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Baltimore's Urban Forest, 1999-2014

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Abstract

An assessment of the vegetation structure, function, and value of Baltimore's urban forest was conducted during 1999, 2004, 2009, and 2014. Data from 193 field plots located throughout Baltimore were analyzed using the i-Tree Eco model developed by the USDA Forest Service, Northern Research Station. In 2014, the most common tree species across public and private lands were American beech, American elm, and green ash (encompassing all woody plants greater than 1 inch in diameter at breast height). The number of trees in Baltimore's urban forest declined from an estimated 2,631,000 trees in 1999 to 2,262,000 trees in 2014. The overall tree density declined from 51 trees per acre in 1999 to 44 trees per acre in 2014. This time period saw a decrease in the proportion of trees in the smallest diameter class (1–6 inches) and a concurrent increase in the proportion of trees in larger diameter classes. American beech was consistently the most common species city-wide over time, while American elm, black cherry, and black locust trees consistently declined in numbers from 1999 to 2014. Leaf area of Baltimore's trees increased from 95.7 square miles in 1999 to 100.7 square miles in 2014. The gross carbon sequestration of Baltimore trees increased from 17.9 thousand tons of carbon per year in 1999 to about 21 thousand tons per year in 2014, while carbon storage decreased from 593 thousand tons of carbon to 577 thousand tons of carbon during this time. Of the species sampled, Northern red oak stores and sequesters the most carbon. The information presented in this report can be used to improve and augment support for urban forest management programs and to inform policy and long-term planning to improve environmental quality and human health in Baltimore.

KEY WORDS: Air pollution removal, carbon sequestration, ecosystem services, tree value, urban forestry inventory.

Cover photo: Baltimore row houses with street trees. USDA Forest Service photo by Morgan Grove.

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Summary

Understanding an urban forest's structure, function, and value can promote management decisions that will improve human health and environmental quality. An assessment of the vegetation structure, function, and value of the Baltimore urban forest was conducted during 1999, 2004, 2009, and 2014. Data from 193 field plots located throughout Baltimore were analyzed using the i-Tree Eco model developed by the USDA Forest Service, Northern Research Station. See Appendix 1 for the relative value of the benefits listed below.

Baltimore's Urban Forest 2014 Summary Statistics:

- Number of trees: 2,270,000.
- Most common species of trees: American beech, American elm, green ash.[1]
- Percentage of trees less than 6 inches (15.2 cm) diameter: 59.6.
- Pollution removal: 452.8 tons/year ($13.4 million/year).[2]
- Carbon storage: 577.3 thousand tons ($98.5 million).
- Carbon sequestration: 21.0 thousand tons ($3.6 million/year).
- Oxygen production: 35.3 thousand tons/year.
- Avoided runoff: 22.0 million cubic feet/year ($1.5 million/year).
- Building energy savings: $5.6 million/year.
- Carbon avoided: 9,000 tons/year ($1.5 million/year).

Summary of Changes in Baltimore's Urban Forest, 1999–2014:

- The number of trees in Baltimore's urban forest declined from an estimated 2,631,000 trees in 1999 to 2,262,000 trees in 2014. The overall tree density declined from 51 trees/acre in 1999 to 44 trees/acre in 2014. This time period saw a decrease in the proportion of trees in the smallest diameter class (1–6 inches) and a concurrent increase in the proportion of trees in larger diameter classes.
- American beech was consistently the most common species citywide over time, while American elm, black cherry, and black locust trees consistently declined in numbers from 1999 to 2014.
- Leaf area of Baltimore's trees increased from 95.7 square miles in 1999 to 100.7 square miles in 2014.
- The gross carbon sequestration of Baltimore trees increased from 17.9 thousand tons of carbon per year in 1999 to about 21 thousand tons per year in 2014 while carbon storage decreased from 593 thousand tons of carbon to 577 thousand tons of carbon during this time. Of the species sampled, Northern red oak stores and sequesters the most carbon.

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[1] Scientific names for species mentioned in the text can be found in Tables 1 and 2 (trees) and Appendix 3 (pests).

[2] Ton: short ton (U.S.) (2,000 pounds); monetary values ($) are reported in U.S. Dollars throughout the report; ecosystem service estimates are reported for trees.

Contents

Top photo: Interior of a Baltimore forest patch. USDA Forest Service photo by Morgan Grove. Bottom photo: Baltimore neighborhood with row houses and green space. USDA Forest Service photo by Morgan Grove.

Background

This report provides a summary of data collected from 1999 to 2014 by the U.S. Department of Agriculture, Forest Service as part of the Baltimore Ecosystem Study, which is part of the National Science Foundation's Long-Term Ecological Research (LTER) Network. The Baltimore Ecosystem Study aims to understand metropolitan Baltimore as a social-ecological system. The program brings together researchers from the biological, physical, and social sciences to collect new data and synthesize existing information on how both the ecological and engineered systems of Baltimore work. Since the establishment of the Baltimore Ecosystem Study in 1998, the i-Tree Eco protocols (formerly UFORE) were used to collect the LTER's long-term citywide vegetation data (e.g., Nowak et al. 2004, Swan et al. 2017). The data are available online at https://lternet.edu/site/baltimore-ecosystem-study/.

The data summarized in this report cover a period of transformational change in environmental governance of Baltimore City. Notably, the TreeBaltimore initiative was established in 2007 and strives to increase the city's urban tree canopy through the establishment, management, and preservation of trees. TreeBaltimore is a mayoral initiative led by the Baltimore City Department of Recreation and Parks in partnership with large and small organizations and individuals focused on tree-planting and tree care in Baltimore City. In addition, the city's Office of Sustainability was established in 2009 and has a mission to provide innovative solutions to Baltimore's challenges by serving as a resource, catalyst, and advocate for a sustainable and resilient city.

In addition to the plot data presented here, Baltimore's tree canopy cover has been monitored using LiDAR data, resulting in a change analysis conducted by the USDA Forest Service and the Spatial Analysis Laboratory of the University of Vermont, which found a 1 percent canopy increase from 2007 to 2015 (O'Neil-Dunne 2017). Baltimore City has also undertaken a complete inventory of street trees and maintained park trees, available at https://www.treebaltimore.org/maps.

The goal of this report is to provide a complementary assessment of Baltimore's urban forest using a plot-based sample that includes trees across all land uses and ownerships. Furthermore, the long-term nature of this dataset provides a rare opportunity to observe changes in urban forest structure and composition over 15 years. The USDA Forest Service Urban Forest Inventory and Analysis (Urban FIA) program began a similar plot-based inventory in 2014. These data are collected continuously and will provide future assessments of the structure, composition, and ecosystem services of Baltimore's trees after the timeframe of this report. For more information about the Urban FIA program, visit https://www.fia.fs.fed.us/program-features/urban/.

Methods

The i-Tree Eco model 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 (Nowak 2020), including:

- Urban forest structure (species composition, tree health, leaf area, etc.).
- Amount of pollution removed hourly by the urban forest, and its associated percent air quality improvement throughout a year.
- 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 sources.
- Structural value of the forest, as well as the value for air pollution removal and carbon storage and sequestration.
- Potential impact of infestations by pests, such as Asian longhorned beetle, emerald ash borer, gypsy moth, and Dutch elm disease.

All field data were collected during the leaf-on season to properly assess tree canopies. Data collection included land use, ground and tree cover, individual tree attributes of species, stem diameter, height, crown width, crown canopy missing and dieback, and distance and direction to residential buildings (Nowak et al. 2005, Nowak et al. 2008).

During data collection, trees were identified to the most specific taxonomic classification possible. Trees that were not classified to the species level may be classified by genus (e.g., ash) or species groups (e.g., hardwood). In this report, tree species, genera, or species groups are collectively referred to as tree species.

Tree Characteristics

Leaf area of trees was assessed using measurements of crown dimensions and percentage of crown canopy missing. Invasive species were identified using an invasive species list for the state of Maryland (Maryland Invasive Species Council 2014a, 2014b). These lists are not exhaustive, and they cover invasive species of varying degrees of invasiveness and distribution. Tree species that are identified as invasive by the state invasive species list are cross-referenced with native range data. This helps eliminate species that are on the state invasive species list but are native to the study area.

Air Pollution Removal

Pollution removal is calculated for ozone, sulfur dioxide, nitrogen dioxide, carbon monoxide, and particulate matter less than 2.5 microns. Particulate matter less than 10 microns (PM10) is another significant air pollutant. Given that i-Tree Eco analyzes particulate matter less than 2.5 microns (PM2.5), which is a subset of PM10, PM10 has not been included in this analysis. PM2.5 is generally more relevant in discussions concerning air pollution effects on human health.

Air pollution removal estimates are derived from calculated hourly tree canopy resistances for ozone; they are also derived from sulfur and nitrogen dioxides based on a hybrid of big-leaf and multi-layer canopy deposition models (Baldocchi 1988, Baldocchi et al. 1987). As the removal of carbon monoxide by vegetation is not directly related to transpiration, removal rates (deposition velocities) for these pollutants were based on average measured values from the literature (Bidwell and Fraser 1972) that were adjusted depending on leaf phenology and leaf area. Particulate removal of PM2.5 was based on methods detailed in Nowak et al. (2013). Recent updates (2011) to air quality modeling are based on improved leaf area index simulations, weather and pollution processing and interpolation, and updated pollutant monetary values (Hirabayashi 2011, Hirabayashi et al. 2011, Hirabayashi et al. 2012).

Trees remove PM2.5 when particulate matter is deposited on leaf surfaces (Nowak et al. 2013). This deposited PM2.5 can be resuspended to the atmosphere or removed during rain events and dissolved or transferred to the soil. This combination of events can lead to positive or negative pollution removal and value depending on various atmospheric factors. Generally, PM2.5 removal is positive with positive benefits. However, there are some cases when net removal is negative or resuspended particles lead to increased pollution concentrations and negative values. During some months (e.g., with no rain), trees resuspend more particles than they remove. Resuspension can also lead to increased overall PM2.5 concentrations if the boundary layer conditions are lower during net resuspension periods than during net removal periods. Since the pollution removal value is based on the change in pollution concentration, it is possible to have situations when trees remove PM2.5 but increase concentrations and thus have negative values during periods of positive overall removal. These events are not common, but can happen.

Default air pollution removal value is calculated based on the change in local incidence of adverse health effects due to trees and national median externality costs. The number of adverse health effects and associated economic value is calculated for ozone, sulfur dioxide, nitrogen dioxide, and particulate matter less than 2.5 microns by using data from the U.S. Environmental Protection Agency's Environmental Benefits Mapping and Analysis Program (BenMAP; Nowak et al. 2014). The model uses a damage-function approach that is based on the local change in pollution concentration and population. National median externality costs were used to calculate the value of carbon monoxide removal (Murray et al. 1994).

