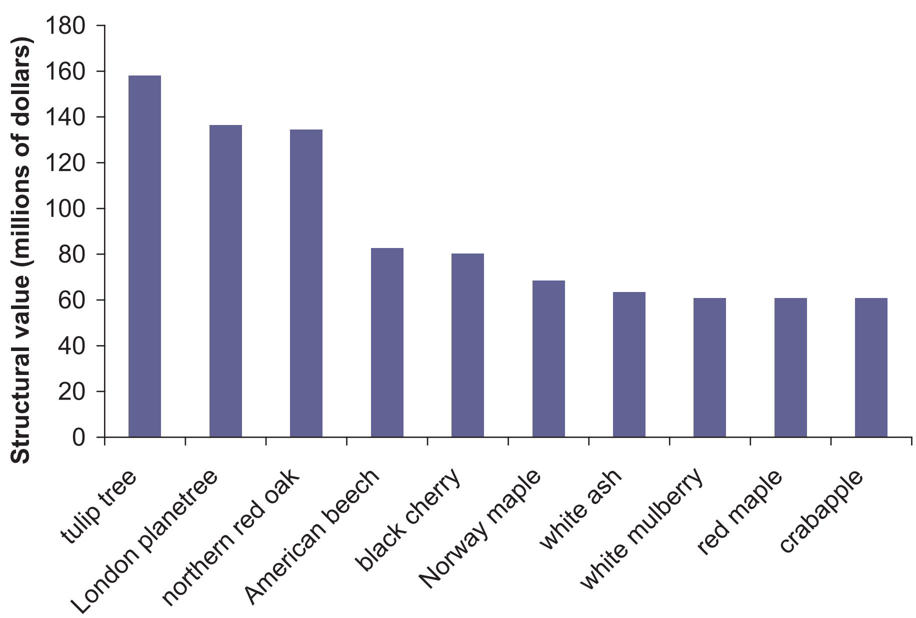
Structural values:

- Structural value: $1.6 billion
- Carbon storage: $9.8 million

Annual functional values:

- Carbon sequestration: $297,000
- Pollution removal: $3.9 million
- Lower energy costs and reduces carbon emissions: $1.19 million

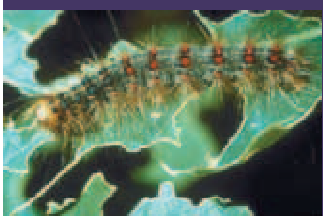
More detailed information on the urban forest in Philadelphia can be found at http://www.fs.fed.us/ne/syracuse/Data/data.htm. Additionally, information on other urban forest values can be found in Appendix I and information comparing tree benefits to estimates of average carbon emissions in the city, average automobile emissions, and average household emissions can be found in Appendix III.



Asian longhorned beetle

Kenneth R. Law
USDA APHIS PPQ
(www.invasive.org)

Gypsy moth

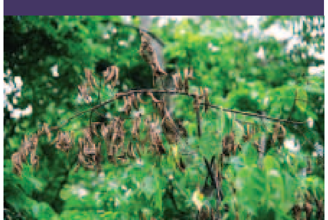


USDA Forest Service Archives
(www.invasive.org)

Emerald ash borer

David Cappaert
Michigan State University
(www.invasive.org)

