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Houston's Urban Forest, 2015

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Abstract

An analysis of the urban forest in Houston, Texas, reveals that this area has an estimated 33.3 million live trees with tree canopy that covers 18.4 percent of the city. Roughly 19.2 million of the city's trees are located on private lands. The most common tree species are yaupon, Chinese tallowtree, Chinese privet, Japanese privet, and sugarberry. Trees in Houston currently store about 2.0 million tons of carbon (7.5 million tons of carbon dioxide [CO_2]); valued at $272 million. In addition, these trees remove about 140,000 tons of carbon per year (513,000 tons CO_2 per year) ($18.6 million per year) and about 2,400 tons of air pollution per year ($20.4 million per year). Houston's urban forest is also estimated to provide 126 million cubic feet of net wood volume and to reduce annual residential energy costs by $53.9 million per year. Reduction in runoff provided by the trees in Houston is estimated at 173 million cubic feet per year with an associated value of $7.8 million per year. The compensatory value of the trees is estimated at $16.3 billion. The information presented in this report can be used to improve and augment support for urban forest management programs and to inform policy and planning to improve environmental quality and human health in Houston. The analysis also provides a basis for monitoring changes in the urban forest over time.

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All photographs courtesy of Texas Forest Service, unless otherwise noted.

Cover: Buffalo Bayou Park—a ribbon of greenspace through downtown Houston.

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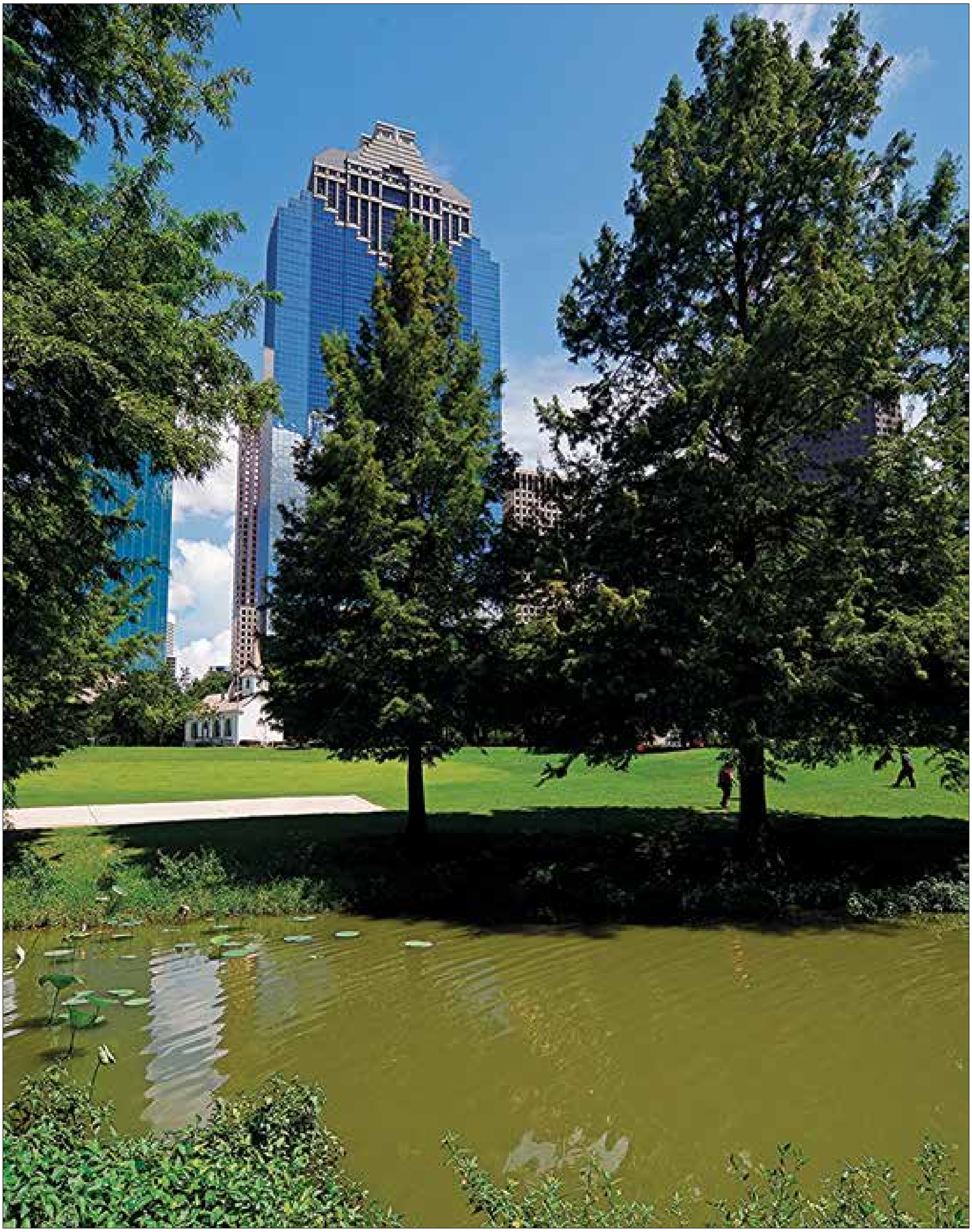

Urban trees in the heart of downtown Houston.

CONTENTS

Houston is the fourth largest city in the United States, with over 2.2 million people.

INTRODUCTION

Urban forests offer a wide range of environmental benefits, such as the provision of wildlife habitat, aesthetic appeal and visual barriers, reduced air temperatures, improved water quality, and mitigated air and noise pollution. Since 1930, the Forest Service, U.S. Department of Agriculture Forest Inventory and Analysis (FIA) program has provided information on the amount, status, and character of forest land across the country. FIA has collected data about trees within FIA-defined forest land, but usually excluded urban trees. Recognizing the importance of urban forests, and with direction from the 2014 U.S. Farm Bill[1] to include urban forest monitoring in its strategic plan, FIA initiated an annualized urban inventory program. For this report, the urban forest includes all trees in the city, both within and outside forested areas, including street trees, trees on public and private lands, and trees that are planted and naturally occurring. FIA has partnered with the Forest Service's i-Tree researchers, who have a long tradition of conducting urban forest inventories and delivering data about urban forests and ecosystems services. The partnership offers an opportunity to use the strengths of each group in the combined urban inventory effort.

A new urban FIA framework has been designed with lessons learned from previous urban inventory pilot studies that were conducted at the State level (Cumming and others 2007, Nowak and others 2007, Nowak and others 2011). This new initiative will build a strategic, consistent national inventory of urban forests.

Houston, Texas, is the second city to complete a full inventory cycle under the FIA Urban Inventory Program (urban FIA). Like Austin, the first city to complete a full urban FIA inventory, this location is ideal because of the Forest Service's established relationships with the State of Texas, and an enthusiasm and willingness on behalf of the Texas A&M Forest Service (TFS) to collaborate and support the program. With an increasing population in Texas and the growing recognition of the environmental and

[1] The Agricultural Act of 2014 (H.R. 2642; Pub. L. 113-79, also known as the 2014 Farm Bill).

economic benefits that trees contribute in urban areas, TFS has a pressing need to provide State agencies, city governments, nonprofit organizations, and consultants with accurate information to strengthen urban forest management and advocacy efforts. In Texas, these urban forests are located in areas where 85 percent of Texans live. TFS has welcomed a partnership with FIA to establish an urban forest inventory in Houston. TFS is applying the credibility and rigor of FIA inventory procedures to urban areas and solidifying TFS and FIA as trusted sources of science-based information about urban forests in Texas. New partnerships, cooperators, and supporters are involved to strengthen support for the sustainability of urban forests. With the implementation of urban FIA in Houston, seamless rural-to-urban resource monitoring continues.

During the 2015 field season, data collection was accelerated and a full, intensified sample of urban FIA data were collected in Houston. To understand Houston's urban forest, the collected data were analyzed using FIA methodologies and the i-Tree Eco modeling software (i-Tree 2016). This report is a summary of the findings of this analysis. Along with this report, an online querying application, My City's Trees at www.mycitystrees.com, has been developed to make the information from this analysis available to numerous stakeholders and to aid in understanding and managing Houston's urban forest.

METHODS

Field Measurements

Within the city limits of Houston (fig. 1), data from 209 field plots were collected between March and September 2015. TFS and FIA crews located the urban forest inventory sampling locations using GPS units and aerial photographs. Two hundred of the 209 sampling locations (fig. 2) were accessible (i.e., were non-hazardous plots with

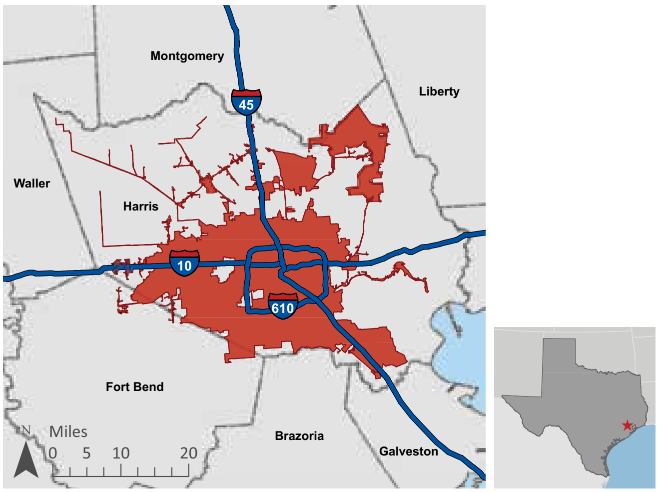


Figure 1—Houston city boundaries as defined by the 2010 U.S. Census.

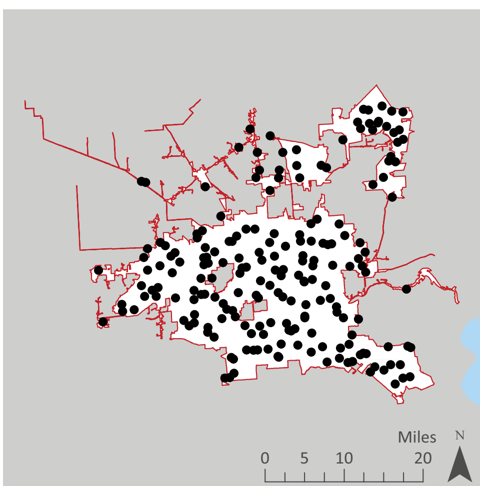


Figure 2—Approximate locations for 200 urban inventory plots, Houston, 2015.

landowner permission to access the plot). These plots were monumented by measuring distance and azimuth to witness objects. Every effort was made to avoid damaging private property and exposing plot location to maintain plot integrity through time.

Each urban forest inventory plot was a one-sixth acre circle with a radius of 48 feet (fig. 3). Each plot contained four nested microplots, each 1⁄300 acre in size with a radius of 6.8 feet and offset 12 feet horizontally in each cardinal direction from the plot center. For more information on urban FIA plots, including sampling design, remeasurement, and plot layout, see appendix 1.

In the urban plot, data were collected for all live and standing dead trees[2] that had a diameter at breast height (d.b.h.) or diameter at root collar (d.r.c.) of 5 inches or greater. In the microplots, data were collected on all live trees with a d.b.h./d.r.c. of 1 inch through 4.9 inches (i.e., saplings). Data for standing dead saplings were not collected on microplots. In FIA, trees are defined based on a regional tree species list. For urban FIA, this list was expanded beyond the traditional FIA tree species list to include exotic and ornamental trees that are not usually seen on rural forest land. The complete urban FIA tree species list is available in the FIA field guide (U.S. Forest Service 2015). Woody perennial plants not meeting the parameters mentioned earlier are considered shrubs.

Generally, inventory crews measured the d.b.h. at 4.5 feet above the ground for each tree. For special situations, such as forked trees, urban FIA protocol was followed (U.S. Forest Service 2015). Diameter measurements were not taken at breast height for trees identified

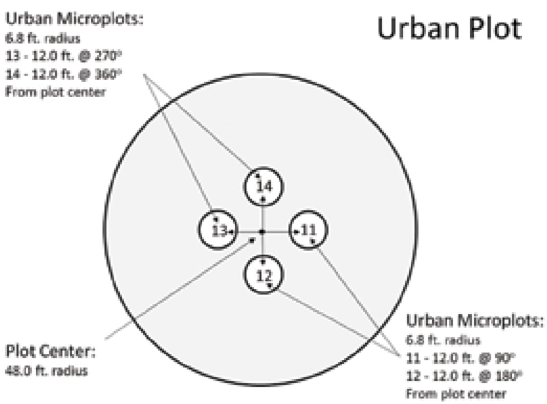


Figure 3—Urban forest inventory plot diagram, Houston, 2015.

[2] In general, FIA defines a tree as a perennial woody plant species that can attain a height of 15 feet at maturity. Trees are distinguished from shrubs, not by their height at the time of sample collection, but rather by the general growth form of the species in a particular region.

Texas A&M Forest Service forester marks plot center.

as woodland species on the regional tree species list. For woodland species, inventory crews measured the d.r.c. at the ground line or stem root collar, whichever was farthest from the ground. These d.b.h. and d.r.c. data are collectively referred to as diameter throughout this report.