For this analysis, pollution removal value is calculated based on the prices of $1,136 per ton (carbon monoxide), $12,384 per ton (ozone), $2,025 per ton (nitrogen dioxide), $959 per ton (sulfur dioxide), and $521,973 per ton (particulate matter less than 2.5 microns).

Carbon Storage and Sequestration

Carbon storage is the amount of carbon bound up in the above-ground and below-ground parts of woody vegetation. To calculate current carbon storage, biomass for each tree was calculated with equations from the literature and measured tree data. Open-grown, maintained trees tend to have less biomass than predicted by forest-derived biomass equations (Nowak 1994). To adjust for this difference, biomass results for open-grown urban trees were multiplied by 0.8. No adjustment was made for trees found in natural stand conditions. Tree dry-weight biomass was converted to stored carbon by multiplying by 0.5.

Carbon sequestration is the removal of carbon dioxide from the air by plants. 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. Net carbon sequestration is estimated by subtracting estimated carbon loss due to tree mortality and decomposition from gross sequestration.

Carbon storage and carbon sequestration values are based on the 2020 U.S. social cost of carbon of $171 per ton of carbon in 2018 dollars (Interagency Working Group on Social Cost of Carbon 2016).

Oxygen Production

The amount of oxygen produced is estimated from carbon sequestration based on atomic weights: net O_2 release (kg/yr) = net C sequestration (kg/yr) × 32/12. To estimate the net carbon sequestration rate, the amount of carbon sequestered as a result of tree growth is reduced by the amount lost resulting from tree mortality. Thus, net carbon sequestration and net annual oxygen production of the urban forest account for decomposition (Nowak et al. 2007).

Avoided Runoff

Annual avoided surface runoff is calculated based on rainfall interception by vegetation, specifically the difference between annual runoff with and without vegetation. Although tree leaves, branches, and bark may intercept precipitation and thus mitigate surface runoff, only the precipitation intercepted by leaves is accounted for in this analysis.

The value of avoided runoff was based on local weather data (NCDC 2005) and the U.S. Forest Service's Community Tree Guide Series (McPherson et al. 1999, 2000, 2001, 2002, 2003, 2004, 2006a, 2006b, 2006c, 2007, 2010; Peper et al. 2009, 2010; Vargas et al. 2007a, 2007b, 2008). For this analysis, avoided runoff value is calculated based on the price of $0.07 per cubic feet.

Building Energy Use

Seasonal effects of trees on residential building energy use were calculated based on procedures described in the literature (McPherson and Simpson 1999) that use distance and direction of trees from residential structures, tree height, and tree condition data. To calculate the monetary value of energy savings, local or custom prices per mega-watt hours (MWH) or million British Thermal Units (MBTU) are utilized. For this analysis, energy saving value is calculated based on the prices of $129.18 per MWH and $15.46 per MBTU.

Structural Values

Structural value is the value of a tree based on the physical resource itself (e.g., the cost of having to replace a tree with a similar tree). Structural values were based on valuation procedures of the Council of Tree and Landscape Appraisers, which uses tree species, diameter, condition, and location information (Nowak et al 2002a, 2002b).

Potential Pest Impacts

The potential pest risk is based on pest range maps and the known pest host species that are likely to experience mortality. Pest range maps for 2012 from the Forest Health Technology Enterprise Team (FHTET) (USDA Forest Service 2014) were used to determine the proximity of each pest to the county in which the urban forest is located. For the county, it was established whether the insect/disease occurs within the county, is within 250 miles of the county edge, is between 250 and 750 miles away, or is greater than 750 miles away. FHTET did not have pest range maps for Dutch elm disease and chestnut blight. The range of these pests was based on known occurrence and the host range, respectively (USDA Forest Service 2014, Worrall 2007).

Relative Tree Effects

The relative value of tree benefits reported in Appendix 1 is calculated to show what carbon storage and sequestration, and air pollutant removal equate to in amounts of municipal carbon emissions, passenger automobile emissions, and house emissions.

Municipal carbon emissions are based on 2010 U.S. per capita carbon emissions (Carbon Dioxide Information Analysis Center 2010). Per capita emissions were multiplied by city population to estimate total city carbon emissions.

Light duty vehicle emission rates (g/mi) for CO, NOx, VOCs, PM10, and SO_2 for 2010 (Bureau of Transportation Statistics 2010, Heirigs et al. 2004), PM2.5 for 2011–2015 (California Air Resources Board 2013), and CO_2 for 2011 (U.S. Environmental Protection Agency 2010) were multiplied by average miles driven per vehicle in 2011 (Federal Highway Administration 2013) to determine average emissions per vehicle.

Household emissions are based on average electricity kWh usage, natural gas BTU usage, fuel oil BTU usage, kerosene BTU usage, LPG (liquefied petroleum gas) BTU usage, and wood BTU usage per household in 2009 (Energy Information Administration 2013, 2014).

CO_2, SO_2, and NOx power plant emission per KWh are from Leonardo Academy (2011). CO emission per kWh assumes 1/3 of 1 percent of C emissions is CO based on Energy Information Administration (1994). PM10 emission per kWh is from Layton (2004).

CO_2, NOx, SO_2, 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 Leonardo Academy (2011).

CO_2 emissions per BTU of wood from Energy Information Administration (2014).

CO, NOx, and SOx emission per BTU based on total emissions and wood burning (tons) from British Columbia Ministry of Water, Land, and Air Protection (2005) and Georgia Forestry Commission (2009).

Tree Characteristics of the Urban Forest

The urban forest of Baltimore had an estimated 2,631,000 trees in 1999 and 2,262,000 trees in 2014. The overall tree density in Baltimore was 51 trees/acre in 1999 and 44 trees/acre in 2014. The most common tree species in Baltimore are American beech, American elm, and tree of heaven.

The number of surviving trees during each time period decreased over time, while there was in increase in both new trees and trees that were dead or removed during each time period (Fig. 1; error bars represent standard error). The overall decrease in number of trees and increase in total leaf area in Baltimore from 1999 to 2014 suggests a trend of larger average tree size, which is reflected in the decrease in the proportion of trees in the smallest diameter class (1–6 inches) and a concurrent increase in the proportion of trees in larger diameter classes (Fig. 2). If this trend continues, it may be problematic for sustainability of the city's urban forest demographic structure.

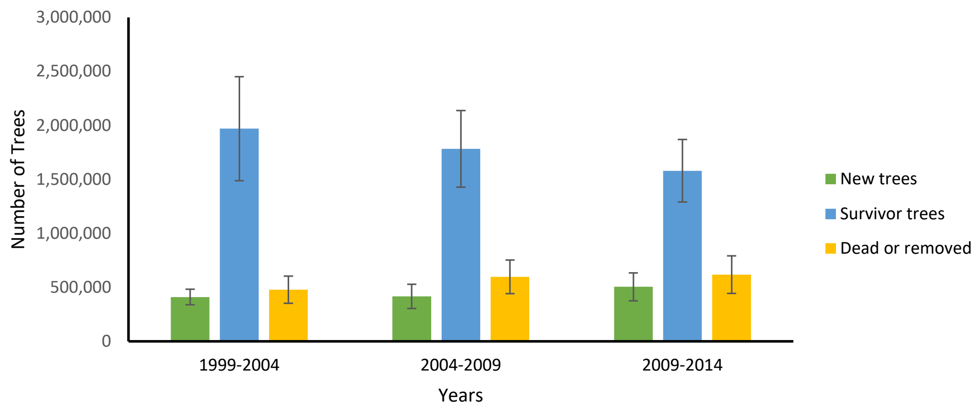

Figure 1.—Change in tree population, Baltimore. Error bars represent one standard error of the mean.

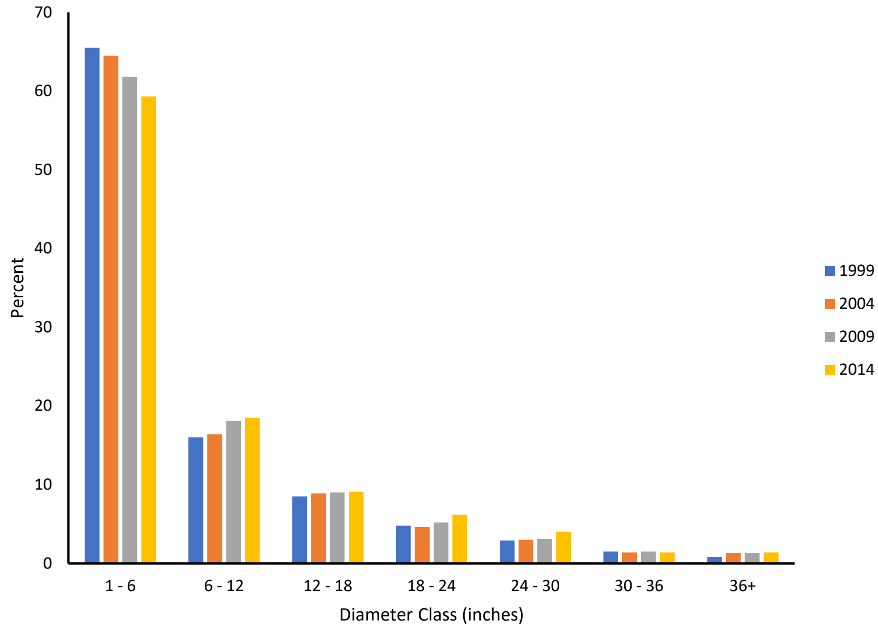

Figure 2.—Percentage of tree population by diameter class, Baltimore.

There were consistent decreases in numbers of American elm, black cherry, and black locust trees over the three time periods (Fig. 3; error bars represent standard error). Numbers of American beech and tree of heaven initially increased and later decreased. Overall, some of Baltimore's most prevalent species are decreasing in numbers, including native and invasive species. American beech has consistently been the most common species citywide over time (Fig. 4).