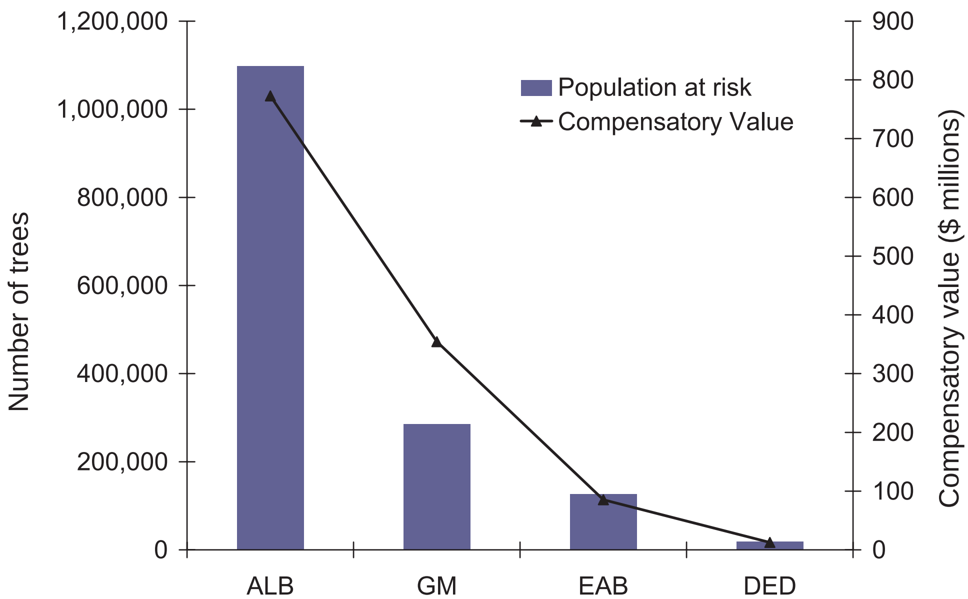
Dutch elm disease



Potential Insect and Disease Impacts

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.

The Asian longhorned beetle (ALB)[15] is an insect that bores into and kills a wide range of hardwood species. ALB represents a potential loss to the Philadelphia urban forest of $773 million in structural value (52 percent of the tree population).



The gypsy moth (GM)[16] is a defoliator that feeds on many species causing widespread defoliation and tree death if outbreak conditions last several years. This pest could potentially result in damage to or a loss of $354 million in structural value (13.5 percent of the population).

Emerald ash borer (EAB)[17] has killed thousands of ash trees in Michigan, Ohio, and Indiana. EAB has the potential to affect 5.9 percent of the population ($68 million in structural value).

American elm, one of the most important street trees in the 20th century, has been devastated by the Dutch elm disease (DED). Since first reported in the 1930s, it has killed more than 50 percent of the native elm population in the United States.[18] Although some elm species have shown varying degrees of resistance, Philadelphia possibly could lose 0.9 percent of its trees to this disease ($22 million in structural value).

Appendix I. Comparison of Urban Forests

A commonly asked question is, "How does this city compare to other cities?" Although comparison among cities should be made with caution as there are many attributes of a city that affect urban forest structure and functions, summary data are provided from other cities analyzed using the UFORE model.

I. City totals, trees only

City	% Tree cover	Number of trees	Carbon storage (tons)	Carbon sequestration (tons/yr)	Pollution removal (tons/yr)	Pollution value U.S. $
Calgary, Canada[a]	7.2	11,889,000	445,000	21,400	326	1,611,000
Atlanta, GA[b]	36.7	9,415,000	1,344,000	46,400	1,663	8,321,000
Toronto, Canada[c]	20.5	7,542,000	992,000	40,300	1,212	6,105,000
New York, NY[b]	20.9	5,212,000	1,350,000	42,300	1,677	8,071,000
Baltimore, MD[d]	21.0	2,627,000	597,000	16,200	430	2,129,000
Philadelphia, PA[b]	15.7	2,113,000	530,000	16,100	576	2,826,000
Washington, DC[e]	28.6	1,928,000	526,000	16,200	418	1,956,000
Boston, MA[b]	22.3	1,183,000	319,000	10,500	284	1,426,000
Woodbridge, NJ[f]	29.5	986,000	160,000	5,560	210	1,037,000
Minneapolis, MN[g]	26.4	979,000	250,000	8,900	306	1,527,000
Syracuse, NY[d]	23.1	876,000	173,000	5,420	109	568,000
San Francisco, CA[a]	11.9	668,000	194,000	5,100	141	693,000
Morgantown, WV[h]	35.5	658,000	93,000	2,890	72	333,000
Moorestown, NJ[f]	28.0	583,000	117,000	3,760	118	576,000
Jersey City, NJ[f]	11.5	136,000	21,000	890	41	196,000
Freehold, NJ[f]	34.4	48,000	20,000	545	22	110,000

II. Per acre values of tree effects

City	No. of trees	Carbon Storage (tons)	Carbon sequestration (tons/yr)	Pollution removal (lbs/yr)	Pollution value U.S. $
Calgary, Canada[a]	66.7	2.5	0.12	3.7	9.0
Atlanta, GA[b]	111.6	15.9	0.55	39.4	98.6
Toronto, Canada[c]	48.3	6.4	0.26	15.5	39.1
New York, NY[b]	26.4	6.8	0.21	17.0	40.9
Baltimore, MD[d]	50.8	11.6	0.31	16.6	41.2
Philadelphia, PA[b]	25.1	6.3	0.19	13.6	33.5
Washington, DC[e]	49.0	13.4	0.41	21.3	49.7
Boston, MA[b]	33.5	9.1	0.30	16.1	40.4
Woodbridge, NJ[f]	66.5	10.8	0.38	28.4	70.0
Minneapolis, MN[g]	26.2	6.7	0.24	16.4	40.9
Syracuse, NY[d]	54.5	10.8	0.34	13.5	35.4
San Francisco, CA[a]	22.5	6.6	0.17	9.5	23.4
Morgantown, WV[h]	119.2	16.8	0.52	26.0	60.3
Moorestown, NJ[f]	62.1	12.4	0.40	25.1	61.3
Jersey City, NJ[f]	14.4	2.2	0.09	8.6	20.7
Freehold, NJ[f]	38.3	16.0	0.44	34.9	88.2