In addition to diameter data, inventory crews identified tree species, measured tree length (i.e., measurement of tree from ground level to tree top), and described tree status, health, and presence of damages. (The complete lists of potential urban tree damages, pests, and diseases can be found in the urban FIA field manual [U.S. Forest Service 2015].) Additional measurements and descriptions were made of each individual tree's crown to further assess its health and leaf surface area. Crown variables recorded include crown ratio (as a percentage of total tree length), crown class (relative to the surrounding trees), crown light exposure, crown dieback, crown diameter, and the absence of foliage. Inventory crews also noted whether each tree was within a maintained (e.g., as evidenced by the presence of landscaping or maintenance activities) or riparian area, whether it was a street tree (e.g., located within 8 feet of the edge of a maintained, surfaced roadway) or a planted tree.

Additional data were collected for live and dead trees greater than 20 feet in height within 60 feet of residential buildings. These data (i.e., distance and direction to building) were used for estimating tree effects on building energy use. Space-conditioned structures (heated and perhaps cooled) were classified as buildings if they were no more than three stories (two stories plus attic) in height above ground level. i-Tree Eco uses an algorithm for single standing structures no larger than 4,000 square feet in total inhabitable (heated or cooled) space, although larger single-family homes or duplexes were included regardless of size. Unheated detached garages, sheds, or other outbuildings were not included. The building affected by the tree did not have to be on the plot.

Data collection methods included the delineation of unique condition classes on the urban plot including the determination of whether a condition was forest land, nonforest land, water, etc. Forested conditions were further delineated based on forest type, stand size, reserve status, etc., in the same manner as traditional FIA methods. Condition classes on nonforest land were established based on land use, ownership, and reserved status (U.S. Forest Service 2015). For each condition on the plot, field crews estimated percentage covers for trees/saplings, shrubs/seedlings, buildings, impervious surfaces, permeable surfaces, herbaceous vegetation, and water.

Please note that the urban FIA data collection protocol described here differs somewhat from the data collection procedures typically prescribed by the i-Tree program. More technical information on the different methodologies is being developed and will be available at http://nrs.fs.fed.us/data/urban when completed.

Urban Forest Effects

The urban FIA field data were analyzed using FIA methodologies and the i-Tree Eco modeling software (Nowak and Crane 2000, Nowak and others 2008). Both the field data and modeling outputs are incorporated into this report and the newly constructed Urban FIA database (Urban FIADB) available at http://www.fia.fs.fed.us/tools-data/.

Results include information on forest structure and associated ecosystem services and monetary values. Structure is a measure of various physical attributes of the urban forest, including tree species composition, number of trees, tree density, tree health, leaf area, biomass, and species diversity. Ecosystem services are determined by forest structure and include such attributes as air pollution removal and carbon storage or sequestration. Monetary values are an estimate of the economic worth of the various forest functions.

Air pollution removal—Air pollution removal estimates are calculated by the i-Tree Eco model. Outputs are provided for ozone (O_3), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and particulate matter less than 2.5 microns ($PM_{2.5}$). Estimates are derived from calculated hourly tree-canopy resistances for O_3, SO_2, and NO_2 based on a hybrid of big-leaf and multi-layer canopy deposition models (Baldocchi 1988, Baldocchi and others 1987). Removal rates for $PM_{2.5}$ varied with wind speed and leaf area (Nowak and others 2013a). Particulate removal also incorporated variable resuspension rates (Nowak and others 2013a).

Pollution removal value, which is also calculated by i-Tree Eco, is estimated as the economic value (i.e., cost of illness, willingness to pay, loss of wages, and the value of statistical life) associated with avoided human health impacts. Outputs from the U.S. Environmental Protection Agency's (EPA) Environmental Benefits Mapping and Analysis Program (BenMAP) were used to estimate the monetary value that result from changes in NO_2, O_3, $PM_{2.5}$, and SO_2 concentrations due to pollution removal by trees. BenMAP is a Windows-based computer program that uses local pollution and population data to estimate the health impacts of human exposure to changes in air quality and calculates the associated economic value of those changes (Nowak and others 2014, U.S. Environmental Protection Agency 2012).

Avoided runoff—Annual surface water runoff that was avoided (referred to as avoided surface runoff) is estimated by i-Tree Eco based on rainfall interception and evapotranspiration by vegetation and ground surface storage and infiltration of precipitation, or more specifically, the difference between annual runoff with and without vegetation. Although tree leaves and bark may intercept precipitation and thus mitigate surface runoff, only the precipitation intercepted and water evapotranspired by leaves is accounted for in this analysis.

Buffalo Bayou, lined with parks and trails, meanders the entire east-west length of the city.

The monetary value associated with avoided runoff is based on estimated annual stormwater management fees for the Coastal Plain region which includes the city of Houston. This regional value is $0.045 per cubic foot of surface runoff as reported in McPherson and others (2006).

Carbon storage and sequestration—Carbon storage is the amount of carbon bound in the tissue of woody vegetation. The carbon data presented in this report are based on standard FIA methodology, the same that is used for the rural FIA inventory (Woodall and others 2011). Aboveground carbon is calculated by multiplying the aboveground dry-weight biomass of each component (i.e., bole, stump, and top) of trees ≥5 inches in diameter by a factor of 0.5. Biomass of the different tree components is based on a combination of sound volume estimates that are derived from regional volume equations, biomass component ratios, and wood specific gravity estimates. For saplings or woodland species, the dry-weight biomass is also multiplied by a factor of 0.5. Biomass of woodland species is not broken down by component but is based on volume for the entire aboveground portion of the tree. The biomass of saplings is estimated directly from biomass equations.

Belowground carbon is equal to one-half the dry weight biomass of coarse roots, which is based on a modeled ratio estimate from the literature. FIA methods are based on studies of modeled tree volume and biomass for trees grown in forest settings, and no adjustments were made to account for the fact that these methods are being applied in urban, nonforest areas. Carbon storage presented in this report is for whole tree carbon, including above- and belowground carbon.

Carbon sequestration is the amount of carbon removed from the atmosphere and turned into tissue by a tree in a single year. Typically, carbon sequestration is estimated by FIA methodologies using remeasurement data. As this is the first complete cycle of Houston urban FIA data, carbon sequestration has been estimated based on projected tree growth. Average annual diameter and height growth was estimated using i-Tree Eco based on local climate, crown competition level, and tree condition and added to the existing tree measurements (in year x) to estimate tree diameter and height in year x+1. Carbon was then calculated for year x+1 using the standard FIA methodology and i-Tree Eco's predicted future tree diameter and height. Carbon sequestration is the difference between the FIA's carbon data for year x and year x+1.

Carbon storage and sequestration was also estimated in i-Tree Eco using methods described in Austin's Urban Forest, 2014 report (Nowak and others 2016). Unlike the FIA methodologies, these model estimates include the carbon contribution of foliage for evergreen trees and applies an adjustment factor for trees in predominantly urban land uses. The i-Tree based carbon estimates are not reported here, but will be available online in the UFIADB at http://www.fia.fs.fed.us/tools-data/.

To estimate the monetary value of carbon storage and sequestration, tree carbon values were multiplied by $133.05 per ton of carbon based on the estimated social costs of carbon for 2015 using a 3-percent discount rate (Interagency Working Group 2013, U.S. Environmental Protection Agency 2015). The social cost of carbon is a monetary value that encompasses the economic impact of increased carbon emissions on factors such as agricultural productivity, human health, and property damages (Interagency Working Group 2013).

Wood volume—In forestry, volume is a measure of the solid content of the tree stem and used to estimate wood quantity. Volume data presented in this report are estimated using standard FIA methodology (Oswalt and Conner 2011, Woodall and others 2011), which are based on volume equations developed for forest grown trees, and include net cubic-foot volume by diameter class and species and net board-foot sawtimber volume by species. Net cubic-foot volume is an estimate of the gross volume in cubic feet minus deductions for rotten, missing, and broken-top cull. Net board-foot sawtimber volume is an estimate of the gross volume in board feet of the saw-log portion of sawtimber minus deductions for total board-foot cull. A sawtimber tree is a live tree of commercial species that is free of defects based on regional specifications and contains at least a 12-foot sawlog or two noncontiguous saw logs 8 feet or longer.

Energy consumption—The effect of trees on residential building energy use was calculated in i-Tree Eco using distance and direction of trees from residential structures, tree height, and tree condition data (McPherson and Simpson 1999). Savings in residential energy costs were calculated based on State average 2012 costs for natural gas (U.S. Energy Information Administration 2014b), 2012/2013 heating season fuel oil costs (U.S. Energy Information Administration 2014c), 2012 residential electricity costs (U.S. Energy Information Administration 2012a), and 2012 costs of wood (U.S. Energy Information Administration 2012b).

Compensatory value—Compensatory values were estimated in i-Tree Eco based on valuation procedures of the Council of Tree and Landscape Appraisers (2000) and reported here for all live trees (Nowak and others 2002a). Following these methods, adjustment factors were applied to each tree to account for the effects of tree species, diameter, condition, and land use on variations in perceived value. More information on i-Tree Eco methods (Nowak and others 2008, Nowak and Crane 2000, Nowak and others 2002b) can be found at www.itreetools.org.

Large-diameter trees contribute significantly to ecosystem services.

ASSESSMENT SUMMARY

To assess Houston's urban forest and establish a baseline for future monitoring, a field study was conducted in 2015 as part of FIA's urban protocol. The standardized field data were processed using FIA methodologies and i-Tree Eco. Study results are summarized in table 1. Throughout this publication, except where explicitly noted, results are for live trees 1 inch in diameter and greater. Under the FIA field protocol for Houston, standing dead trees were only recorded for trees with diameters 5 inches and greater. Please refer to the Standing Dead Tree section for that component of the urban forest.

Table 1—Summary of the urban forest features, Houston, 2015

Feature	Estimate
Number of trees[a]	
Live saplings (1 to 4.9 inches in diameter)	23.9 million (72.0 percent of live trees)
Live trees (≥ 5 inches in diameter)	9.3 million (28.0 percent of live trees)
Standing dead trees (≥ 5 inches in diameter)	722,000
On private lands	19.2 million
Tree cover	18.4 percent
Most abundant species by:	
Number of trees (live)	Yaupon, Chinese tallowtree, Chinese privet, Japanese privet, sugarberry
Leaf area	Sugarberry, Chinese tallowtree, yaupon, live oak, loblolly pine
Pollution removal	2,400 tons/year ($20.4 million/year)
VOC emissions	4,600 tons/year
Avoided runoff	173 million cubic feet/year ($7.8 million/year)
Carbon storage[b]	2.0 million tons ($272 million)
Carbon sequestration	140,000 tons/year ($18.6 million/year)
Net volume	126 million cubic feet
Value of reduced building energy use[b]	$53.9 million/year
Value of reduced carbon emissions[b]	$14.4 million/year
Compensatory value	$16.3 billion

Note: ton = short ton (U.S.) (2,000 lbs.).

VOC = volatile organic compound.

[a] Diameter measurements were taken at breast height (d.b.h.) or root collar (d.r.c.) for woodland species.

[b] These estimates are for the live and dead tree population. All other estimates are based on the live tree population only, except where noted.

Urban Forest Structure and Composition

Number of trees—Houston's urban forest has an estimated 33.3 million trees (standard error [SE] of 5.3 million). The five most common species in the urban forest in terms of number of trees were yaupon, Chinese tallowtree, Chinese privet, Japanese privet, and sugarberry (fig. 4). The 10 most common species account for 74.2 percent of all live trees. Sixty-three unique tree species were sampled in Houston, including Osage-orange for which only dead trees were observed (table 2); these species and their relative abundance are presented in appendix 2.

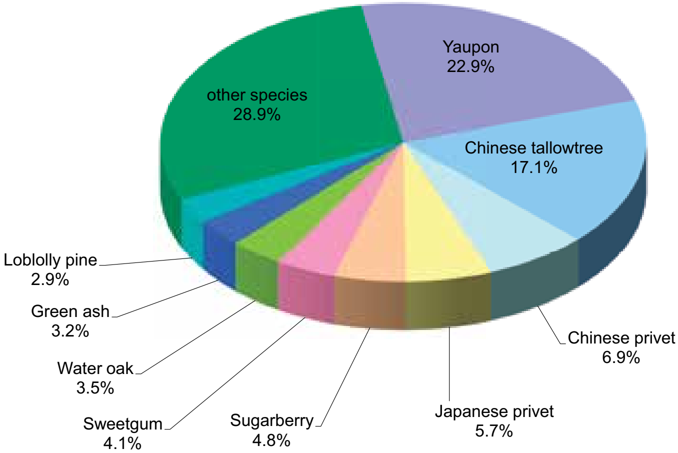


Figure 4—Urban forest species composition as a percentage of all live trees, Houston, 2015.