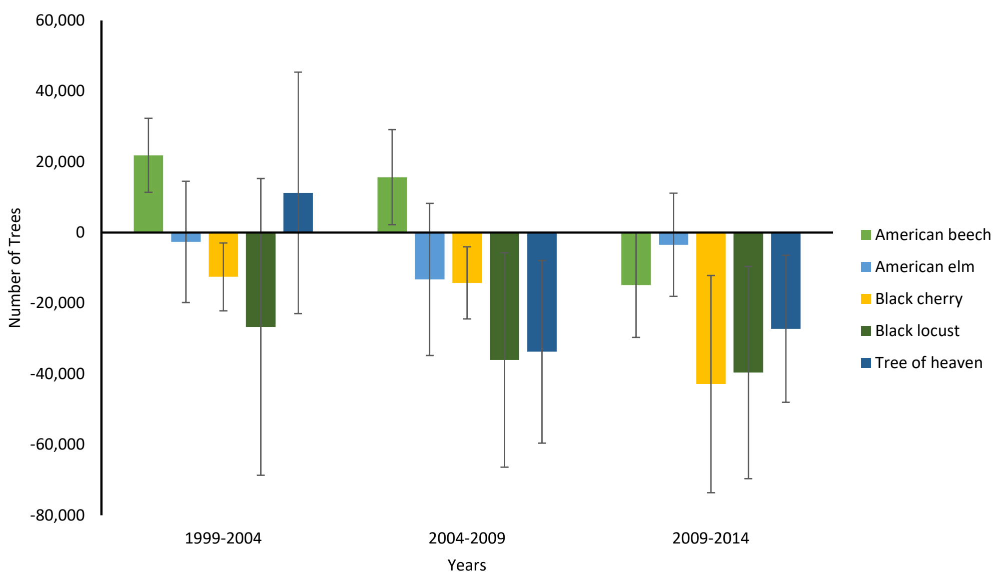

Figure 3.—Net change in population of the five most common species by number, Baltimore. Error bars represent one standard error of the mean.

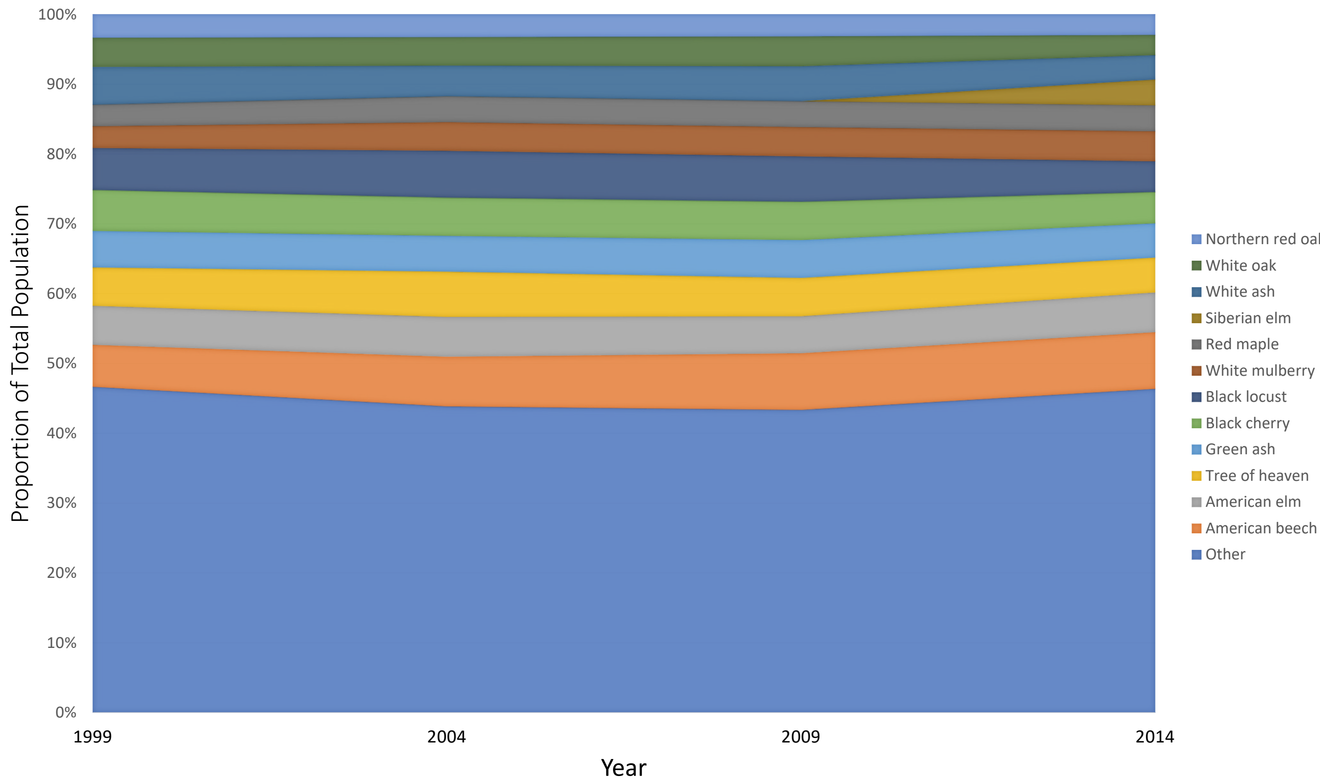

Figure 4.—Tree species composition in Baltimore, 1999–2014.

Urban forests are composed of a mix of native and exotic tree species. 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 it 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 1999, about 78 percent of Baltimore's trees were species native to North America, while 77 percent were native to Maryland. In 2014, 71 percent of Baltimore's trees were species native to North America, while 70 percent were native to Maryland. Most exotic tree species have an origin from Asia (Fig. 5; 15 percent of the species in 1999 and 22 percent in 2014).

Invasive plant species are often characterized by their vigor, ability to adapt, reproductive capacity, and general lack of natural enemies. These abilities enable them to displace native plants and make them a threat to natural areas. Three tree species found in Baltimore are identified as invasive on the state invasive species list (Maryland Invasive Species Council 2014a, 2014b). These invasive species comprised 6.9 percent of the tree population in 2014. These three invasive species are tree of heaven (4.7 percent of population in 2014), Norway maple (1.0 percent in 2014), and Callery pear (0.8 percent in 2014) (see Appendix 2 for a complete list of invasive species).

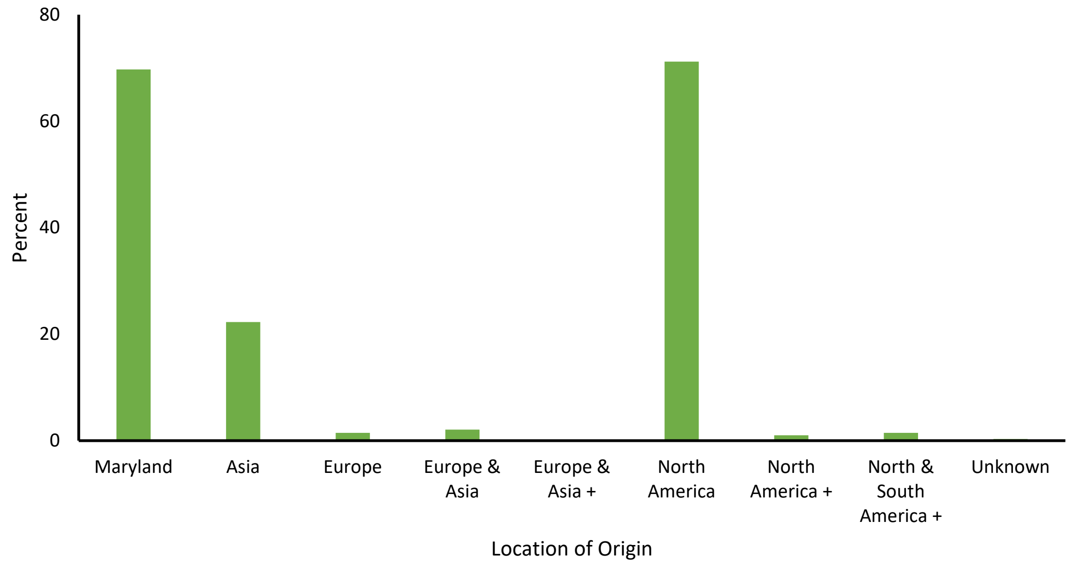

Figure 5.—Percent of 2014 Baltimore live tree population by area of native origin.

Urban Forest Leaf Area and Ground Cover

Many tree benefits equate directly to the amount of healthy leaf surface area of the plant. Trees provided 95.7 square miles of leaf area in 1999 and 100.7 square miles in 2014. Total leaf area is greatest in Forest, High Density Residential, and Medium/Low Density Residential land uses (Fig. 6).

In Baltimore, the most dominant species in terms of leaf area were white ash, tulip tree, and American beech in 1999, and tulip tree, American beech, and silver maple in 2014. The 10 species with the greatest importance values in 2014 are listed in Table 1. Importance values (IV) are calculated as the sum of percent population and percent leaf area. High importance values do not mean that these trees should necessarily be encouraged in the future; rather these species currently dominate the urban forest structure. Ash species declined in importance values, which may reflect the early stages of emerald ash borer invasion in Baltimore during recent years.

Common ground cover classes (including cover types beneath trees and shrubs) in Baltimore include grass (26 percent), buildings (21 percent), tar (19 percent), and cement (12 percent) (Fig. 7).

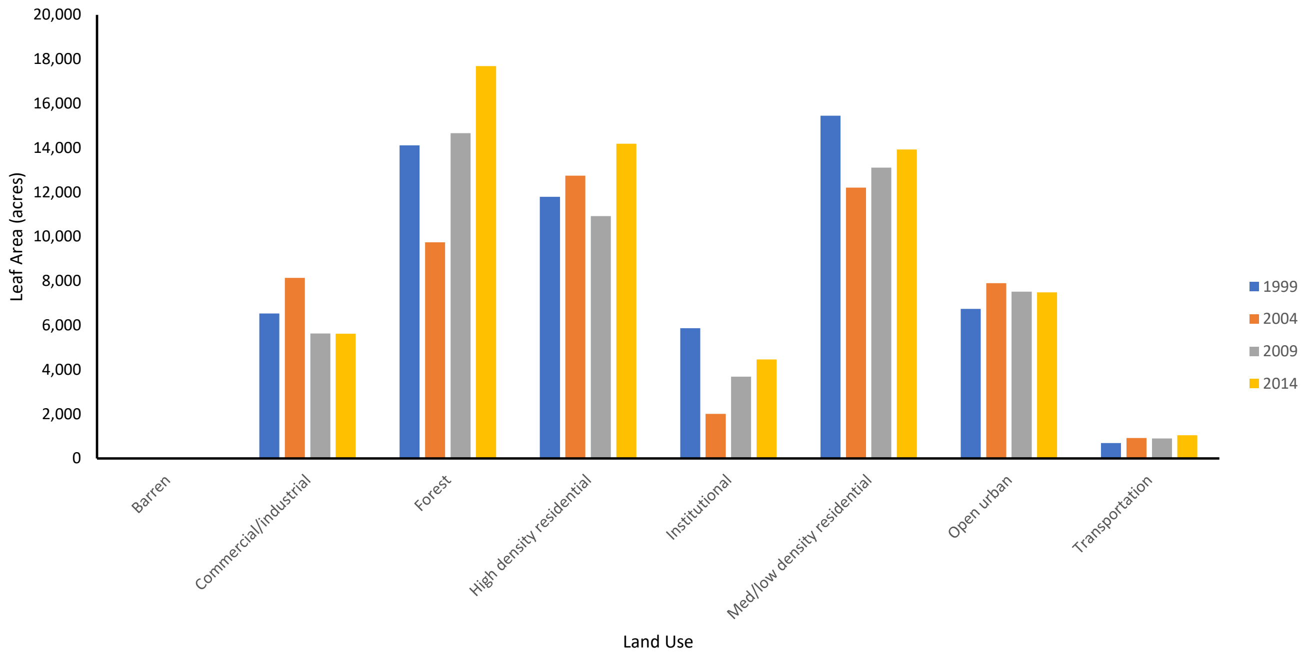

Figure 6.—Leaf area by land use stratum, Baltimore.