Data collection group

[a] City personnel
[b] ACRT, Inc.
[c] University of Toronto
[d] U.S. Forest Service
[e] Casey Trees Endowment Fund
[f] New Jersey Department of Environmental Protection
[g] Davey Resource Group
[h] West Virginia University

Appendix II. 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 in 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 III. Relative Tree Effects

The urban forest in Philadelphia 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[19], average passenger automobile emissions[20], and average household emissions.[21]

General tree information:

Average tree diameter (d.b.h.) = 8.0 in.
Median tree diameter (d.b.h.) = 5.4 in.
Average number of trees per person = 1.4
Number of trees sampled = 1,433
Number of species sampled = 84

Average tree effects by tree diameter:

	Carbon storage			Carbon sequestration			Pollution removal	
D.b.h. Class (inch)	(lbs)	($)	(miles) [a]	(lbs/yr)	($/yr)	(miles)[a]	(lbs)	($)
1-3	8	0.08	30	1.9	0.02	7	0.1	0.18
3-6	57	0.53	210	6.7	0.06	24	0.2	0.45
6-9	172	1.59	630	10.8	0.10	40	0.4	0.98
9-12	342	3.15	1,250	17.1	0.16	63	0.6	1.57
12-15	587	5.40	2,150	21.6	0.20	79	0.8	2.04
15-18	973	8.96	3,560	29.7	0.27	109	1.3	3.24
18-21	1,443	13.29	5,290	37.0	0.34	135	1.8	4.50
21-24	1,930	17.77	7,070	50.3	0.46	184	1.7	4.17
24-27	2,606	24.00	9,540	67.5	0.62	247	2.3	5.58
27-30	3,463	31.90	12,680	82.7	0.76	303	2.8	6.93
30+	6,152	56.66	22,530	92.0	0.85	337	3.0	7.36

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

The Philadelphia urban forest provides:

Carbon storage equivalent to:
Amount of carbon (C) emitted in city in 22 days or
Annual carbon emissions from 318,000 automobiles or
Annual C emissions from 159,800 single family houses

Carbon monoxide removal equivalent to:
Annual carbon monoxide emissions from 45 automobiles or
Annual carbon monoxide emissions from 200 single family houses

Nitrogen dioxide removal equivalent to:
Annual nitrogen dioxide emissions from 6,500 automobiles or
Annual nitrogen dioxide emissions from 4,300 single family houses

Sulfur dioxide removal equivalent to:
Annual sulfur dioxide emissions from 65,500 automobiles or
Annual sulfur dioxide emissions from 1,100 single family houses

Particulate matter less than 10 micron (PM_{10}) removal equivalent to:
Annual PM_{10} emissions from 568,400 automobiles or
Annual PM_{10} emissions from 54,900 single family houses

Annual C sequestration equivalent to:
Amount of C emitted in city in 0.7 days or
Annual C emissions from 9,700 automobiles or
Annual C emissions from 4,900 single family homes