Table 2—Tree species sampled in the urban forest, Houston 2015

Genus	Species	Common name	Live trees: Diameter is ≥1 and <5 inches		Live trees: Diameter is ≥5 inches		Diameter[a]	
			number	*%*[b]	*number*	*%*[b]	Median	Average
							- - - - inches - - - -	
Acer	*negundo*	Boxelder	328,000	1.4	205,000	2.2	3.8	6.3
Betula	*nigra*	River birch	0	0.0	24,000	0.3	7.4	7.4
Carpinus	*caroliniana*	American hornbeam	146,000	0.6	39,000	0.4	4.9	5.4
Carya	*aquatica*	Water hickory	0	0.0	53,000	0.6	7.0	7.1
Carya	*illinoinensis*	Pecan	0	0.0	376,000	4.0	11.0	12.8
Carya	*ovata*	Shagbark hickory	0	0.0	24,000	0.3	26.0	26.0
Celtis	*laevigata*	Sugarberry	786,000	3.3	799,000	8.6	5.0	5.5
Celtis	*occidentalis*	Hackberry	0	0.0	88,000	0.9	9.6	11.4
Citrus	*sinensis*	Sweet orange	769,000	3.2	12,000	0.1	3.5	3.1
Crataegus	species	Hawthorn spp.	655,000	2.7	13,000	0.1	3.0	2.7
Cupressus	*sempervirens*	Italian cypress	147,000	0.6	0	0.0	1.3	1.3
Cupressus	species	Cypress	0	0.0	12,000	0.1	15.0	15.0
Diospyros	*virginiana*	Common persimmon	456,000	1.9	12,000	0.1	1.5	1.6
Fraxinus	*americana*	White ash	0	0.0	26,000	0.3	13.1	10.5
Fraxinus	*berlandieriana*	Berlandier ash	0	0.0	59,000	0.6	14.0	14.6
Fraxinus	*caroliniana*	Carolina ash	0	0.0	12,000	0.1	22.4	22.4

continued

Table 2 (continued)—Tree species sampled in the urban forest, Houston 2015

Genus	Species	Common name	Live trees				Diameter[a]	
			Diameter is ≥1 and <5 inches		Diameter is ≥5 inches		Median	Average
			number	*%*[b]	*number*	*%*[b]	- - - - *inches* - - - -	
Fraxinus	*pennsylvanica*	Green ash	328,000	1.4	735,000	7.9	7.0	8.5
Fraxinus	*velutina*	Velvet ash	0	0.0	47,000	0.5	13.4	14.1
Gleditsia	*triacanthos*	Honeylocust	154,000	0.6	0	0.0	1.1	1.1
Ilex	*vomitoria*	Yaupon	7,599,000	31.7	12,000	0.1	1.5	1.6
Juniperus	*pinchotii*	Pinchot juniper	0	0.0	12,000	0.1	8.5	8.5
Juniperus	*virginiana*	Eastern redcedar	164,000	0.7	56,000	0.6	3.8	4.9
Lagerstroemia	*indica*	Crapemyrtle	0	0.0	279,000	3.0	9.4	11.1
Ligustrum	*amurense*	Amur privet	0	0.0	12,000	0.1	5.3	5.3
Ligustrum	*japonicum*	Japanese privet[c]	1,518,000	6.3	379,000	4.1	2.3	3.9
Ligustrum	*sinense*	Chinese privet[c]	2,293,000	9.6	0	0.0	2.2	2.3
Liquidambar	*styraciflua*	Sweetgum	638,000	2.7	715,000	7.7	5.3	6.1
Maclura	*pomifera*	Osage-orange[d]	0	0.0	0	0.0	N/a	N/a
Magnolia	*grandiflora*	Southern magnolia	0	0.0	49,000	0.5	10.4	8.9
Melia	*azedarach*	Chinaberry[c]	0	0.0	204,000	2.2	8.8	11.0
Morus	*alba*	White mulberry[c]	0	0.0	49,000	0.5	31.5	18.8
Morus	*rubra*	Red mulberry	0	0.0	12,000	0.1	5.4	5.4
Nyssa	*sylvatica*	Blackgum	0	0.0	12,000	0.1	22.0	22.0
Ostrya	*virginiana*	Eastern hophornbeam	0	0.0	12,000	0.1	5.3	5.3
Phoenix	*dactylifera*	Date palm	0	0.0	12,000	0.1	22.6	22.6
Pinus	*palustris*	Longleaf pine	0	0.0	12,000	0.1	5.2	5.2
Pinus	*taeda*	Loblolly pine	328,000	1.4	648,000	7.0	6.9	8.9
Planera	*aquatica*	Water-elm	0	0.0	12,000	0.1	6.9	6.9
Platanus	*mexicana*	Mexican sycamore	0	0.0	12,000	0.1	31.5	31.5
Platanus	*occidentalis*	American sycamore	0	0.0	35,000	0.4	14.9	19.7
Poncirus	*trifoliata*	Hardy orange[c]	0	0.0	12,000	0.1	5.4	5.4
Pyrus	*calleryana*	Callery pear[c]	884,000	3.7	47,000	0.5	3.5	3.3
Pyrus	*communis*	Common pear	0	0.0	12,000	0.1	5.1	5.1
Quercus	*falcata*	Southern red oak	0	0.0	28,000	0.3	29.9	30.2
Quercus	*lyrata*	Overcup oak	0	0.0	13,000	0.1	18.9	18.9
Quercus	*nigra*	Water oak	594,000	2.5	577,000	6.2	3.8	8.3
Quercus	*pagoda*	Cherrybark oak	0	0.0	75,000	0.8	16.1	15.6
Quercus	*phellos*	Willow oak	0	0.0	288,000	3.1	12.3	12.4
Quercus	*shumardii*	Shumard oak	154,000	0.6	13,000	0.1	1.9	3.3
Quercus	*stellata*	Post oak	0	0.0	148,000	1.6	15.4	18.7
Quercus	*virginiana*	Live oak	0	0.0	676,000	7.3	13.6	15.7
Sabal	*mexicana*	Mexican palmetto	0	0.0	49,000	0.5	13.5	15.7
Salix	*nigra*	Black willow	0	0.0	237,000	2.5	7.6	7.4
Samanea	*saman*	Raintree	0	0.0	47,000	0.5	10.1	10.9
Tilia	*americana*	Carolina basswood	0	0.0	12,000	0.1	11.5	11.5
Triadica	*sebifera*	Chinese tallowtree[c]	4,289,000	17.9	1,404,000	15.1	2.3	3.7
Ulmus	*alata*	Winged elm	164,000	0.7	145,000	1.6	4.3	5.5
Ulmus	*americana*	American elm	737,000	3.1	296,000	3.2	2.9	5.0
Ulmus	*crassifolia*	Cedar elm	328,000	1.4	67,000	0.7	2.6	2.9
Ulmus	*parvifolia*	Chinese elm[c]	0	0.0	63,000	0.7	8.0	8.8
Ulmus	*rubra*	Slippery elm	0	0.0	12,000	0.1	13.4	13.4
Vaccinium	*arboreum*	Farkleberry	328,000	1.4	0	0.0	1.2	1.2
Zanthoxylum	*clava-herculis*	Hercules' club	164,000	0.7	26,000	0.3	4.8	4.8

N/a = not applicable.

[a] Diameter measurements were taken at breast height (d.b.h.) or root collar (d.r.c.) for woodland species. Median and average diameter measurements are estimated for live trees only.

[b] Percent estimates represent the percent of trees in the diameter class. For example, 2.2 percent of live trees >5 inches diameter are boxelders.

[c] Invasive species.

[d] Osage-orange was the only species sampled for which there were no live trees.

The city was divided into areas based on National Land Cover data to analyze variability of the urban forest across the city by land cover. Plots were categorized among the following land cover classes (table 3):

- Developed–Open: open space (mostly lawn) on developed land
- Developed–High: high intensity developed land
- Developed–Medium: medium intensity developed land
- Developed–Low: low intensity developed land
- Water: open water
- Grass/Herb/Crop: barren land, grassland/herbaceous, and pasture/hay lands
- Forest/Scrub: evergreen forest, deciduous forest, mixed forest, shrub/scrub, and woody wetland lands.

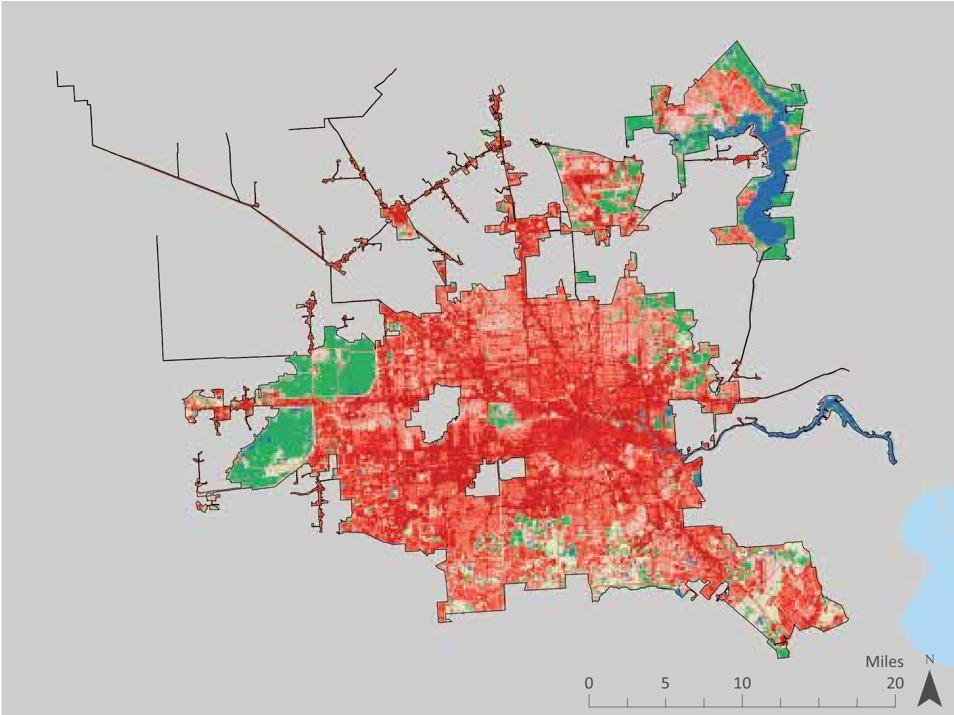
The land cover definitions[3] are based on the 2011 National Land Cover Database (NLCD) (Homer and others 2015) (for complete definitions of each category, see appendix 3). The distribution of the land cover classes across Houston shows that large contiguous areas of Forest/Scrub land are primarily in the western area of the city, as well as the northeastern side of the city and around Lake Houston (fig. 5). The central portion of the city, especially that which is encircled by Interstate-610, is primarily Developed, though Houston's Memorial Park located in that region is visible as a large patch of Forest/Scrub land surrounded by Developed land cover. See appendix 4 for information on species distribution by land cover.

Table 3—Distribution of trees and plots among NLCD land cover categories, Houston, 2015

Land cover	Live trees: Diameter is ≥1 and <5 inches	Live trees: Diameter is ≥5 inches	Plots	City land area
	- - - - - - - - - - *number*	- - - - - - - - - -		*percent*
Developed–Medium	2,800,000	1,702,000	55	26.8
Developed–Low	1,230,000	1,402,000	39	19.8
Developed–High	584,000	563,000	28	18.1
Developed–Open	3,510,000	904,000	27	13.1
Forest/Scrub	15,724,000	4,747,000	24	13.1
Grass/Herb/Crop	100,000	0	14	4.6
Water	0	0	13	4.5
Total	23,948,000	9,318,000	200	100.0

NLCD = National Land Cover Database.

[3] Land cover definitions provided at http://www.mrlc.gov/nlcd11_leg.php.



Land Cover and Percentage of Total

- Developed-Open (13%)
- Developed-Low (20%)
- Developed-Medium (27%)
- Developed-High (18%)
- Forest/Scrub (13%)
- Grass/Herb/Crop (5%)
- Water (4%)

Figure 5—Land cover distribution based on National Land Cover Database (Homer and others 2015), Houston, 2015. Land was classified into one of seven land cover classes.

Plots were also classified in the field based on FIA land use categories (table 4). These land use categories, as opposed to the land cover classes described earlier, provide a specific look at how the land is being used by the local population in Houston. Developed land is used primarily by humans for purposes other than forestry or agriculture and include the following categories: Residential, Multi-family Residential, Rights-of-way, Commercial, and Other Developed (i.e., institutional, transportation, cultural, recreation, park, and golf course land uses). In Houston, Other Nonforest areas encompass agricultural land, managed wildlife openings, water, and land that does not fall into any of the classes described earlier.

Table 4—Distribution of trees among FIA land use categories, Houston, 2015

Land use	Live trees: Diameter is ≥1 and <5 inches	Live trees: Diameter is ≥5 inches	City land area
	- - - - - - - - *number* - - - - - - - -		*percent*
Forest Land	19,534,000	5,092,000	12.1
Residential	1,807,000	2,263,000	24.2
Multi-family Residential	584,000	274,000	6.1
Rights-of-way	1,038,000	501,000	14.6
Commercial	831,000	219,000	16.0
Other Developed	0	933,000	17.9
Other Nonforest	154,000	36,000	9.1
Total	23,948,000	9,318,000	100.0

Sam Houston Park—28.5 percent of live trees were found on local and State government property.