Table 1.—Tree species with the greatest importance values (IV), 1999-2014

Species Name	1999 IV	2004 IV	2009 IV	2014 IV	2014 Percent Population	2014 Percent Leaf Area
American beech (*Fagus grandifolia*)	12.8	12.2	16.0	16.7	8.1	8.5
Tulip tree (*Liriodendron tulipifera*)	9.1	6.4	9.6	13.1	2.1	11.0
American elm (*Ulmus americana*)	11.1	11.0	11.2	9.7	5.7	4.0
Red maple (*Acer rubrum*)	8.8	9.2	8.8	9.0	3.7	5.3
Northern red oak (*Quercus rubra*)	8.6	8.8	9.9	8.4	2.9	5.5
Silver maple (*Acer saccharinum*)	10.9	11.6	10.3	8.3	2.2	6.1
Green ash (*Fraxinus pennsylvanica*)	6.9	7.6	7.8	8.0	4.9	3.1
Tree of heaven (*Ailanthus altissima*)	8.9	9.6	8.1	7.4	5.0	2.5
White mulberry (*Morus alba*)	5.8	8.2	7.2	7.2	4.3	2.9
White ash (*Fraxinus americana*)	11.8	7.2	8.7	6.7	3.5	3.3

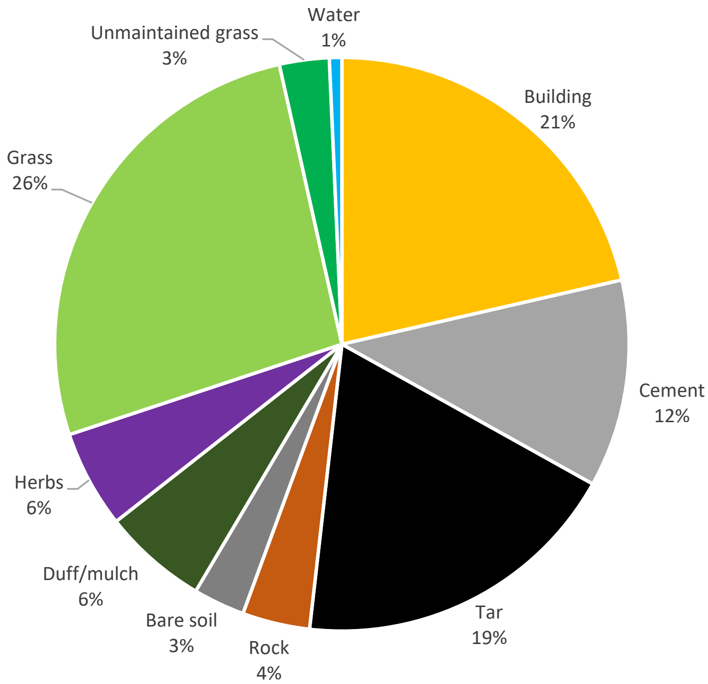

Figure 7.—Percent of land by ground cover classes in Baltimore, 2014.

Air Pollution Removal by Urban Trees

Poor air quality is a common problem in many urban areas. It can lead to decreased human health, 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 reduces air pollutant emissions from the power sources. 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 (Nowak and Dwyer 2000).

Pollution removal by trees and shrubs in Baltimore was estimated using field data and recent available pollution and weather data from 2005 (NCDC 2005). Because 2005 pollution and weather data were used to model all years of pollution removal, changes over time are due to changes in forest structure and not annual changes in pollution and weather. Pollution removal was greatest for ozone (Fig. 8). It is estimated that trees and shrubs removed 429.3 tons of air pollution (ozone (O_3), carbon monoxide (CO), nitrogen dioxide (NO_2), particulate matter less than 2.5 microns (PM2.5)[1], and sulfur dioxide (SO_2) per year in 1999, and removed 452.8 tons of air pollution in 2014 with an associated value of $13.4 million.

[3]Trees remove PM2.5 when particulate matter is deposited on leaf surfaces. This deposited PM2.5 can be resuspended to the atmosphere or removed during rain events and dissolved or transferred to the soil. This combination of events can lead to positive or negative pollution removal and value depending on various atmospheric factors.

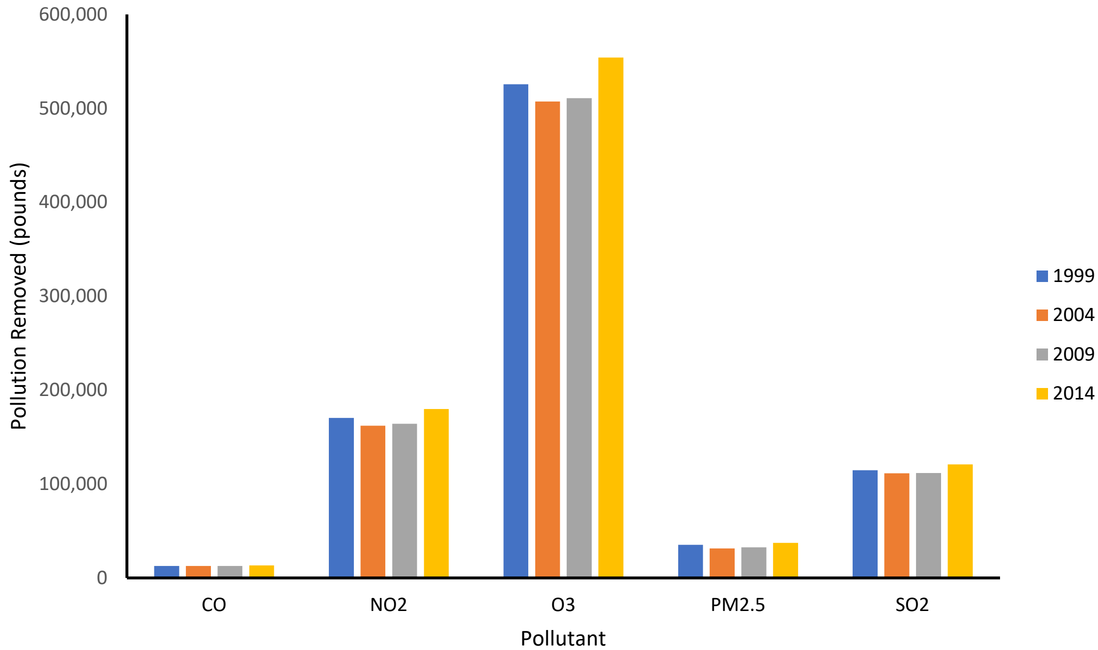

Figure 8.—Annual pollution removal by urban trees, Baltimore.

In 2014, trees in Baltimore emitted an estimated 208.1 tons of volatile organic compounds (VOCs) (146.4 tons of isoprene and 61.4 tons of monoterpenes). Emissions vary among species based on species characteristics (e.g., some genera such as oaks are high isoprene emitters) and amount of leaf biomass. Forty-two percent of the urban forest's VOC emissions were from Northern red oak and Norway spruce. These VOCs are precursor chemicals to ozone formation.

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 altering energy use in buildings, and consequently altering carbon dioxide emissions from fossil-fuel based power sources (Abdollahi et al. 2000).

Carbon sequestration is the amount of carbon taken up by trees in 1 year while carbon storage represents the total stock of all carbon currently held in standing trees. Trees reduce the amount of carbon in the atmosphere by sequestering carbon in new growth every year. The amount of carbon annually sequestered increases with the size of the trees. The gross sequestration of Baltimore trees was about 17.9 thousand tons of carbon per year in 1999 and about 21 thousand tons per year in 2014 (Fig. 9). Net carbon sequestration in the urban forest was about 12.8 thousand tons in 1999 and 13.2 thousand tons in 2014. Gross sequestration of Baltimore trees in 2014 had an associated value of $3.6 million/year.

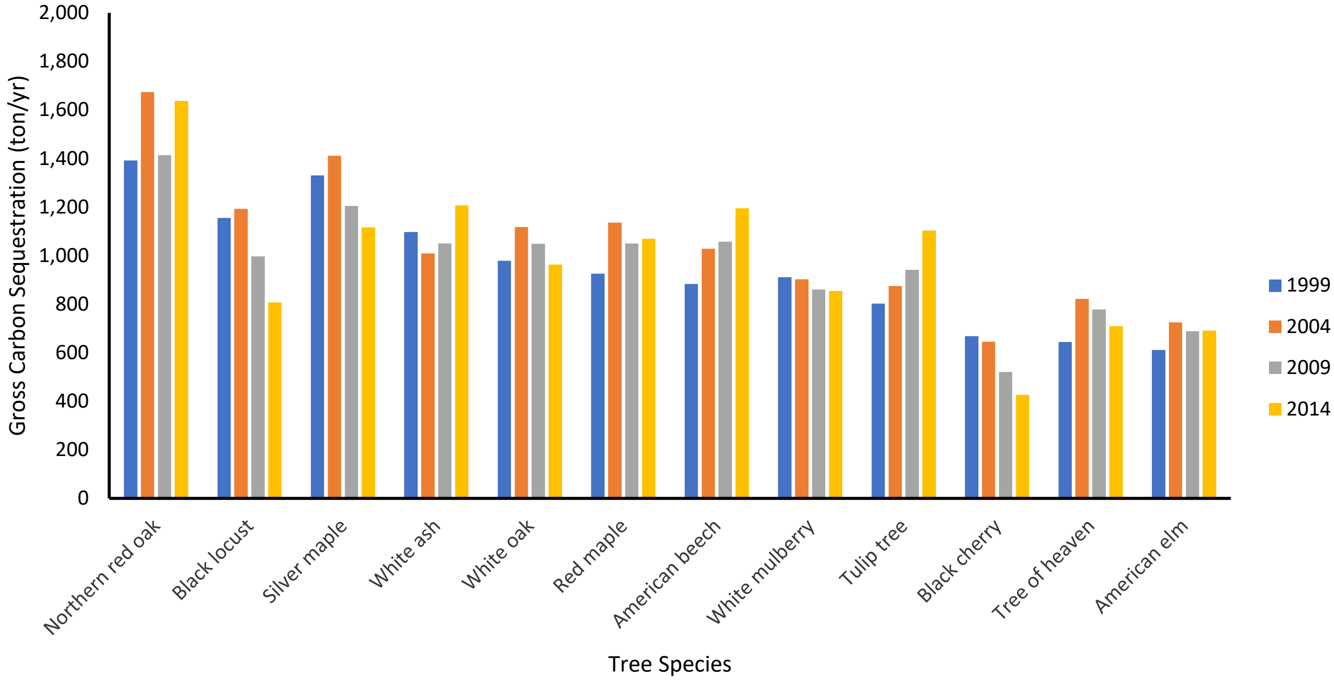

Figure 9.—Estimated annual gross carbon sequestration for urban tree species with the greatest sequestration, Baltimore.