Appendix IV. Tree Planting Index Map

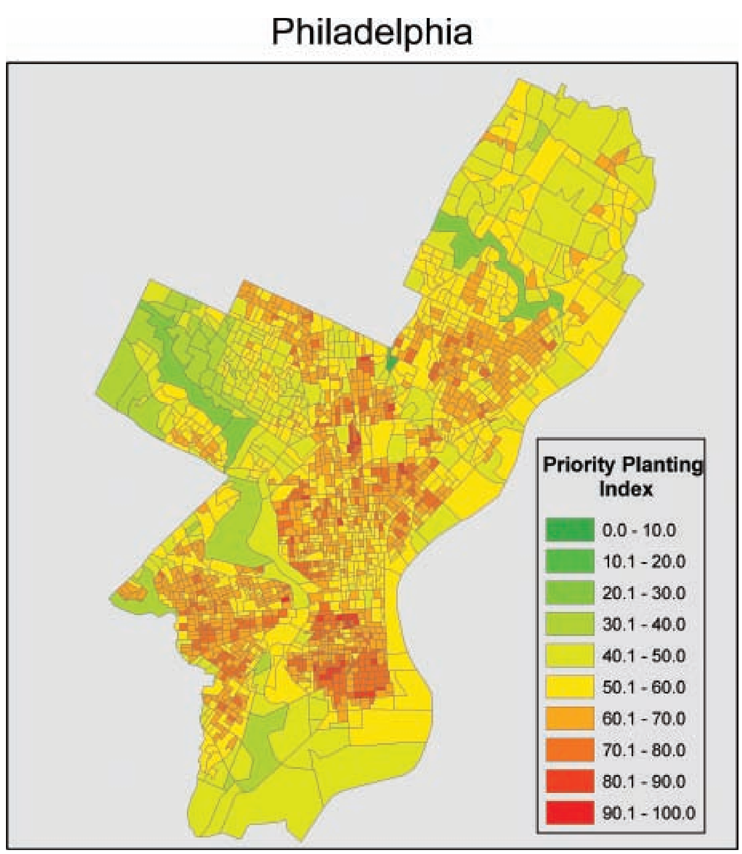
To determine the best locations to plant trees, tree canopy and impervious cover maps from National Land Cover Data[22] were used in conjunction with 2000 U.S. Census data to produce an index of priority planting areas. Index values were produced for each census block with the higher the index value, 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 (m^2/capita), the greater the priority for tree planting

Each criteria was standardized[23] 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.



Appendix V. List of Species Sampled in Philadelphia

Genus	Species	Common Name	% Population	% Leaf Area	IV[a]	Potential pest [b] ALB	GM	EAB	DED
Acer	negundo	boxelder	5.6	1.8	7.4	▲			
Acer	palmatum	Japanese maple	0.8	1	1.8	▲			
Acer	platanoides	Norway maple	2.6	5.4	8.0	▲			
Acer	rubrum	red maple	6.6	5.5	12.1	▲			
Acer	saccharinum	silver maple	1.3	1.9	3.2	▲			
Acer	saccharum	sugar maple	0.3	0.9	1.2	▲			
Acer	pseudoplatanus	sycamore maple	1.1	1	2.1	▲			
Ailanthus	altissima	tree of heaven	7.1	3.4	10.5				
Alnus	species	alder	0	0	0.0	▲	▲		
Aralia	spinosa	devils walking stick	0.4	0	0.4				
Betula	lenta	black birch	0.2	0.3	0.5	▲			
Betula	pendula	European white birch	0.1	0	0.1	▲	▲		
Betula	alleghaniensis	yellow birch	0.1	0.1	0.2	▲			
Broussonetia	papyrifera	paper mulberry	0.2	0.1	0.3				
Carpinus	caroliniana	American hornbeam	0.2	0.1	0.3				
Carya	cordiformis	bitternut hickory	0.3	0.4	0.7				
Carya	species	hickory	0.2	0	0.2				
Carya	tomentosa	mockernut hickory	0.1	0	0.1				
Carya	glabra	pignut hickory	0.3	0.1	0.4				
Catalpa	speciosa	northern catalpa	0.5	0.4	0.9				
Catalpa	bignonioides	southern catalpa	0.1	0	0.1				
Cedrus	atlantica	atlas cedar	0.1	0.1	0.2				
Cornus	species	dogwood	0.2	0.1	0.3				
Cornus	florida	flowering dogwood	1.4	0.9	2.3				
Crataegus	species	hawthorn	0.7	0.6	1.3		▲		
Euonymus	species	euonymus	0	0	0.0				
Fagus	grandifolia	American beech	1.4	5.3	6.7				
Fraxinus	pennsylvanica	green ash	0.9	0.6	1.5	▲		▲	

Continued

Appendix V continued.