The majority of trees in Houston are located on FIA-defined Forest Land (81.6 percent for trees ≥1 and <5 inches in diameter, and 54.6 percent for trees ≥5 inches in diameter). However, Forest Land only covers 12.1 percent of Houston's total area. Of the land uses recorded, Residential land (including Multi-family Residential) is the dominant class in Houston by area, comprising over 30 percent of the total area and 27.2 percent of the trees 5 inches in diameter and larger (table 4).

Tree density—The urban tree density in Houston is 83 trees per acre. Based on NLCD land cover categories, the highest density of 390 trees per acre occurs in the Forest/Scrub category, followed by Developed–Open (84 trees per acre) and Developed–Medium land (42 live trees per acre) (fig. 6). The Forest/Scrub land cover is present in 13.1 percent of the city and contains 61.5 percent of the trees. The Developed–Medium category covers 26.8 percent of the land area and contains 13.5 percent of the trees. Based on the FIA-designated land use categories, the greatest density of live trees is found on Forest Land (505.5 trees per acre). Of the developed land uses, Residential areas have the highest density with 41.7 trees per acre (fig. 7).

Tree density ranges from 6 to 1,602 trees per acre based on plots where trees are present (fig. 8). Live trees were observed on 107 of the 200 plots sampled. The majority of plots (77) with live trees present had less than 75 trees per acre. Twenty-one plots had a live tree density greater than 250 trees per acre and these are primarily located on the outer edges of the city where Forest/Scrub land tends to occur.

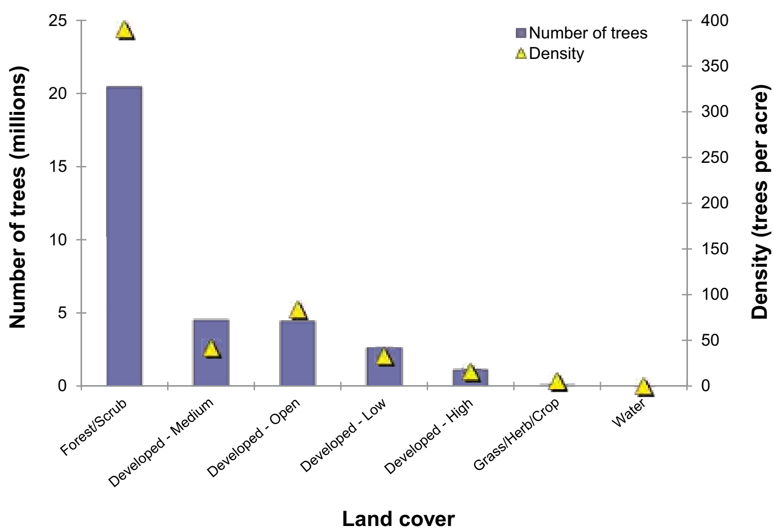


Figure 6—Number of trees and tree density by land cover, Houston, 2015.

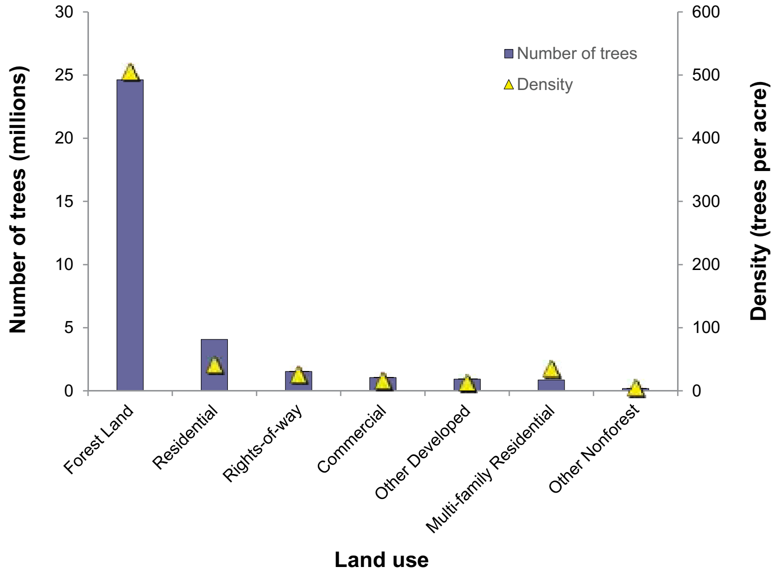


Figure 7—Number of trees and tree density by land use, Houston, 2015.

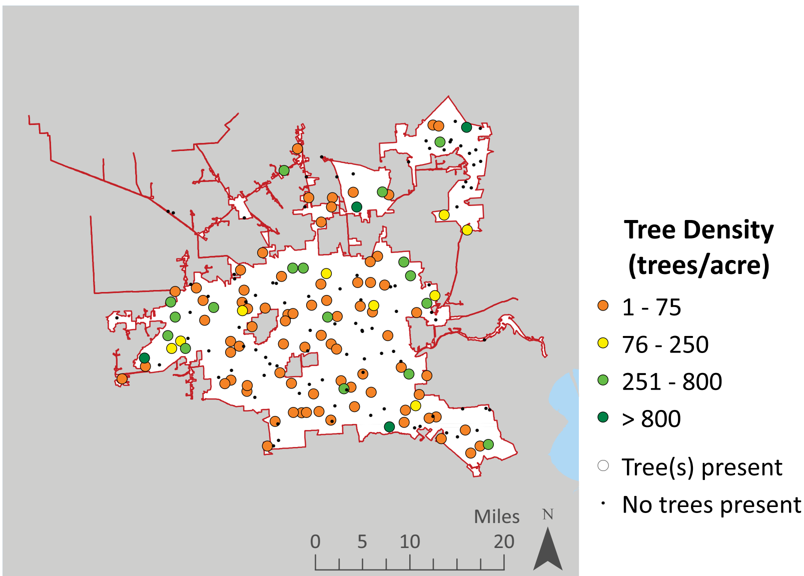


Figure 8—Tree density by plot, Houston, 2015.

Loblolly pine provides the greatest net volume in the city of Houston.

Leaf area—Leaf area is an important measure as many ecosystem services are derived from leaves. Leaf area index (LAI) is a measure of the sum of all leaves' surface area (one side) divided by the area of a land cover class. As each land cover class has a different amount of land area, LAI standardizes the leaf area on an equal area basis (acres of leaves per acre of land). Total leaf area is greatest in Forest/Scrub land cover (44.5 percent of Houston's total leaf area) followed by Developed–Medium (23.1 percent) (fig. 9). Forest/Scrub also had the highest LAI (3.5), followed by Developed—Low with an LAI of 0.9 (fig. 9). Higher LAIs indicate a greater leaf surface area per acre of land.

Leaf area among the FIA land use categories is greatest in Forest Land which contains more than half of all the leaf area in the city (fig. 10). Following Forest Land, the amount of leaf area is greatest in Residential (30.2 percent of all leaf area) and Other Developed (7.6 percent) areas. Leaf area index ranges from 4.4 in Forest Land to less than 0.1 in Other Nonforest.

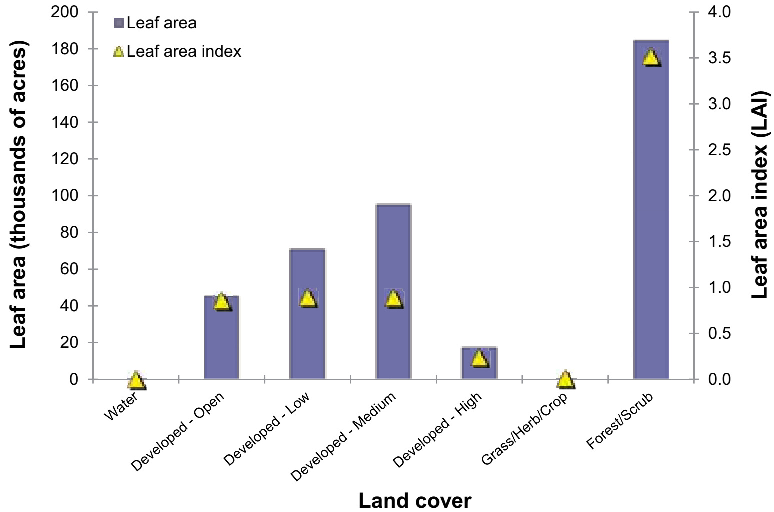


Figure 9—Leaf area and leaf area index by land cover, Houston, 2015.

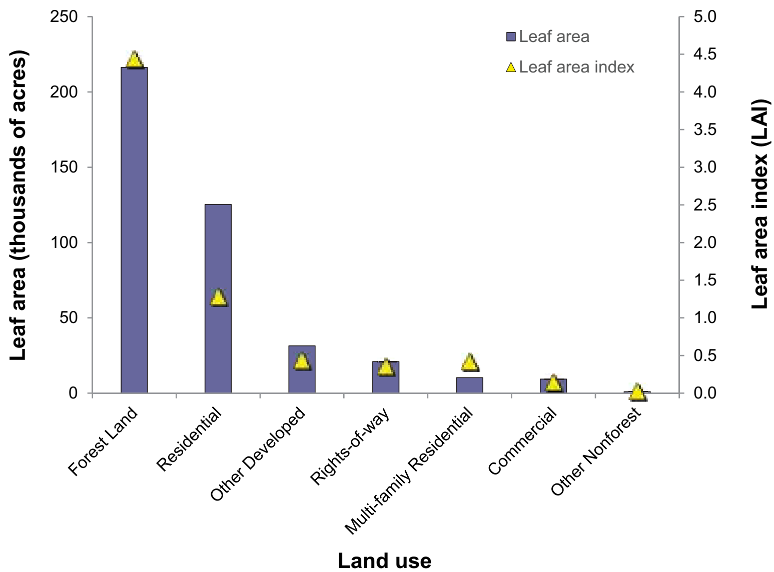


Figure 10—Leaf area and leaf area index by land use, Houston, 2015.

Leaf area has a positive correlation with environmental benefits (i.e., the greater the leaf area, the greater the benefit). In Houston's urban forest, tree species with the greatest leaf area are sugarberry, Chinese tallowtree, and yaupon (fig. 11). Of trees accounting for at least 1.0 percent of the population, live oak, pecan, and sugarberry have the greatest average leaf area per tree (i.e., they are large trees). Small tree species that account for at least 1.0 percent of the population and have percent leaf area to percent population ratios less than 0.6 are yaupon, Chinese tallowtree, Chinese privet, Japanese privet, callery

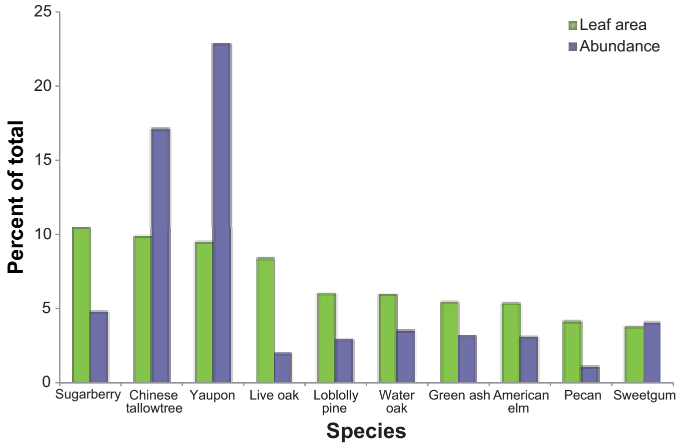


Figure 11—Percentage of live tree population and total leaf area for 10 most common species by leaf area, Houston, 2015.

pear, sweet orange, hawthorn species, common persimmon, cedar elm and farkleberry. These 10 common small species account for 63.3 percent of the population, but only 27.2 percent of the leaf area, and have an average d.b.h. of 2.6 inches.

Importance values (IVs) are calculated using a formula that combines the relative leaf area and relative abundance. High importance values do not mean that these trees should be encouraged in the future; rather these species currently dominate the urban forest structure in terms of their population and leaf area (a representation of environmental services). The species in the urban forest with the greatest IVs are yaupon, Chinese tallowtree, and sugarberry (table 5).

Table 5—Percentage of total population and leaf area and importance value of species[a], Houston, 2015

Common name	Population	Leaf area	IV[b]
	- - - - - - *percent*	- - - - - -	
Yaupon	22.9	9.5	32.4
Chinese tallowtree	17.1	9.9	27.0
Sugarberry	4.8	10.4	15.2
Live oak	2.0	8.4	10.5
Water oak	3.5	6.0	9.5
Loblolly pine	2.9	6.0	9.0
Japanese privet	5.7	3.1	8.8
Chinese privet	6.9	1.9	8.8
Green ash	3.2	5.5	8.7
American elm	3.1	5.4	8.5

[a] List contains the 10 species with the highest importance values.
[b] IV = Population (%) + Leaf area (%).

Live oak in Glenwood Cemetery.