Carbon storage can influence global climate change. As a tree grows, it stores more carbon by holding it in its accumulated tissue. As a tree dies and decays, it releases much of the stored carbon back into the atmosphere. Thus, carbon storage is an indication of the amount of carbon that can be released if trees are allowed to die and decompose. Maintaining healthy trees will keep the carbon stored in trees and help the trees sequester carbon annually, but tree maintenance can contribute to carbon emissions (Nowak et al. 2002c). When a tree dies, using the wood in long-term wood products, to heat buildings, or to produce energy will help reduce carbon emissions from wood decomposition or from fossil-fuel-based power plants.

Trees in Baltimore were estimated to store 593 thousand tons of carbon in 1999 and 577 thousand tons of carbon in 2014 (Fig. 10) with an associated value of $98.5 million in 2014. Of the species sampled, Northern red oak stores and sequesters the most carbon (approximately 11.2 percent of the total carbon stored in 1999 and 12.1 percent of the total carbon stored in 2014; and 7.8 percent of all sequestered carbon in 1999 and 7.8 percent of all sequestered carbon in 2014).

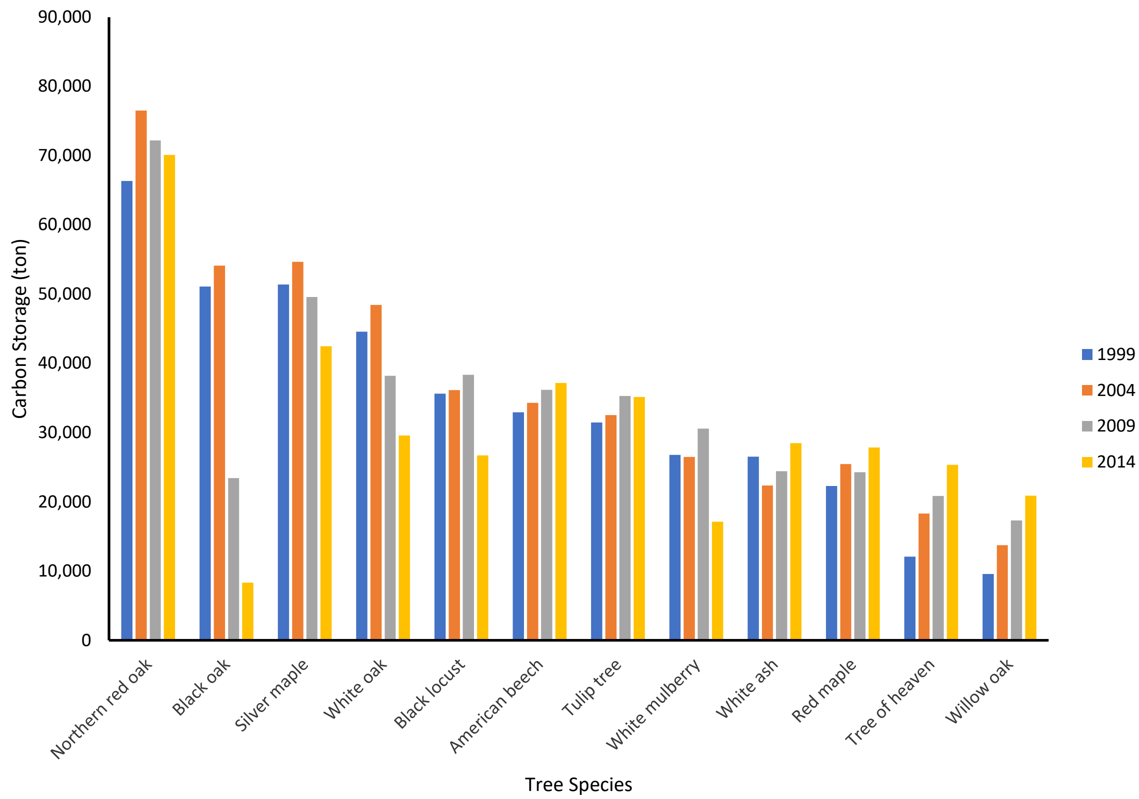

Figure 10.—Estimated carbon storage for urban tree species with the greatest storage, Baltimore.

The overall number of trees in Baltimore's urban forest is declining, along with the amount of carbon stored, yet the amount of carbon sequestered and the total leaf area of the urban forest is increasing over the same time period. This pattern suggests that dead and declining trees with high carbon storage values but low leaf area and carbon sequestration rates are being removed while the remaining trees are growing, increasing their leaf area and carbon sequestration over time.

Baltimore's urban forest had net carbon gain during 1999–2004, while the following time periods saw net carbon loss as the biomass of live trees that were removed increased over time (Fig. 11). These calculations (Figs. 11–15; error bars represent standard error) include only trees that were alive at the first measurement time (following Bechtold and Patterson 2005). Some trees that undergo mortality are left as standing dead trees or are left as fallen woody debris, while others are removed completely from the site. These different management actions have implications for urban carbon cycling. Typically, increases in biomass and carbon occur in small increments (incremental diameter growth of smaller trees over time) while large amounts of biomass are lost when larger, older trees die or are removed as they reach senescence.

Some of the most common species had consistent net losses in biomass/carbon over time (black locust) while others showed increases during some time periods and loss during others (Fig. 12). However, all of the five most common species had net carbon loss during the most recent time period (2009–2014). Although there was a loss in number of American elm trees from 1999 to 2009 (Fig. 3), there was also a net carbon gain for this species, meaning that surviving larger trees put on enough biomass to make up for the loss in numbers. This trend reversed during 2009–2014 as more large American elms likely died or were removed from the population.

During all three time periods, Baltimore's urban forest gained more carbon in the growth of small and medium diameter trees (< 9 inches d.b.h.) than was lost in tree removals of this size (Fig. 13). However, during 2004–2009 and 2009–2014, the city lost more carbon in the removal of large diameter trees (> 9 inches d.b.h.) than was gained in this size class (Fig. 14). Despite the ingrowth of small trees into the city's urban forest, the loss of large trees ultimately leads to a net decrease in carbon storage over time. Preservation of large trees and continued planting can help mitigate this loss.

Open urban land uses had consistent net carbon gain over time while others showed large fluctuations between gain and loss across time periods (commercial/industrial, forest) or smaller fluctuations (transportation) (Fig. 15). Only open urban land uses (which includes parks) had a net carbon gain during the most recent time period (2009–2014). Large fluctuations in live tree carbon storage are generally driven by loss of large mature trees, which can store 1,000 times more carbon than smaller trees that are added to the population. Loss of these large trees on a plot may have a large influence in the population estimates of carbon storage.

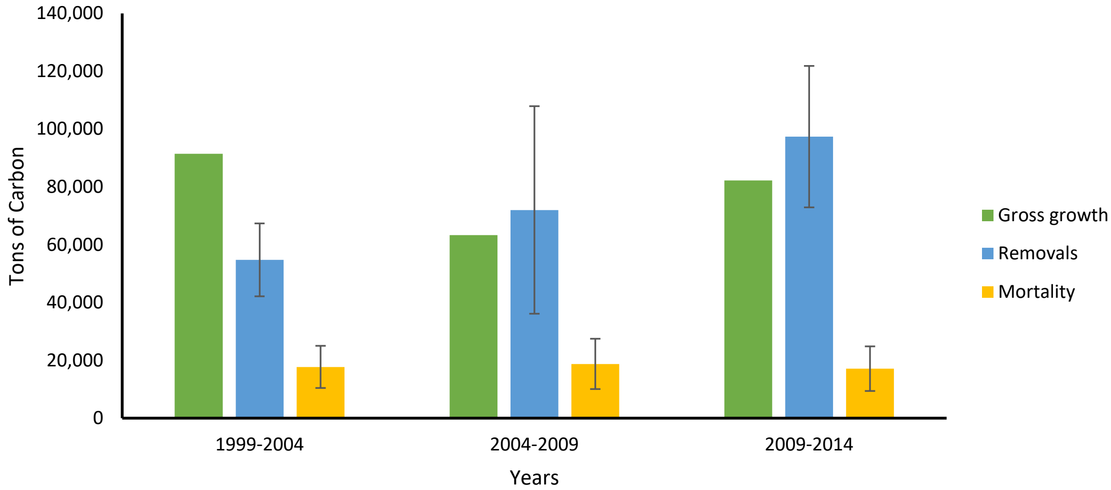

Figure 11.—Change in live tree carbon over time, Baltimore. Error bars represent one standard error of the mean.