			%	%		Potential pest [b]			
Genus	Species	Common Name	Population	Leaf Area	IV[a]	ALB	GM	EAB	DED
Fraxinus	americana	white ash	5.1	4	9.1	🌲		🌲	
Gleditsia	triacanthos	honeylocust	0.5	0.6	1.1				
Hamamelis	virginiana	witch hazel	0.2	0.1	0.3				
Ilex	opaca	American holly	0.9	0.6	1.5				
Juglans	nigra	black walnut	1.1	2.9	4.0				
Juniperus	virginiana	eastern red cedar	0.4	1.4	1.8				
Lindera	benzoin	spicebush	0	0	0.0				
Liquidambar	styraciflua	sweetgum	0.5	0.8	1.3		🌲		
Liriodendron	tulipifera	tulip tree	2.8	9.4	12.2				
Magnolia	species	magnolia	0	0	0.0				
Magnolia	x soulangeana	saucer magnolia	0.1	0.2	0.3				
Magnolia	grandiflora	southern magnolia	0.1	0	0.1				
Magnolia	tripetala	umbrella magnolia	0.1	0	0.1				
Malus	species	crabapple	7.5	2.4	9.9	🌲	🌲		
Morus	alba	white mulberry	3.5	2.6	6.1				
Nyssa	sylvatica	black tupelo	0.6	0.4	1.0				
Ostrya	virginiana	eastern hophornbeam	0.3	0.1	0.4		🌲		
Other	species	other species	5.2	0.8	6.0				
Paulownia	tomentosa	royal paulownia	1.3	0.5	1.8				
Phellodendron	amurense	amur corktree	2.4	0.8	3.2				
Picea	mariana	black spruce	0.1	0.2	0.3				
Picea	pungens	blue spruce	0.3	0.6	0.9				
Picea	abies	Norway spruce	0.6	0.9	1.5				
Pinus	nigra	Austrian pine	1.1	0.3	1.4				
Pinus	strobus	eastern white pine	1.1	1.8	2.9				
Pinus	ponderosa	ponderosa pine	0.1	0.2	0.3				
Platanus	occidentalis	American sycamore	0.9	2.1	3.0				
Platanus	acerifolia	London planetree	1.5	8.4	9.9				

Continued

Appendix V continued.

Genus	Species	Common Name	% Population	% Leaf Area	IV[a]	Potential pest[b] ALB	GM	EAB	DED
Populus	grandidentata	bigtooth aspen	0	0	0.0	🌲	🌲		
Populus	deltoides	eastern cottonwood	1.2	1.5	2.7	🌲	🌲		
Populus	heterophylla	swamp cottonwood	0.6	1.4	2.0	🌲	🌲		
Populus	alba	white poplar	0.1	0	0.1	🌲	🌲		
Prunus	serotina	black cherry	10.2	5.6	15.8	🌲			
Prunus	species	cherry	1.1	1.2	2.3	🌲			
Prunus	cerasifera	cherry plum	0.6	0.6	1.2	🌲			
Prunus	persica	nectarine	0.1	0	0.1	🌲			
Prunus	pensylvanica	pin cherry	0.2	0.1	0.3	🌲			
Prunus	avium	sweet cherry	0	0	0.0	🌲			
Pseudotsuga	menziesii	Douglas fir	0.1	0.2	0.3				
Pyrus	calleryana	callery pear	0.4	0.5	0.9				
Quercus	velutina	black oak	0.2	0.5	0.7		🌲		
Quercus	rubra	northern red oak	2.2	4.5	6.7		🌲		
Quercus	species	oak	0.2	0.6	0.8		🌲		
Quercus	palustris	pin oak	0.5	0.4	0.9		🌲		
Quercus	alba	white oak	0.2	0.3	0.5		🌲		
Rhus	typhina	staghorn sumac	0.1	0	0.1		🌲		
Robinia	pseudoacacia	black locust	1.5	2	3.5	🌲			
Salix	species	willow	0.2	0.1	0.3	🌲	🌲		
Sassafras	albidum	sassafras	1.7	0.7	2.4	🌲			
Sophora	japonica	Japanese pagoda tree	0.6	0.9	1.5				
Taxus	species	yew	0.2	0	0.2				
Thuja	occidentalis	northern white cedar	2.9	1.8	4.7				
Tilia	americana	American basswood	0.3	0.8	1.1		🌲		
Tsuga	canadensis	eastern hemlock	1	1	2.0				
Ulmus	americana	American elm	0.9	1.4	2.3	🌲			🌲
Ulmus	pumila	Siberian elm	1.3	1.6	2.9	🌲			
Viburnum	burkwoodii	viburnum	0.2	0.3	0.5				

References

1 Nowak, D.J.; Crane, D.E. 2000. **The Urban Forest Effects (UFORE) Model: quantifying urban forest structure and functions.** In: Hansen, M.; Burk, T., eds. Integrated tools for natural resources inventories in the 21st century. Proceedings of IUFRO conference. Gen. Tech. Rep. NC-212. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station: 714-720.