Tree size—Tree size is an important characteristic of the urban forest structure. Average diameter of trees is highly variable, ranging from 1.0 to 34.9 inches on plots where trees are present (fig. 12). Plots containing trees with an average diameter >15 inches are scattered about the city, with a slightly greater prevalence in the interior areas than along the city's edge. Of the 107 plots with live trees present, 28 had an average diameter of 15 inches or more. Additionally, these plots generally have a lower tree density indicating that they are composed of few, mostly large diameter trees.

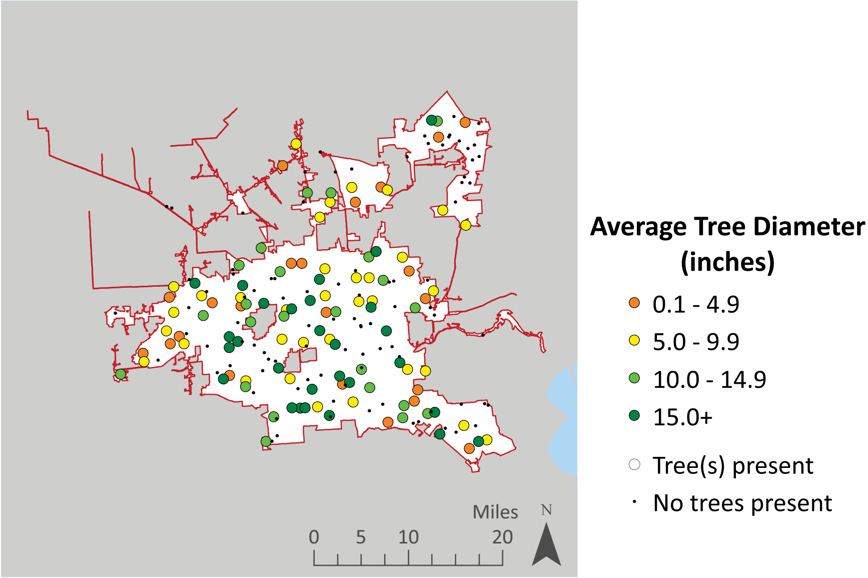


Figure 12—Average tree diameter by plot, Houston, 2015.

Large diameter trees generally have larger tree crowns than small diameter trees. Thus, healthy, large diameter trees contribute significantly to the ecosystem services provided by the urban forest primarily because leaf area has a positive correlation with environmental benefits (Nowak and others 2014). Trees with diameters <5 inches account for 72.0 percent of the tree population in Houston (fig. 13). Trees in this diameter class also contain 23.9 percent of the total leaf area. Four of the 10 most abundant tree species in Houston (i.e., yaupon, Chinese privet, Japanese privet, and Chinese tallowtree) have 75 percent or more of their population in the 1- to 5-inch diameter class (fig. 14). Trees that have diameters ≥15 inches account for 5.3 percent of the tree population, but comprise 32.6 percent of the total leaf area. Though these large diameter trees are a small percentage of the tree population, they are an important part of the urban forest in Houston. For more information about environmental benefits by diameter class, see appendix 5.

Species composition—Tree species composition varies between the small diameter (<5 inches) and large diameter trees (≥15 inches). The 10 most common species of small diameter trees are yaupon (31.7 percent of trees in d.b.h. class), Chinese tallowtree (17.9 percent), Chinese privet (9.6 percent), Japanese privet (6.3 percent), callery pear (3.7 percent), sugarberry (3.3 percent), sweet orange (3.2 percent), American elm (3.1 percent), hawthorn species (2.7 percent), and sweetgum (2.7 percent). The 10 most

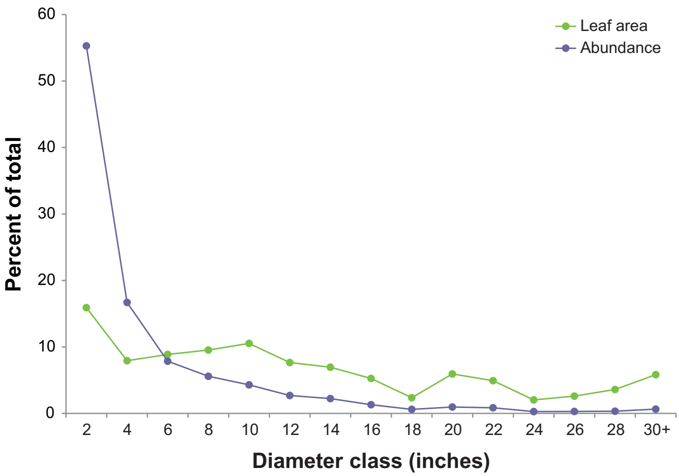


Figure 13—Percentage of total population and leaf area by tree diameter class, Houston, 2015. Diameter classes are designated by their midpoint (e.g., 2 is actually 1 to 2.9 inches). Diameter measurements were taken at breast height (d.b.h.) or root collar (d.r.c.) for woodland species.

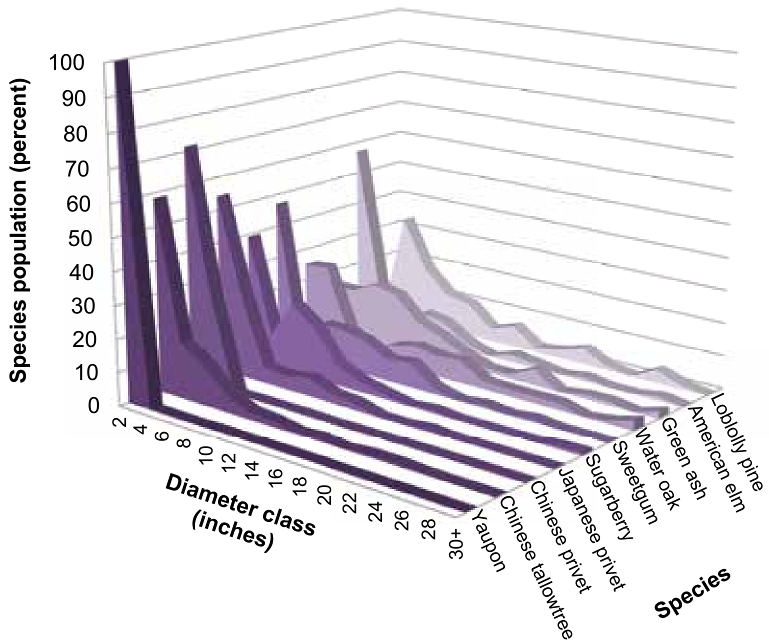


Figure 14—Percentage of species population by diameter class for 10 most common species, Houston, 2015. Diameter classes are designated by their midpoint (e.g., 2 is actually 1 to 2.9 inches). Diameter measurements were taken at breast height (d.b.h.) or root collar (d.r.c.) for woodland species.

common species of large diameter trees are live oak (15.0 percent of trees in class), water oak (12.8 percent), loblolly pine (8.5 percent), Chinese tallowtree (7.7 percent), green ash (7.1 percent), post oak (6.2 percent), pecan (6.2 percent), willow oak (3.8 percent), American elm (3.4 percent), and sweetgum (2.7 percent). Three species—Chinese tallowtree, American elm, and sweetgum—are among the 10 most common small diameter trees and the 10 most common large diameter trees (fig. 15).

Chinese privet, Japanese privet, and callery pear, three of the 10 most common small diameter trees, are classified as invasive. Chinese tallowtree is one of the 10 most common small and large diameter trees and is also classified as invasive. Mean and median diameter by species is presented in appendix 2. Mean and median diameter by land cover and species is presented in appendix 6.

Houston's urban forest is a mix of native tree species and exotic species that were introduced by residents or other means. Urban forests often have higher tree species diversity than the surrounding native landscapes because of tree species introduced from

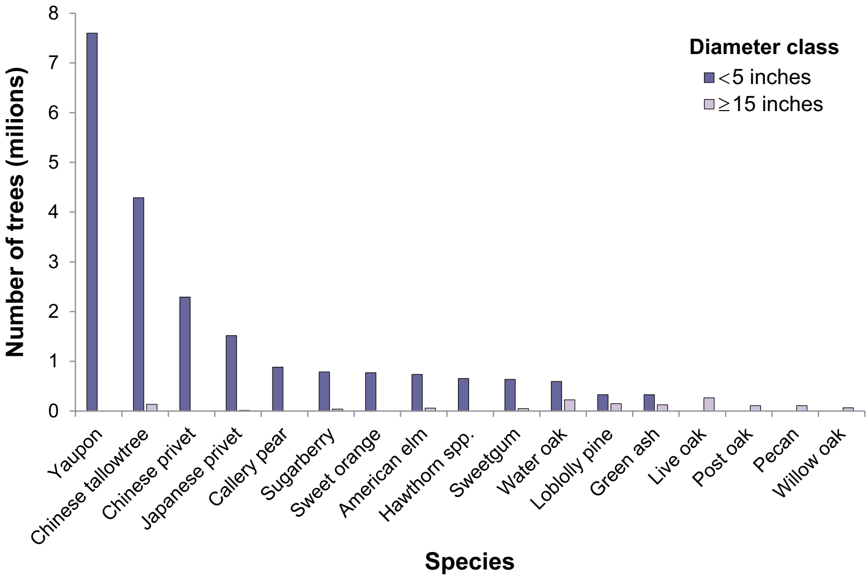


Figure 15—Number of trees by size (small trees <5 inches; large trees ≥15 inches in diameter) made up by the most common tree species in those classes, Houston, 2015.

outside the region (Nowak 2010). Increased tree diversity can minimize the overall impact or destruction by a species-specific insect or disease (Lacan and McBride 2008, Santamour 1990), but the increase in the number of exotic plants can also pose a risk to native plants if exotic species are invasive and/or capable of displacing native species. In Houston, 60.4 percent of the trees (live and standing dead) are native to Texas. Trees with a native origin outside of North America are mostly from Asia and Australia (18.9 percent of live and standing dead trees).

Invasives—Invasive plant species are often characterized by their vigor, ability to adapt, reproductive capacity, and lack of natural enemies. These factors enable them to displace native plants and threaten natural areas (National Agriculture Library 2015). Eight of the 63 tree species sampled in Houston are identified on the local invasive species list (City of Houston 2010, U.S. Forest Service 2014b). These nonnative invasive species comprise 33.5 percent of the tree population and 18.8 percent of the city leaf area. The most common invasive species are Chinese tallowtree, Chinese privet, and Japanese privet (table 6). Of the 200 total plots, invasive tree species occurred on slightly less than a quarter of the plots (49 plots). Plots with invasives occur throughout the city and do not seem to be limited to specific areas within the city (fig. 16).

Table 6—Tree species that are classified as invasive[a] and were observed in the inventory, Houston, 2015

Common name	Proportion of all live trees	Leaf area as a proportion of all leaf area	Number of plots found[b]
	- - - - - - - *percent*	- - - - - - -	
Chinese tallowtree	17.1	9.9	35
Chinese privet	6.9	1.9	3
Japanese privet	5.7	3.1	7
Callery pear	2.8	0.8	3
Chinaberry	0.6	1.5	5
Chinese elm	0.2	1.0	2
White mulberry	0.1	0.5	3
Hardy orange	<0.1	<0.1	1

[a] Species is listed on Houston invasive species list (City of Houston 2010, U.S. Forest Service 2014b).
[b] Number includes all plots that the species was found on whether the tree sampled was live or standing dead.

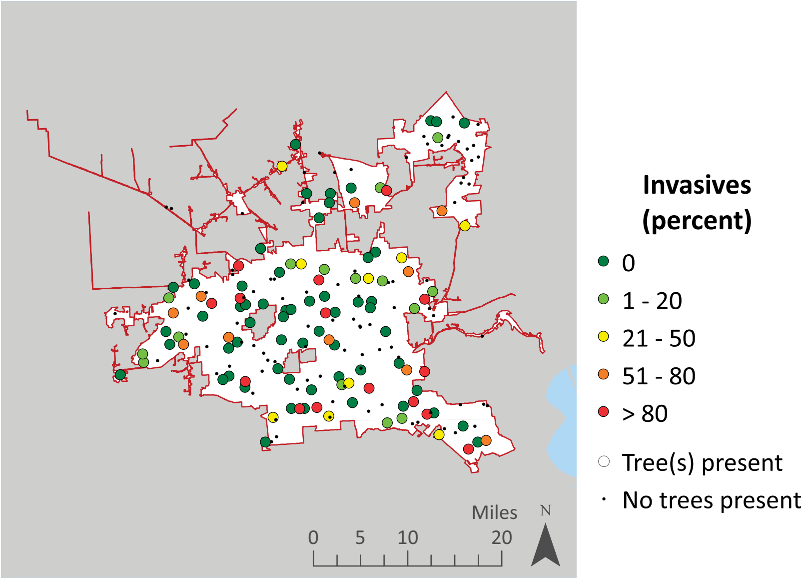


Figure 16—Proportion of invasive trees as a percent of all trees, by plot, Houston, 2015.

Some trees, like the Chinese tallowtree, while providing benefits, can be a source of concern as an invasive species.

Trees provide many social, economic, and environmental benefits to Houston residents.