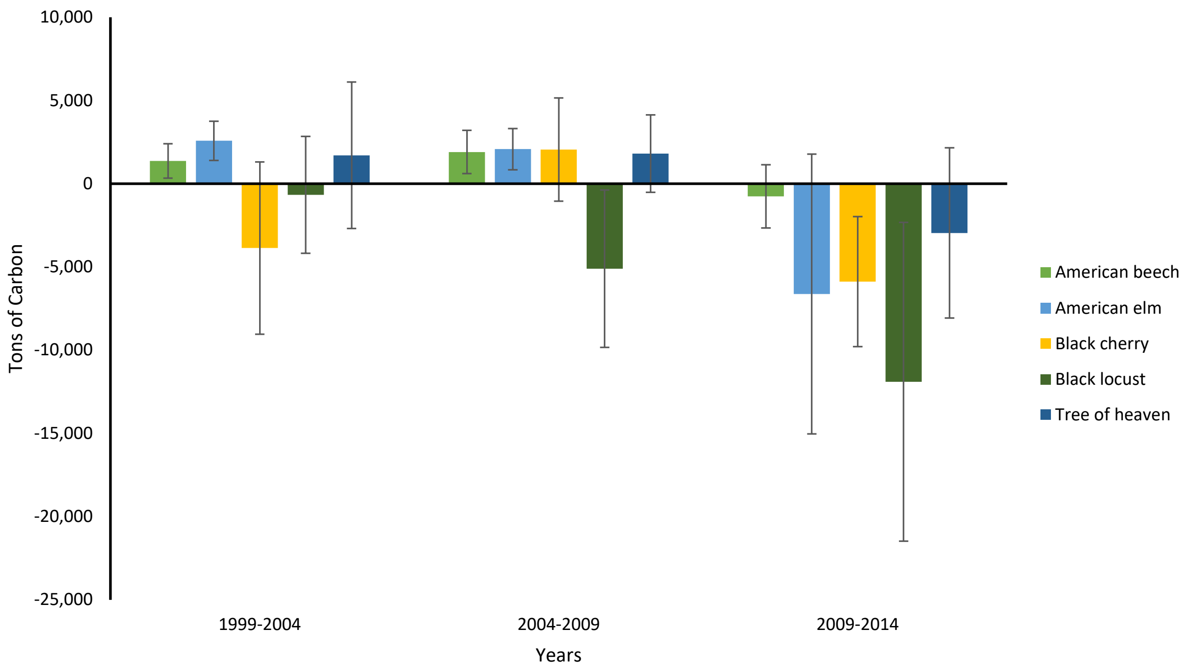

Figure 12.—Net live tree carbon change in top five species, Baltimore. Error bars represent one standard error of the mean.

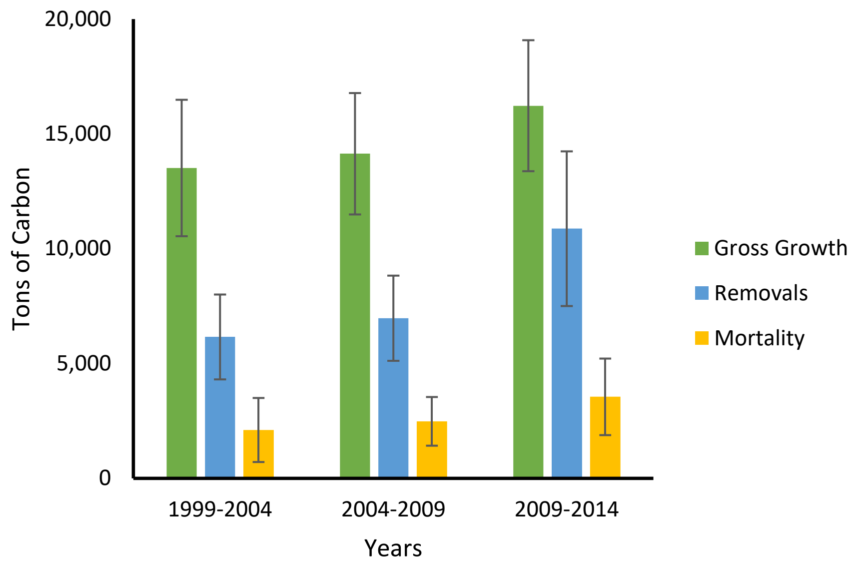

Figure 13.—Change in small/medium-diameter live tree carbon, Baltimore. Error bars represent one standard error of the mean.

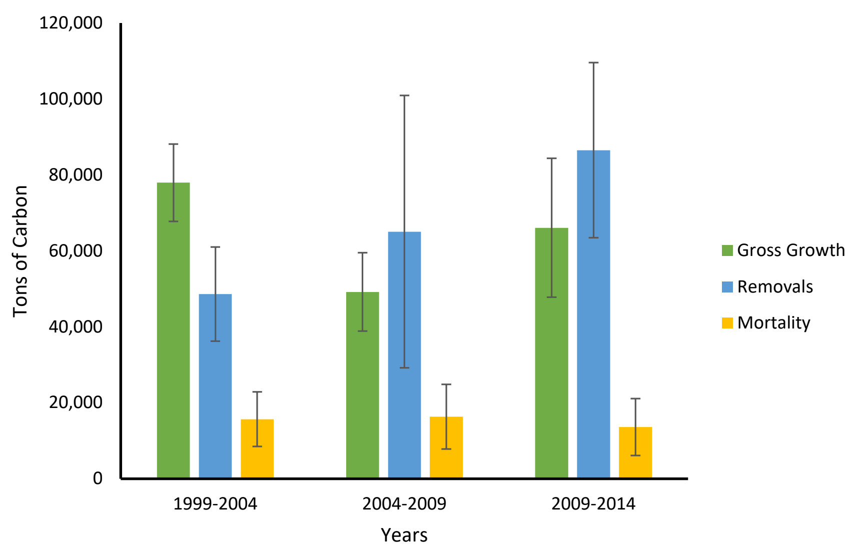

Figure 14.—Change in large-diameter, live tree carbon, Baltimore. Error bars represent one standard error of the mean.

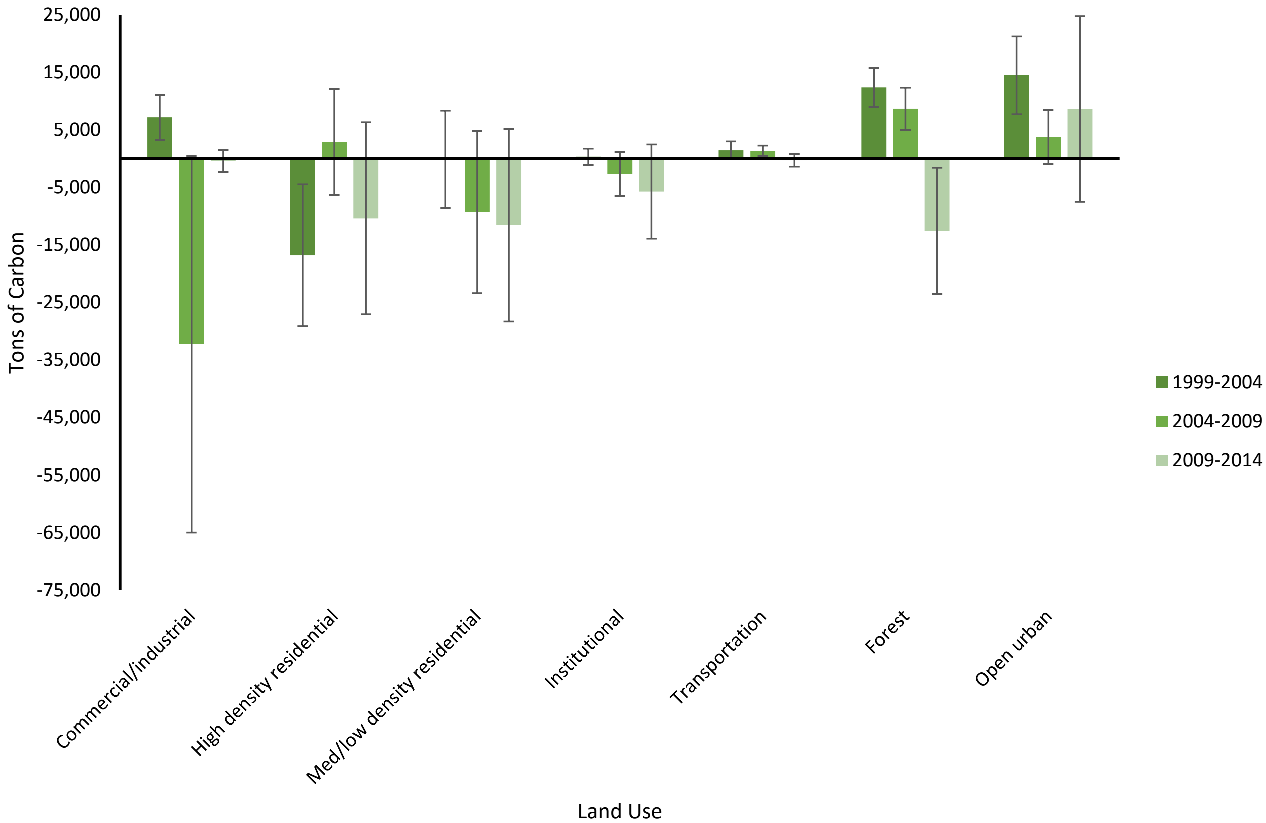

Figure 15.—Net live tree carbon change by land use strata, Baltimore. Error bars represent one standard error of the mean.

Oxygen Production

Oxygen production is one of the most commonly cited benefits of urban trees. The net annual oxygen production of a tree is directly related to the amount of carbon sequestered by the tree, which is tied to the accumulation of tree biomass.

In 2014, trees in Baltimore were estimated to produce 35.3 thousand tons of oxygen per year (Table 2). However, this tree benefit is relatively insignificant because of the large and relatively stable amount of oxygen in the atmosphere and extensive oxygen production by aquatic systems. Our atmosphere has an enormous reserve of oxygen. If all fossil-fuel reserves, all trees, and all organic matter in soils were burned, atmospheric oxygen would only drop a few percent (Broecker 1996).

Table 2.—The top 20 oxygen-producing tree species, 2014

Species	Oxygen (thousand tons)	Net Carbon Sequestration (tons/yr)	Number of Trees	Leaf Area (square miles)
Tulip tree (*Liriodendron tulipifera*)	2.68	1,005.5	47,500	11.1
White ash (*Fraxinus americana*)	2.60	975.1	78,300	3.3
White oak (*Quercus alba*)	2.27	850.3	65,100	2.2
Silver maple (*Acer saccharinum*)	2.22	833.4	49,800	6.2
American beech (*Fagus grandifolia*)	2.17	814.6	184,900	8.6
Northern red oak (*Quercus rubra*)	2.13	800.4	65,500	5.5
White mulberry (*Morus alba*)	2.12	795.8	96,900	2.9
American elm (*Ulmus americana*)	1.64	615.4	129,600	4.1
Red maple (*Acer rubrum*)	1.63	610.1	84,400	5.3
Willow oak (*Quercus phellos*)	1.34	503.7	37,100	3.4
Eastern white pine (*Pinus strobus*)	1.32	493.1	53,100	2.7
Southern red oak (*Quercus falcata*)	1.25	469.0	4,100	1.8
Norway spruce (*Picea abies*)	1.23	461.6	14,800	5.2
American sycamore (*Platanus occidentalis*)	1.00	373.9	23,300	2.3
Callery pear (*Pyrus calleryana*)	0.96	358.6	17,700	1.2
Oriental arborvitae (*Platycladus orientalis*)	0.85	319.2	16,500	0.3
Green ash (*Fraxinus pennsylvanica*)	0.85	317.1	112,300	3.1
Japanese maple (*Acer palmatum*)	0.83	309.9	14,800	1.4
Boxelder (*Acer negundo*)	0.80	300.8	43,100	2.1
Chestnut oak (*Quercus prinus*)	0.73	274.6	14,800	0.5

Avoided Runoff

Surface runoff can be a cause for concern in many urban areas as it can contribute pollution to streams, wetlands, rivers, lakes, and oceans (Müller et al. 2020). During precipitation events, some portion of the precipitation is intercepted by vegetation (trees and shrubs) while the other portion reaches the ground. The portion of the precipitation that reaches the ground and does not infiltrate into the soil becomes surface runoff (Nowak et al. 2020). In urban areas, the large extent of impervious surfaces increases the amount of surface runoff.