2 Nowak, D.J.; Crane, D.E.; Stevens, J.C.; Hoehn, R.E. 2005. **The urban forest effects (UFORE) model: field data collection manual.** V1b. [Newtown Square, PA]: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 34 p. http://www.fs.fed.us/ne/syracuse/Tools/downloads/UFORE_Manual.pdf

3 Nowak, D.J. 1994. **Atmospheric carbon dioxide reduction by Chicago's urban forest.** In: McPherson, E.G.; Nowak, D.J.; Rowntree, R.A., eds. Chicago's urban forest ecosystem: results of the Chicago Urban Forest Climate Project. Gen. Tech. Rep. NE-186. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station: 83-94.

4 Baldocchi, D. 1988. **A multi-layer model for estimating sulfur dioxide deposition to a deciduous oak forest canopy.** Atmospheric Environment. 22: 869-884.

5 Baldocchi, D.D.; Hicks, B.B.; Camara, P. 1987. **A canopy stomatal resistance model for gaseous deposition to vegetated surfaces.** Atmospheric Environment. 21: 91-101.

6 Bidwell, R.G.S.; Fraser, D.E. 1972. **Carbon monoxide uptake and metabolism by leaves.** Canadian Journal of Botany. 50: 1435-1439.

7 Lovett, G.M. 1994. **Atmospheric deposition of nutrients and pollutants in North America: an ecological perspective.** Ecological Applications. 4: 629-650.

8 Zinke, P.J. 1967. **Forest interception studies in the United States.** In: Sopper, W.E.; Lull, H.W., eds. Forest hydrology. Oxford, UK: Pergamon Press: 137-161.

9 McPherson, E.G.; Simpson, J.R. 1999. **Carbon dioxide reduction through urban forestry: guidelines for professional and volunteer tree planters.** Gen. Tech. Rep. PSW-171. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 237 p. Can be accessed through http://www.fs.fed.us/psw/publications/gtrs.shtml

10 Nowak, D.J.; Crane, D.E.; Dwyer, J.F. 2002. **Compensatory value of urban trees in the United States**. Journal of Arboriculture. 28(4): 194-199.

11 Nowak, D.J.; Crane, D.E.; Stevens, J.C.; Ibarra, M. 2002. **Brooklyn's urban forest.** Gen. Tech. Rep. NE-290. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 107 p.

12 Nowak D.J.; Dwyer, J.F. 2000. **Understanding the benefits and costs of urban forest ecosystems.** In: Kuser, John E., ed. Handbook of urban and community forestry in the northeast. New York: Kluwer Academics/Plenum: 11-22.

13 Murray, F.J.; Marsh L.; Bradford, P.A. 1994. **New York state energy plan, vol. II: issue reports.** Albany, NY: New York State Energy Office.

14 Abdollahi, K.K.; Ning, Z.H.; Appeaning, A., eds. 2000. **Global climate change and the urban forest.** Baton Rouge, LA: GCRCC and Franklin Press. 77 p.

15 Northeastern Area State and Private Forestry. 2005. **Asian Longhorned Beetle.** Newtown Square, PA:

U.S. Department of Agriculture, Northeastern Area State and Private Forestry. http://www.na.fs.fed.us/fhp/alb/

16 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/

17 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

18 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

Explanation of Calculations of Appendix III and IV

19 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.

20 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.)

21 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 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.

22 National Land Cover Data available at: www.epa.gov/mrlc/nlcd.html.

23 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).

Nowak, David J.; Hoehn, Robert E. III, Crane, Daniel E.; Stevens, Jack C.; Walton, Jeffrey T. 2007. **Assessing urban forest effects and values, Philladelphia's urban forest.** Resour. Bull. NRS-7. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 22 p.

An analysis of trees in Philadelphia reveals that this city has about 2.1 million trees with canopies that cover 15.7 percent of the area. The most common tree species are black cherry, crabapple, and tree of heaven. The urban forest currently stores about 530,000 tons of carbon valued at $9.8 million. In addition, these trees remove about 16,100 tons of carbon per year ($297,000 per year) and about 802 tons of air pollution per year ($3.9 million per year). The structural, or compensatory, value is estimated at $1.8 billion. Information on the structure and functions of the urban forest can be used to improve and augment support for urban forest management programs and to integrate urban forests within plans to improve environmental quality in the Philadelphia area.

KEY WORDS**:** urban forestry, ecosystem services, air pollution removal, carbon sequestration, tree value

Printed on Recycled Paper

Manuscript received for publication 5 December 2006

Northern
RESEARCH STATION
USDA Forest Service
www.nrs.fs.fed.us

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