Trees on Private lands—During field data collection, lands are classified into categories of ownership that include Private, State and Local Government, and Federal Government. The distribution of trees by ownership class can be an invaluable source of information for understanding and managing the urban forest. In Houston, 57.9 percent of the live tree population is found on Private lands (table 7). Nearly a quarter of the 19.2 million trees on Private lands are yaupon, followed by Chinese privet (11.9 percent) and Japanese privet (9.9 percent) (table 8).

Table 7—Distribution of live saplings and trees among ownership classes, Houston, 2015

Ownership class	Live trees: Diameter is ≥1 and <5 inches	Live trees: Diameter is ≥5 inches	Live trees: Total	City land area[a]
		percent		
Private	57.4	58.9	57.9	65.2
State and Local Government	30.3	23.9	28.5	23.4
Federal Government	12.3	17.2	13.7	6.1
Total	100.0	100.0	100.0	94.7

[a] Remaining 5.3 percent of city land area is not assigned an ownership class as it is water.

Table 8—Species composition on Private lands, Houston, 2015
For example, 24.2 percent of trees on Private lands are yaupon.

Species	Trees	Species	Trees	Species	Trees
	%		%		%
Yaupon	24.2	Crapemyrtle	0.8	River birch	0.1
Chinese privet	11.9	Honeylocust	0.8	White ash	0.1
Japanese privet	9.9	Italian cypress	0.8	Carolina ash	0.1
Sweetgum	6.5	American hornbeam	0.8	Date palm	0.1
Chinese tallowtree	5.5	Hackberry	0.5	Hardy orange	0.1
Callery pear	4.8	Post oak	0.4	Pinchot juniper	0.1
Sugarberry	4.3	Willow oak	0.4	American sycamore	0.1
Sweet orange	4.1	Cherrybark oak	0.4	Amur privet	0.1
Water oak	3.2	Chinese elm	0.3	Common pear	0.1
Live oak	2.6	Berlandier ash	0.3	Longleaf pine	0.1
Boxelder	2.6	Mexican palmetto	0.3	Mexican sycamore	0.1
Common persimmon	2.4	Southern magnolia	0.3	Red mulberry	0.1
Loblolly pine	1.9	Green ash	0.2	Shagbark hickory	0.1
Pecan	1.9	Raintree	0.2	Slippery elm	0.1
Farkleberry	1.7	Black willow	0.2	Blackgum	0.1
Eastern redcedar	1.1	Winged elm	0.2	Cypress	0.1
American elm	1.0	White mulberry	0.2	Eastern hophornbeam	0.1
Chinaberry	0.9	Southern red oak	0.1		
Shumard oak	0.9	Cedar elm	0.1		

Trees in maintained areas—Each tree was classified as to whether it was found in a maintained or nonmaintained area. Maintained areas are defined as those which are regularly impacted by mowing, weeding, herbicide applications, etc. If a tree is found in a maintained area, it does not necessarily imply it received maintenance. Examples of maintained areas include lawns, rights-of-way, and parks.

Overall, 20.0 percent of trees (6.7 million) were classified as growing in maintained areas. The percentage of trees that are in maintained areas ranges from 0 percent on some plots, to 100 percent on other plots. There were 77 plots in Houston that had trees classified in maintained areas (fig. 17). Of these plots, only five also had trees in unmaintained areas. These five plots were distributed mostly around the edge of the city's boundaries.

Land covers with the highest proportion of trees in maintained areas are Developed–High, Developed–Low, and Developed–Medium (table 9). One hundred percent of callery pear trees sampled were in maintained areas (table 10). Of the maintained tree population, 15.6 percent are Japanese privet, 14.0 percent are callery pear, and 11.7 percent are sweet orange (table 11).

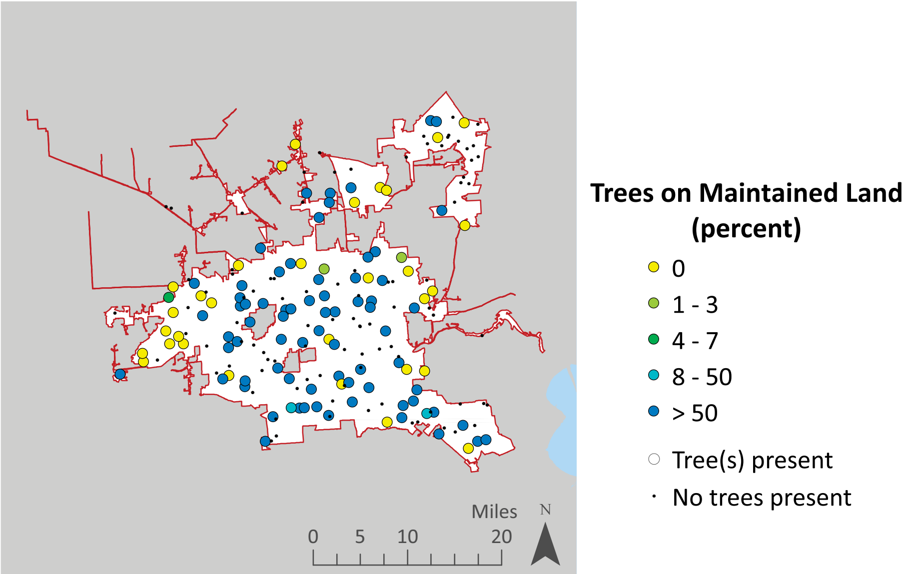


Figure 17—Percentage of trees on maintained area, by plot, Houston, 2015.

Table 9—Percentage of trees in maintained areas by land cover, Houston, 2015

Land cover	Trees
	percent
Developed–High	100.0
Developed–Low	85.2
Developed–Medium	64.5
Developed–Open	4.0
Forest/Scrub	0.9
Grass/Herb/Crop	0.0
Total	20.0

Table 10—Percentage of trees in maintained areas (minimum sample size = 10 live trees) by species, Houston, 2015

For example, 100 percent of callery pear trees are in maintained areas.

Species	Trees	Species	Trees
	%		%
Callery pear	100.0	Loblolly pine	21.6
Live oak	96.5	Sugarberry	14.4
Crapemyrtle	95.6	American elm	10.5
Pecan	93.4	Green ash	7.4
Post oak	82.2	Chinese tallowtree	4.5
Japanese privet	54.7	Sweetgum	2.7
Water oak	35.0	Boxelder	2.5
Chinaberry	29.2	Yaupon	0.2
Willow oak	23.3		

Houston skyline framed by crapemyrtle along Buffalo Bayou trail.

Table 11—Species composition in maintained areas, Houston, 2015
For example, 15.6 percent of trees in maintained areas are Japanese privet.

Species	Trees	Species	Trees	Species	Trees
	%		%		%
Japanese privet	15.6	Hackberry	1.1	River birch	0.4
Callery pear	14.0	Willow oak	1.0	Cherrybark oak	0.4
Sweet orange	11.7	Chinese elm	0.9	Boxelder	0.2
Live oak	9.8	Chinaberry	0.9	White ash	0.2
Water oak	6.2	Berlandier ash	0.9	Carolina ash	0.2
Pecan	5.3	Eastern redcedar	0.8	Pinchot juniper	0.2
Crapemyrtle	4.0	Mexican palmetto	0.7	Date palm	0.2
Chinese tallowtree	3.8	Southern magnolia	0.7	Hardy orange	0.2
Sugarberry	3.4	Velvet ash	0.7	Yaupon	0.2
Loblolly pine	3.2	Raintree	0.7	Longleaf pine	0.2
Shumard oak	2.3	White mulberry	0.6	Mexican sycamore	0.2
Italian cypress	2.2	Sweetgum	0.6	Common pear	0.2
Post oak	1.8	American sycamore	0.5	Slippery elm	0.2
American elm	1.6	Southern red oak	0.4		
Green ash	1.2	Cedar elm	0.4		

Tree and ground cover—Estimates of tree and shrub cover in Houston were assessed in the field. Tree cover in Houston is estimated at 18.4 percent and shrub cover is 7.5 percent, based on field crew assessments. Tree cover ranges from 2 to 95 percent on plots where trees are present, while shrub cover on plots ranges from 0 percent to 85 percent (figs. 18 and 19). Plots with higher amounts of tree cover (>55 percent) mostly overlap with areas of Forest/Scrub land, particularly on the western side and around the outer portions of the city. Of the 200 plots sampled, 112 had some shrub cover. The plots with more than 26 percent shrub cover are more prevalent around the outer edges of the city where Forest/Scrub land cover is common (fig. 19).

Ground cover in Houston was also estimated by field crews; ground cover categories include all manmade and natural cover types within the plots, including cover beneath trees and shrubs. Herbaceous cover (grass and other nonwoody plants) accounts for 37.4 percent of all ground cover. Herbaceous cover is the most common ground cover type in the following land cover areas: Developed–Open, Developed–Low, Grass/Herb/Crop, and Forest/Scrub (fig. 20). Developed–Medium and Developed–High land covers were dominated by impervious ground covers, while areas of the Water land cover were dominated by water.

The dominant ground cover type varies across the 200 plots in Houston (fig. 21). Herbaceous ground cover is dominant on the greatest number of plots, while water is the dominant ground cover on the fewest plots. Of the plots with no trees present, herbaceous cover is the most common dominant ground cover, occurring on 33 plots. Impervious ground cover was the second most common, occurring on 29 plots.

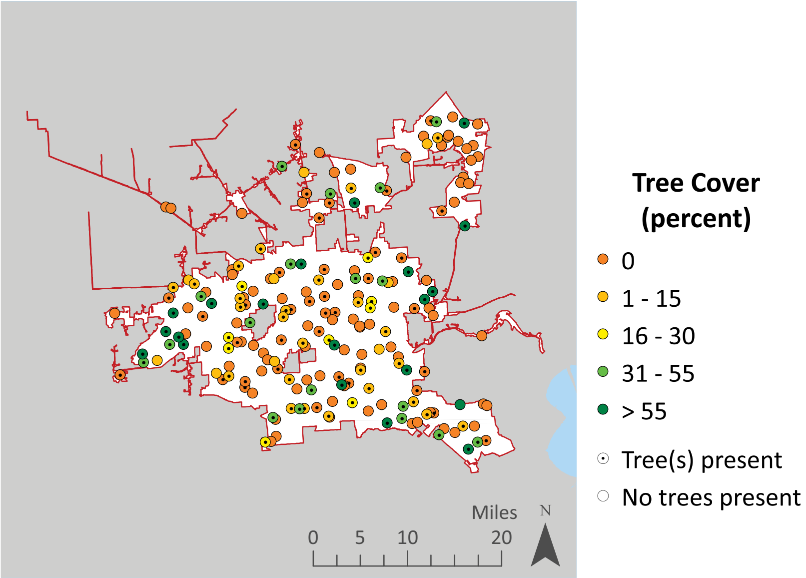


Figure 18—Percentage of tree cover by plot, Houston, 2015.

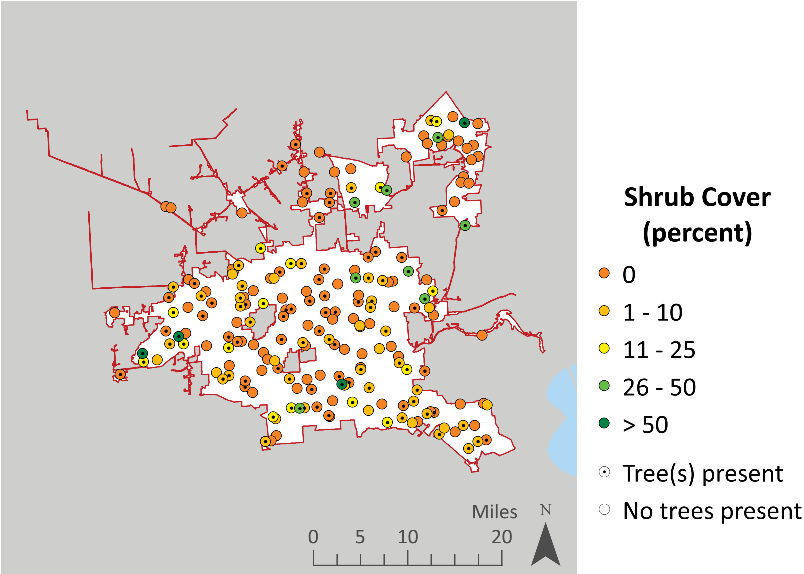


Figure 19—Percentage shrub cover by plot, Houston, 2015.