Urban trees and shrubs are beneficial in reducing surface runoff. Trees and shrubs intercept precipitation, while their root systems promote infiltration and storage in the soil. The trees of Baltimore helped to reduce runoff by an estimated 19.8 million cubic feet in 1999 and an estimated 22 million cubic feet in 2014 (Fig. 16) with an associated value of $1.5 million/year in 2014. Avoided runoff is estimated based on local weather from the Baltimore-Washington International Airport weather station (NCDC 2005). In Baltimore, the total annual precipitation in 2005 was 50.3 inches.

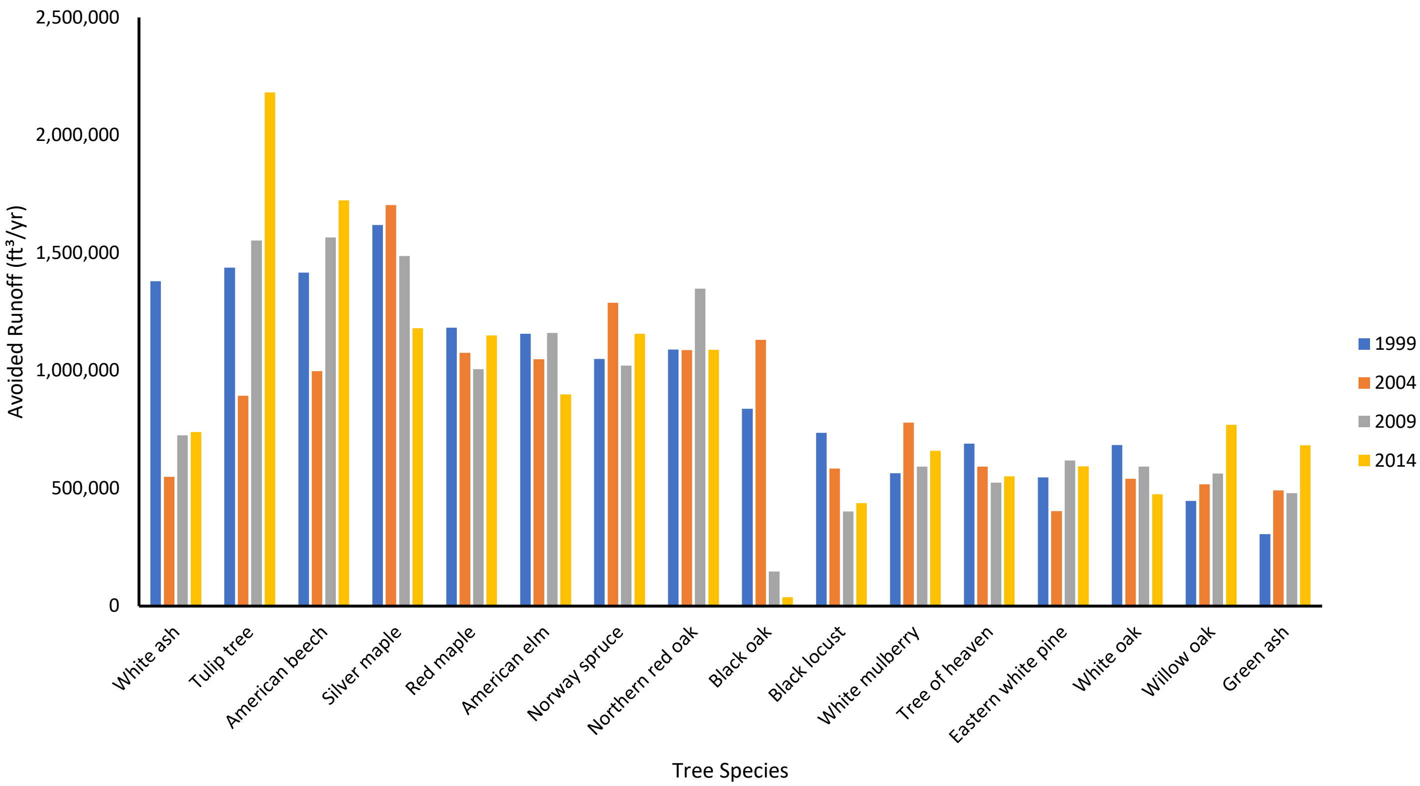

Figure 16.—Avoided runoff for species with the greatest overall impact on runoff, Baltimore.

Trees and Building Energy Use

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 (McPherson and Simpson 1999).

In 2014, trees in Baltimore were estimated to reduce energy-related costs from residential buildings by $5,621,000 annually (Tables 3, 4). Trees also provided an additional $1,536,000 in value by reducing the amount of carbon released by fossil-fuel based power plants (a reduction of 9,000 tons of carbon emissions).

Table 3.—Annual energy savings due to trees near residential buildings 2014

	Heating	Cooling	Total
MBTU[a]	180,300	N/A	180,300
MWH[b]	2,800	19,200	21,900
Carbon avoided (tons)	5,400	3,600	9,000

[a]MBTU = 1 million British Thermal Units.

[b]MWH = megawatt-hour.

Table 4.—Annual savings ($)[a] in residential energy expenditure during heating and cooling seasons 2014

	Heating	Cooling	Total
MBTU[b]	2,787,000	N/A	2,787,000
MWH[c]	358,000	2,476,000	2,834,000
Carbon avoided	917,000	619,000	1,536,000

[a]Based on the prices of $129.18 per MWH and $15.46 per MBTU.

[b]MBTU = 1 million British Thermal Units.

[c]MWH = megawatt-hour.

Structural and Functional Values

Urban forests have a structural value based on the trees themselves (e.g., the cost of having to replace a tree with a similar tree); they also have functional values (either positive or negative) based on the functions the trees perform.

The structural value of an urban forest tends to increase with a rise in the number and size of healthy trees (Nowak et al. 2002a). Annual functional values also tend to increase with increased number and size of healthy trees. 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 trees in Baltimore have the following structural values (in 2014):

- Structural value: $3.6 billion.
- Carbon storage: $98.5 million.

Urban trees in Baltimore have the following annual functional values (in 2014):

- Carbon sequestration: $3.6 million.
- Avoided runoff: $1.5 million.
- Pollution removal: $13.4 million.
- Energy costs and carbon emission values: $7.1 million.

Potential Pest Impacts

Various insects and diseases can infest urban forests, potentially killing trees and reducing the health, structural value, and sustainability of the urban forest. Thirty-six pests were analyzed for their potential impact and compared with pest range maps (USDA Forest Service 2014) for the conterminous United States to determine their proximity to Baltimore City. Ten of the 36 pests analyzed are located within the city. Figure 17 summarizes the number of trees at risk from the most threatening pests located in Baltimore City. For a complete analysis of all pests, see Appendix 3.

Dogwood anthracnose (DA) (Mielke and Daughtrey 1988) is a disease that affects dogwood species, specifically flowering and Pacific dogwood. This disease threatens 2.5 percent of the 2014 tree population, which represents a potential loss of $26.1 million in structural value.

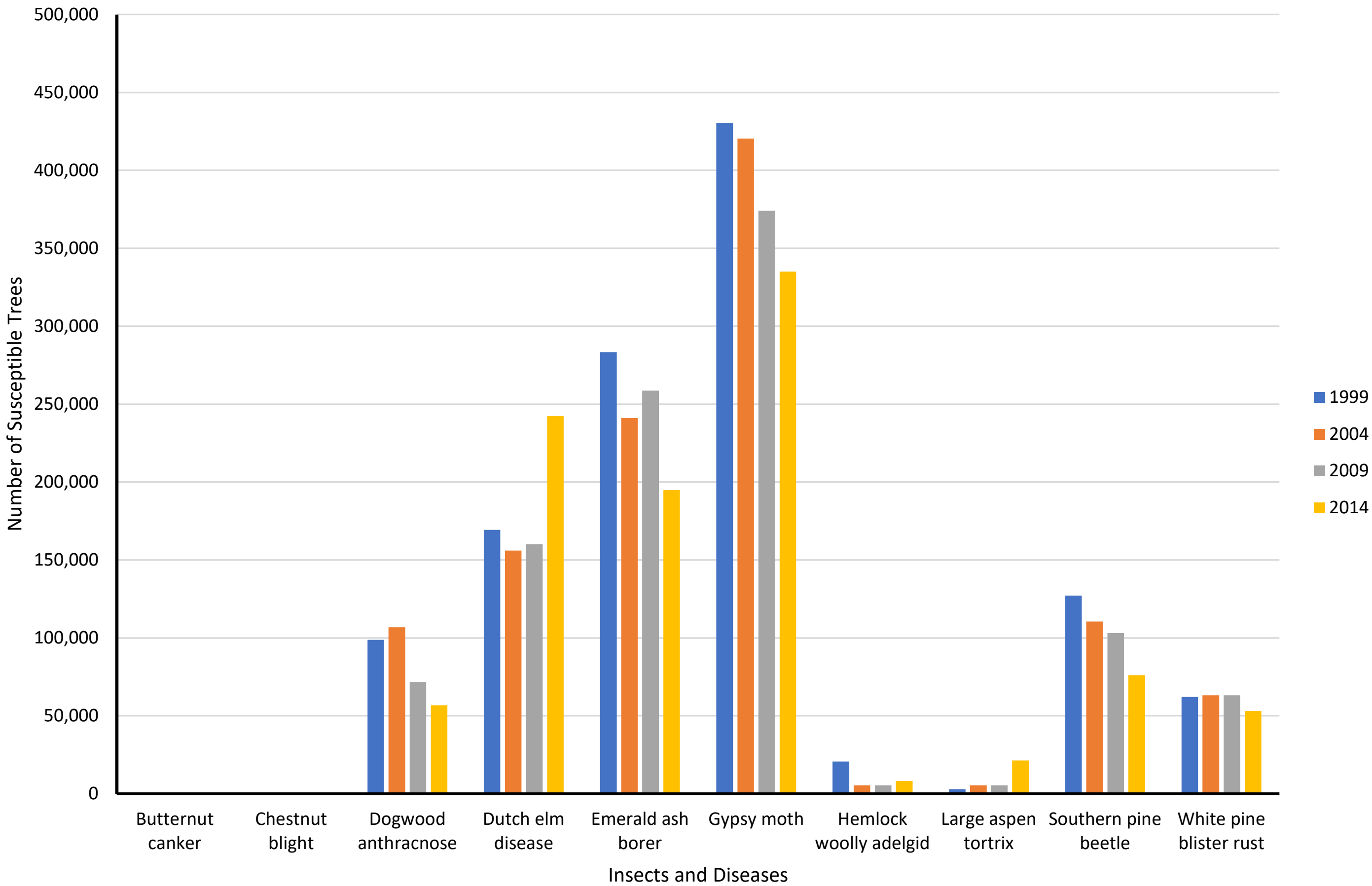

Figure 17.—Number of trees at risk from most threatening pests located in Baltimore.