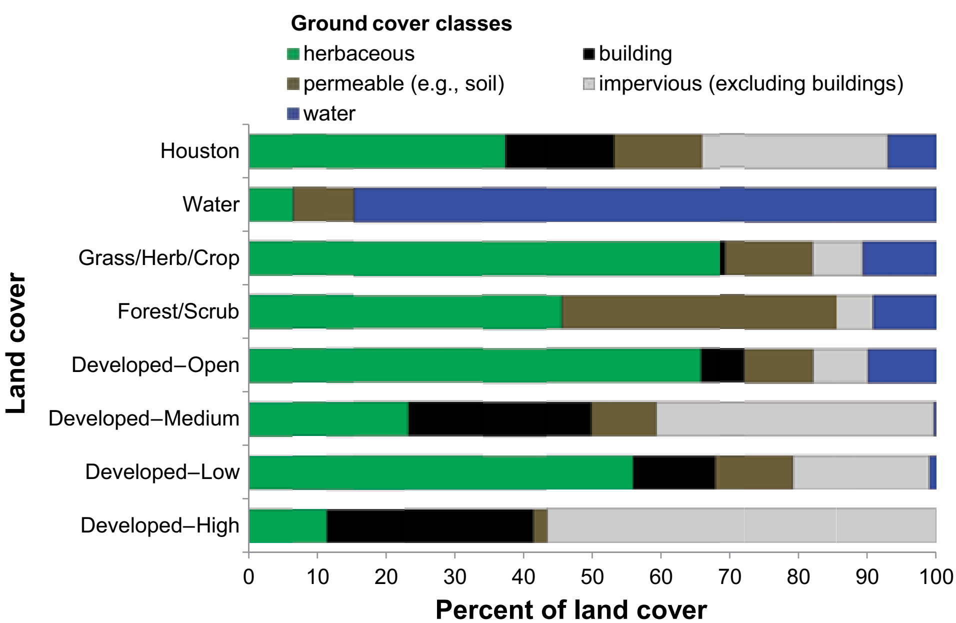


Figure 20—Ground cover distribution by land cover type, Houston, 2015.

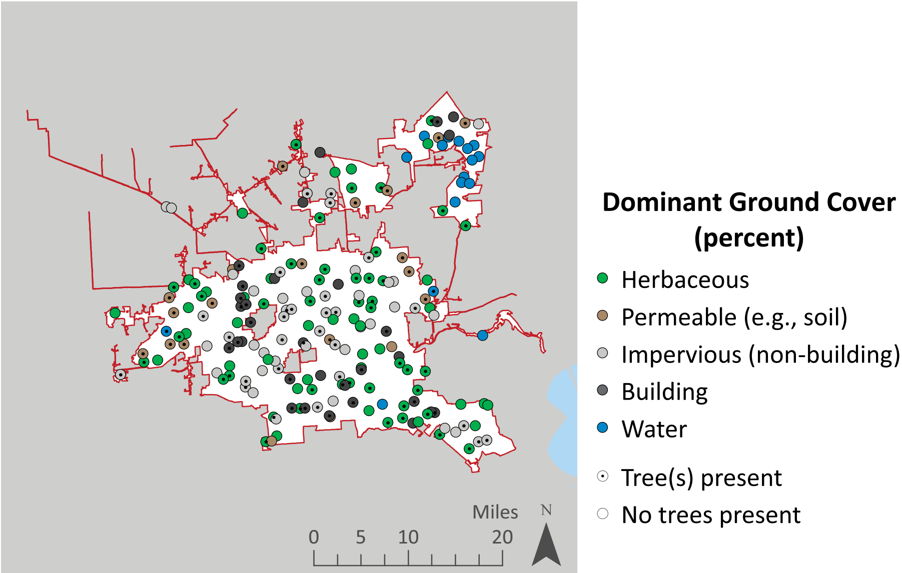


Figure 21—Dominant ground cover by plot, Houston, 2015.

Urban Forest Values

The urban forest values associated with air pollution removal, volatile organic compound (VOC) emissions, avoided runoff, carbon sequestration, and compensatory value exclude dead trees as these benefits are based mainly on existing leaf area, leaf biomass, or live tree conditions. However, standing dead trees do contribute to and are included in estimates of carbon storage and energy effects.

Air pollution removal—Poor air quality is a common problem in many urban areas. It can damage landscape material, adversely affect ecosystem processes, and reduce visibility. Air pollution is also associated with significant human health effects that impact the pulmonary, cardiac, vascular, and neurological systems and human mortality (e.g., Pope and others 2002). The urban forest can help improve air quality by directly removing pollutants from the air and reducing energy consumption in buildings, which consequently reduces air pollutant emissions from power plants and other sources. While trees emit VOCs that can contribute to ozone formation, integrative studies have revealed that an increase in tree cover tends to lead to reduced ozone formation (Nowak and Dwyer 2000).

Pollution removal by trees in Houston was estimated using the 2015 field data and hourly pollution and weather data for the year 2013. Pollution removal was greatest for O_3 (1,888 tons removed per year), followed by NO_2 (376 tons/year), $PM_{2.5}$ (116 tons/year), and SO_2 (34 tons/year) (fig. 22). The value associated with pollution removal was greatest

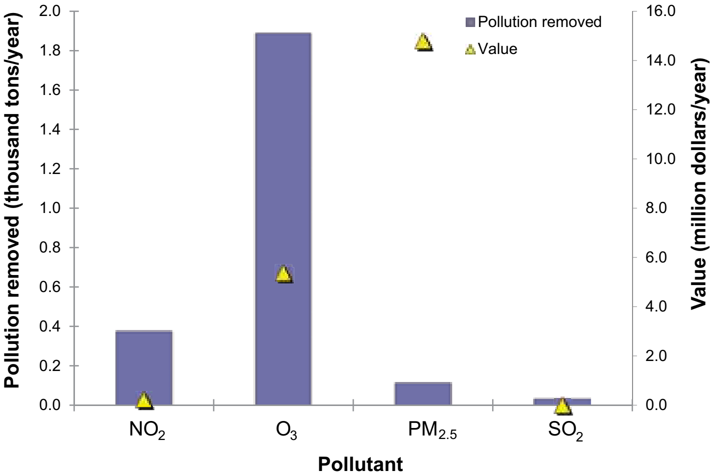


Figure 22—Annual air pollution removal and value by urban trees, Houston, 2015.

for $PM_{2.5}$ ($14.8 million), followed by O_3 ($5.4 million), NO_2 ($229,000), and SO_2 ($8,000). It is estimated that trees alone remove 2,400 tons of air pollution (NO_2, O_3, $PM_{2.5}$, and SO_2) per year with an associated value of $20.4 million.

Decreases in pollution concentration due to pollution removal by trees also have a positive effect on human health in Houston. The economic value of pollution removal is based on avoided health effects due to lower pollution concentrations (Nowak and others 2014, U.S. Environmental Protection Agency 2012). For example, in 2015, reductions in NO_2 concentration resulted in an estimated 119 fewer cases of acute respiratory symptoms with an associated value of $3,766 (table 12).

In 2015, trees in Houston emitted an estimated 4,552 tons of VOCs (4,086 tons of isoprene and 466 tons of monoterpenes). Emissions vary among species based on species characteristics (e.g., some genera such as oaks are high isoprene emitters) and leaf biomass. Ninety percent of the urban forest's VOC emissions were from oak and sweetgum genera (fig. 23). These VOCs are precursor chemicals to ozone formation.[4] General recommendations for improving air quality with trees are given in appendix 7.

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[4] Some economic studies have estimated VOC emission costs. These costs are not included here as there is a tendency to add positive dollar estimates of ozone removal effects with negative dollar values of VOC emission effects to determine whether tree effects are positive or negative in relation to ozone. This combining of dollar values to determine tree effects should not be done; rather estimates of VOC effects on ozone formation (e.g., via photochemical models) should be conducted and directly contrasted with ozone removal by trees (i.e., ozone effects should be directly compared, not dollar estimates). In addition, air temperature reductions by trees have been shown to significantly reduce ozone concentrations (Cardelino and Chameides 1990, Nowak and others 2000) but are not considered in this analysis. Photochemical modeling that integrates tree effects on air temperature, pollution removal, VOC emissions, and emissions from power plants can be used to determine the overall effect of trees on ozone concentrations.

Table 12—Associated value ($/year) and incidence (number of cases/year) of avoided health effects from changes in pollution concentrations due to pollution removal by trees, Houston, 2015

Health effect	NO_2		SO_2		O_3		$PM_{2.5}$	
	$/year	*cases/ year*	*$/year*	*cases/ year*	*$/year*	*cases/ year*	*$/year*	*cases/ year*
Acute bronchitis	N/a	N/a	N/a	N/a	N/a	N/a	197	2.24
Acute myocardial infarction	N/a	N/a	N/a	N/a	N/a	N/a	40,952	0.46
Acute respiratory symptoms	3,766	119.27	123	3.91	201,811	2,360.69	116,099	1,184.47
Asthma exacerbation	153,215	1,832.86	3,101	39.22	N/a	N/a	77,515	953.54
Chronic bronchitis	N/a	N/a	N/a	N/a	N/a	N/a	255,953	0.92
Emergency room visits	655	1.57	63	0.15	493	1.18	618	1.49
Hospital admissions	71,609	2.37	4,894	0.16	58,430	1.89	N/a	N/a
Hospital admissions, cardiovascular	N/a	N/a	N/a	N/a	N/a	N/a	10,131	0.26
Hospital admissions, respiratory	N/a	N/a	N/a	N/a	N/a	N/a	7,032	0.22
Lower respiratory symptoms	N/a	N/a	N/a	N/a	N/a	N/a	1,507	29.02
Mortality	N/a	N/a	N/a	N/a	5,010,646	0.64	14,239,079	1.83
School loss days	N/a	N/a	N/a	N/a	98,910	1,007.33	N/a	N/a
Upper respiratory symptoms	N/a	N/a	N/a	N/a	N/a	N/a	953	21.24
Work loss days	N/a	N/a	N/a	N/a	N/a	N/a	41,192	199.54
Total value	229,246	N/a	8,182	N/a	5,370,290	N/a	14,791,231	N/a

N/a indicates that the value is not estimated for that pollutant and health effect. The same health effects were not analyzed for each pollutant.

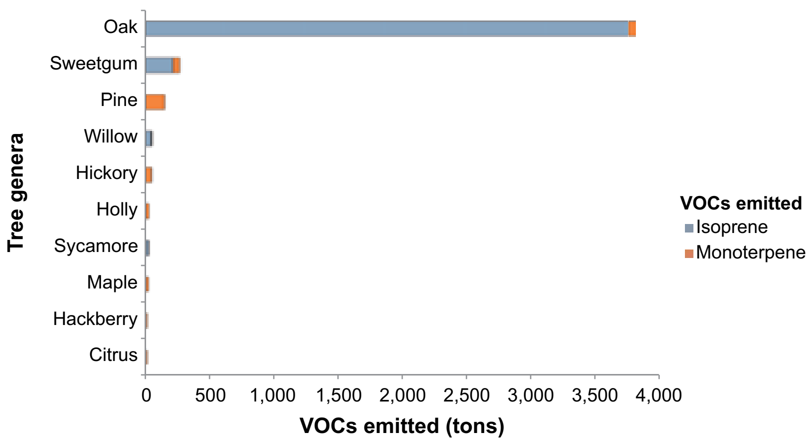

Figure 23—Annual volatile organic compounds (VOCs) emitted by tree genera with greatest emissions, Houston, 2015.

Avoided runoff—Surface water runoff (commonly referred to as surface runoff or stormwater runoff) can be a cause for concern in many urban areas as it can contribute pollution to streams, wetlands, rivers, lakes, and oceans. 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 or end up in surface depression storage becomes surface runoff (Hirabayashi 2012). In urban areas, the large extent of impervious surfaces increases the amount of surface runoff.

Urban trees are beneficial in reducing surface runoff. Trees intercept precipitation while their root systems promote infiltration and water storage in the soil. Avoided runoff due to trees is estimated by contrasting runoff estimates with and without trees. Avoided runoff is less than tree interception estimates, as in many cases soils would absorb some of the precipitation that would be intercepted by trees. The trees of Houston help to reduce runoff by an estimated 173 million cubic feet per year, with an estimated value of $7.8 million/year. Tree species with the greatest overall impact on runoff are sugarberry, Chinese tallowtree, and yaupon due to their large leaf surface area (fig. 24).

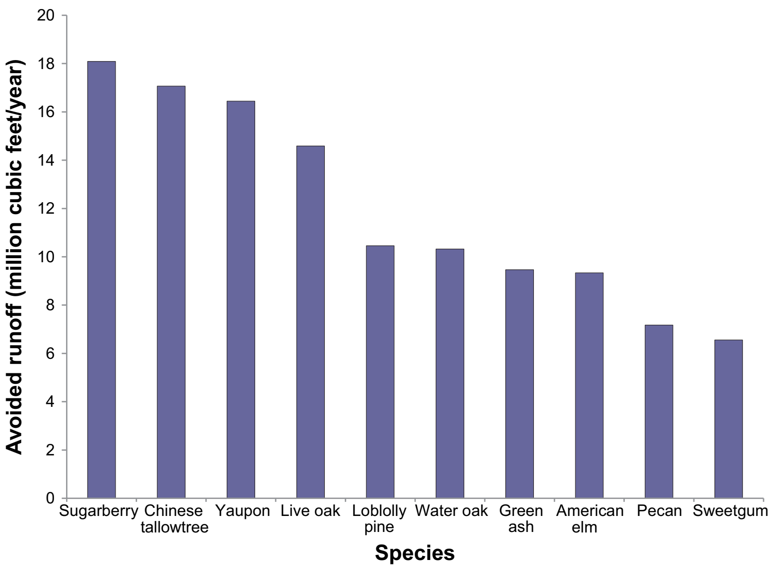

Figure 24—Avoided runoff for species with greatest overall impact on runoff, Houston, 2015. Avoided runoff by species is proportional to leaf area as runoff reduction is estimated on a city-wide basis.