American elm, one of the most important street trees in the 20th century, has been devastated by the Dutch elm disease (DED) (Haugen 1998). Since first reported in the 1930s, it has killed over 50 percent of the native elm population in the United States. Although some elm species have shown varying degrees of resistance, Baltimore could possibly lose 10.7 percent of its trees to this pest ($118 million in structural value).

Emerald ash borer (EAB) (Michigan State University 2010) has killed thousands of ash trees in parts of the United States. EAB has the potential to affect 8.6 percent of the city's 2014 tree population ($222 million in structural value).

The gypsy moth (GM) (Northeastern Area State and Private Forestry 2005) is a defoliator that feeds on many species causing widespread defoliation and tree death if outbreak conditions last several years. This pest threatens 14.8 percent of the city's 2014 tree population, which represents a potential loss of $1 billion in structural value.

As one of the most damaging pests to eastern hemlock and Carolina hemlock, hemlock woolly adelgid (HWA) (USDA Forest Service 2005) has played a large role in hemlock mortality in the United States. HWA has the potential to affect 0.4 percent of the 2014 tree population ($1.1 billion in structural value).

Quaking aspen is a principal host for the defoliator, large aspen tortrix (LAT) (Ciesla and Kruse 2009). LAT poses a threat to 0.9 percent of the Baltimore urban forest, which represents a potential loss of $50 million in structural value.

Although the southern pine beetle (SPB) (Clarke and Nowak 2009) will attack most pine species, its preferred hosts are loblolly, Virginia, pond, spruce, shortleaf, and sand pines. This pest threatens 3.4 percent of the 2014 tree population, which represents a potential loss of $335.1 million in structural value.

Since its introduction to the United States in 1900, white pine blister rust (eastern United States) (WPBR) (Nicholls and Anderson 1977) has had a detrimental effect on white pines, particularly in the Lake States. WPBR has the potential to affect 2.3 percent of the 2014 tree population ($195.1 million in structural value).

In summary, gypsy moth threatens more of Baltimore's trees than any other pest, and a prolonged outbreak could be devastating to the city's urban forest. In addition, emerald ash borer is another species of great concern, as it has recently become established in Baltimore and is causing widespread ash mortality in all trees that are not treated. Ongoing vigilance to identify emerging pests and pathogens will help sustain a healthy and diverse forest in Baltimore City.

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Appendix 1. Relative Tree Effects

The urban forest in Baltimore provides benefits that include carbon storage, carbon sequestration, and air pollutant removal. To estimate the relative value of these benefits, 2014 tree benefits were compared to estimates of average municipal carbon emissions, average passenger automobile emissions, and average household emissions.

2014 carbon storage is equivalent to:

- Amount of carbon emitted in Baltimore in 64 days.
- Annual carbon (C) emissions from 408 thousand automobiles.
- Annual C emissions from 167 thousand single-family houses.

2014 carbon monoxide removal is equivalent to:

- Annual carbon monoxide emissions from 61 automobiles.
- Annual carbon monoxide emissions from 168 single-family houses.

2014 nitrogen dioxide removal is equivalent to:

- Annual nitrogen dioxide emissions from 12,900 automobiles.
- Annual nitrogen dioxide emissions from 5,800 single-family houses.

2014 sulfur dioxide removal is equivalent to:

- Annual sulfur dioxide emissions from 650 thousand automobiles.
- Annual sulfur dioxide emissions from 1,720 single-family houses.

2014 annual carbon sequestration is equivalent to:

- Amount of carbon emitted in Baltimore in 2.3 days.
- Annual C emissions from 14,900 automobiles.
- Annual C emissions from 6,100 single-family houses.

Appendix 2. Invasive Species

Inventoried tree species listed as invasive in Maryland for selected years.[a]

Year/ Species Name[b]	Number of Trees	% of Trees	Leaf Area (ac)	Percent Leaf Area
1999				
Tree of heaven	146,600	5.6	2,028.5	3.3
Norway maple	18,400	0.7	559.5	0.9
Callery pear	16,200	0.6	280.5	0.5
Total	181,200	6.9	2,868.4	4.7
2004				
Tree of heaven	164,700	6.5	1,645.4	3.1
Callery pear	16,200	0.6	579.3	1.1
Norway maple	14,900	0.6	369.1	0.7
Autumn olive	2,900	0.1	47.0	0.1
Total	198,700	7.9	2,640.9	4.9
2009				
Tree of heaven	132,800	5.5	1,496.6	2.7
Callery pear	17,700	0.7	789.3	1.4
Norway maple	14,900	0.6	482.2	0.9
Autumn olive	5,800	0.2	10.7	0.0
Total	171,200	7.0	2,778.9	4.9
2014				
Tree of heaven	107,200	4.7	1,582.0	2.5
Norway maple	22,400	1.0	395.5	0.6
Callery pear	17,700	0.8	781.2	1.2
Total	147,300	6.5	2,758.8	4.3

[a]Species are determined to be invasive if they are listed on the State of Maryland's invasive species list (Maryland Invasive Species Council 2014a, 2014b).

[b]Scientific names: autumn olive (*Elaeagnus umbellate*), Callery pear (*Pyrus calleryana*), Norway maple (*Acer platanoides*), and tree of heaven (*Ailanthus altissima*).

Appendix 3. Potential Risk of Pests

Thirty-six insects and diseases were analyzed to quantify their potential impact on the 2014 urban forest. As each insect/disease is likely to attack different host tree species, the implications for Baltimore will vary. The number of trees at risk reflects only the known host species that are likely to experience mortality.

Code	Scientific Name	Common Name	Trees at Risk (number)	Value ($ millions)
AL	*Phyllocnistis populiella*	Aspen leafminer	6,800	45.2
ALB	*Anoplophora glabripennis*	Asian longhorned beetle	727,100	784.9
BBD	*Neonectria faginata*	Beech bark disease	184,900	207.4
BC	*Sirococcus clavigignenti juglandacearum*	Butternut canker	0	0.0
BWA	*Adelges piceae*	Balsam woolly adelgid	0	0.0
CB	*Cryphonectria parasitica*	Chestnut blight	0	0.0
DA	*Discula destructiva*	Dogwood anthracnose	56,700	26.1
DBSR	*Leptographium wageneri var. pseudotsugae*	Douglas-fir black stain root disease	0	0.0
DED	*Ophiostoma novo-ulmi*	Dutch elm disease	242,300	117.6
DFB	*Dendroctonus pseudotsugae*	Douglas-fir beetle	0	0.0
EAB	*Agrilus planipennis*	Emerald ash borer	194,800	222.0
FE	*Scolytus ventralis*	Fir engraver	0	0.0
FR	*Cronartium quercuum f. sp. Fusiforme*	Fusiform rust	0	0.0
GM	*Lymantria dispar*	Gypsy moth	335,200	1,025.3
GSOB	*Agrilus auroguttatus*	Goldspotted oak borer	0	0.0
HWA	*Adelges tsugae*	Hemlock woolly adelgid	8,300	10.6
JPB	*Dendroctonus jeffreyi*	Jeffrey pine beetle	0	0.0
LAT	*Choristoneura conflictana*	Large aspen tortrix	21,300	50.0
LWD	*Raffaelea lauricola*	Laurel wilt	24,100	4.7
MPB	*Dendroctonus ponderosae*	Mountain pine beetle	14,800	129.4
NSE	*Ips perturbatus*	Northern spruce engraver	0	0.0
OW	*Ceratocystis fagacearum*	Oak wilt	208,600	847.4
PBSR	*Leptographium wageneri var. ponderosum*	Pine black stain root disease	0	0.0
POCRD	*Phytophthora lateralis*	Port-orford-cedar root disease	0	0.0
PSB	*Tomicus piniperda*	Pine shoot beetle	67,900	324.5
PSHB	*Euwallacea nov. sp.*	Polyphagous shot hole borer	43,100	48.6
SB	*Dendroctonus rufipennis*	Spruce beetle	14,800	129.4

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Appendix 3 Continued

Code	Scientific Name	Common Name	Trees at Risk (number)	Value ($ millions)
SBW	*Choristoneura fumiferana*	Spruce budworm	0	0.0
SOD	*Phytophthora ramorum*	Sudden oak death	82,700	406.3
SPB	*Dendroctonus frontalis*	Southern pine beetle	76,100	335.1
SW	*Sirex noctilio*	Sirex wood wasp	53,100	195.1
TCD	*Geosmithia morbida*	Thousand canker disease	6,900	17.6
WM	*Operophtera brumata*	Winter moth	1,020,900	1,675.3
WPB	*Dendroctonus brevicomis*	Western pine beetle	0	0.0
WPBR	*Cronartium ribicola*	White pine blister rust	53,100	195.1
WSB	*Choristoneura occidentalis*	Western spruce budworm	14,800	129.4

Appendix 4. Metric and U.S. Standard Equivalents

U.S. Standard Equivalents

When you know:	Multiply by:	To find:
Millimeters (mm)	0.0394	Inches
Centimeters (cm)	0.394	Inches
Meters (m)	3.28	Feet
Square kilometers (km^2)	0.386	Square miles
Kilograms (kg)	2.205	Pounds
Kilograms (kg)	0.0011	Tons

Metric Equivalents

When you know:	Multiply by:	To find:
Inches (in)	2.54	Centimeters
Feet (ft)	0.305	Meters
Square miles (mi^2)	2.59	Square kilometers
Cubic ft (ft^3)	0.0283	Cubic meters
Tons (ton)	907	Kilograms
British thermal units (BTU)	1,050	Joules

Northern Research Station