Carbon storage and sequestration—Climate change is an issue of global concern that threatens to impact species existence, vulnerable ecosystems (e.g., coral reefs, polar and coastal areas), food production, water resources, and human health (Intergovernmental Panel on Climate Change 2014). Trees can help mitigate climate change by annually sequestering atmospheric carbon (from carbon dioxide [CO_2]) and storing it in its accumulated plant tissue. They can also reduce the amount of energy used to heat or cool buildings, thus reducing CO_2 emissions from fossil-fuel based power sources (Abdollahi and others 2000).

When a tree dies and decays (or is burned), 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. Although tree maintenance practices (e.g., pruning) can contribute to carbon emissions, maintaining healthy trees helps to maximize the amount of carbon stored in trees (Nowak and others 2002c). Using removed trees for wood products is one way to help forestall carbon emissions due to wood decomposition. Wood from removed trees can also be used to produce energy (e.g.,

Urban trees support activities that can improve human health.

heat buildings), helping reduce fossil-fuel based carbon emissions. Trees in Houston store an estimated 2.0 million tons of carbon (7.5 million tons of CO_2) valued at $272 million.

Average carbon storage is highly variable, ranging from 0.0 to 44.7 tons per acre based on plots where trees are present (fig. 25). Plots with greater average carbon storage generally have higher tree density and/or more large trees.

In addition to carbon storage, which accounts for past carbon sequestration/accumulation, healthy trees continue to annually sequester carbon in new tissue growth. The amount of carbon annually sequestered is increased with healthier and larger diameter trees. Gross sequestration by urban trees in Houston is about 140,000 tons of carbon per year (513,000 tons per year of CO_2) with an associated value of $18.6 million per year.

Of all the species sampled, live oak stores the most carbon, estimated at 14.7 percent of total carbon stored, and annually sequesters the most carbon, estimated at 11.0 percent of all sequestered carbon (figs. 26 and 27). Trees >30 inches in diameter store the most carbon in the city. They also store the most carbon on a per tree basis (figs. 28 and 29).

Wood volume—Understanding the net volume of wood provided by a community's trees can serve a variety of purposes. From a management perspective, a thorough knowledge of wood volume can help predict potential storm damage and can support

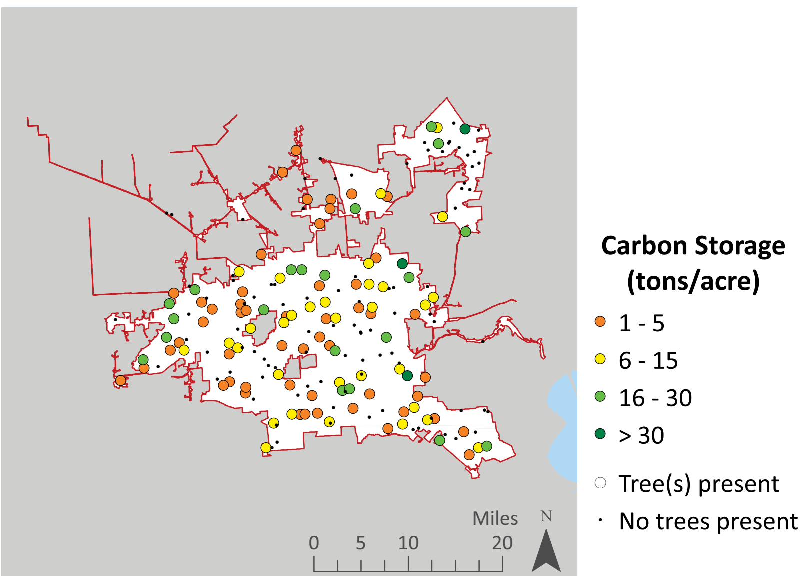

Figure 25—Average carbon storage per acre by plot, Houston, 2015.

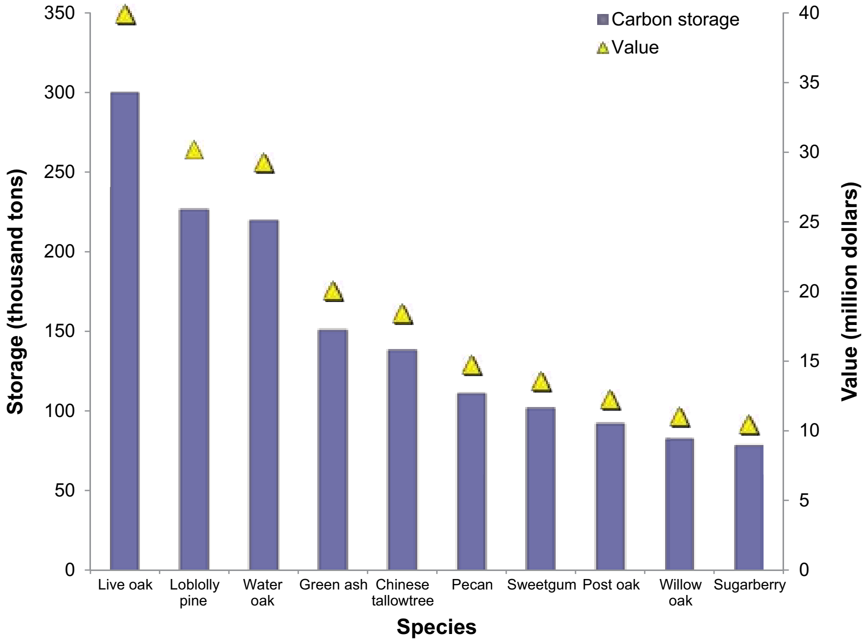

Figure 26—Estimated annual carbon storage and value for urban tree species with the greatest storage, Houston, 2015.

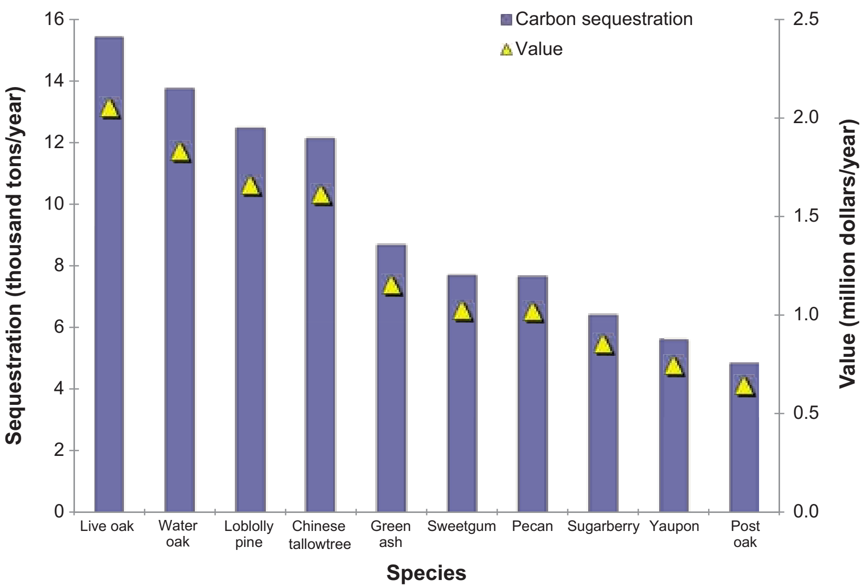

Figure 27—Estimated annual carbon sequestration and value for urban tree species with the greatest sequestration, Houston, 2015.

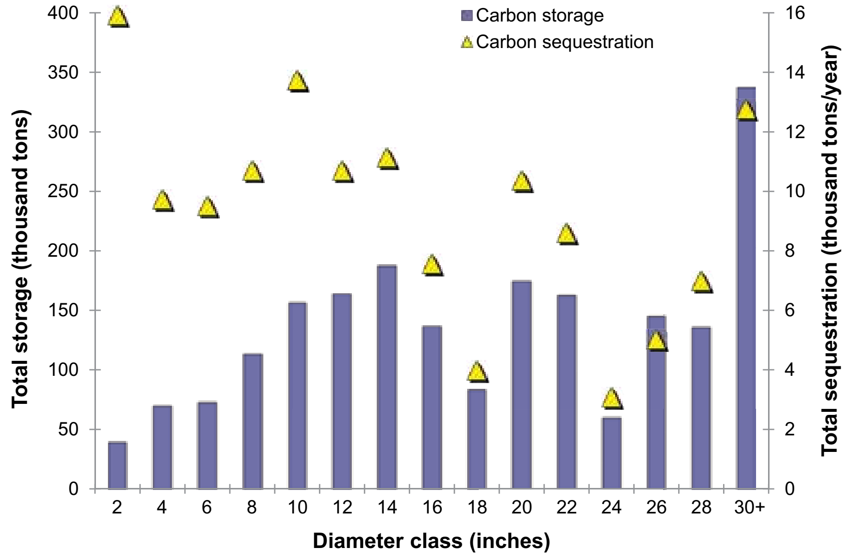

Figure 28—Estimated total carbon storage and sequestration by tree diameter class, Houston, 2015. Diameter classes are designated by their midpoint (e.g., 2 is actually 1 to 2.9 inches). Diameter measurements were taken at breast height (d.b.h.) or root collar (d.r.c.) for woodland species.

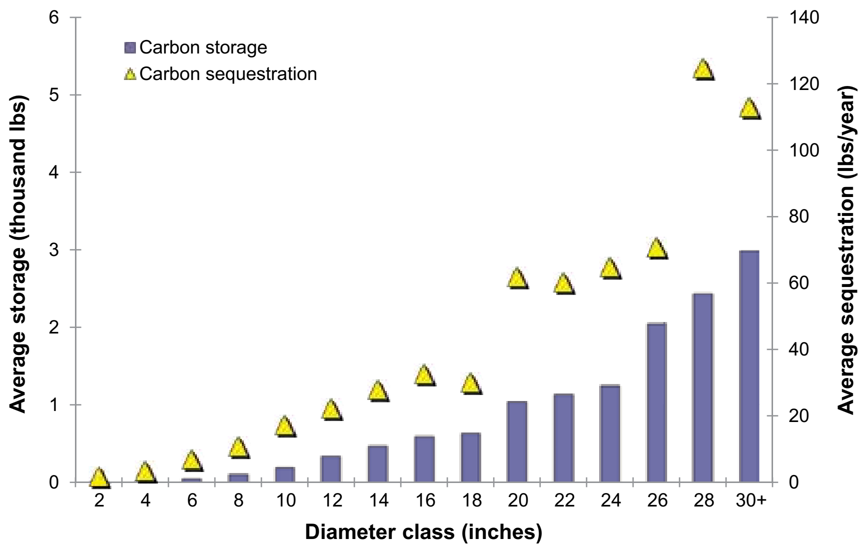

Figure 29—Estimated average per tree carbon storage and sequestration by tree diameter class, Houston, 2015. Diameter classes are designated by their midpoint (e.g., 2 is actually 1 to 2.9 inches). Diameter measurements were taken at breast height (d.b.h.) or root collar (d.r.c.) for woodland species.

pre-planning for post-disaster recovery. Volume data can also inform urban wood markets, which add value to aging or downed trees and incentivize their use for wood products, such as lumber and other building materials, handcrafted furniture, nature-based landscape supplies, and biofuel.

In Houston, trees are estimated to contain 126 million cubic feet of net volume and 219 million board feet of net sawtimber volume. Loblolly pine contributes the most net cubic-foot volume at 12.8 percent of the city total (table 13). Loblolly pine also contributes 35.7 percent of the total net board-foot sawtimber volume (table 14). By diameter class, the greatest net cubic-foot volume is provided by trees 29 inches or greater in diameter (fig. 30).

Energy consumption—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 Houston, interactions between trees and buildings are projected to annually decrease energy requirements by 319,000 million British Thermal Units (MBTUs) and 13,000 megawatt-hours (MWHs) during the heating season (table 15). Based on average energy costs in 2012 (U.S. Energy Information Administration 2012a, 2012b, 2014b, 2014c),

Table 13—Net cubic-foot volume for species with the greatest net volume, Houston, 2015

Common name	Net volume	
	cubic feet	*percent*
Loblolly pine	16,145,000	12.8
Live oak	14,220,000	11.3
Water oak	13,957,000	11.0
Green ash	9,899,000	7.8
Chinese tallowtree	7,795,000	6.2
Sweetgum	7,628,000	6.0
Pecan	6,782,000	5.4
Post oak	5,655,000	4.5
Sugarberry	5,282,000	4.2
Willow oak	5,108,000	4.0
Other species	33,902,000	26.8
Total	126,373,000	100.0

Table 14—Net board-foot sawtimber volume for species with the greatest net volume, Houston, 2015

Common name	Net volume	
	board feet	*percent*
Loblolly pine	78,176,000	35.7
Green ash	28,551,000	13.0
Water oak	19,208,000	8.8
Willow oak	18,243,000	8.3
Southern red oak	17,126,000	7.8
Pecan	11,945,000	5.4
American sycamore	10,168,000	4.6
Sweetgum	9,262,000	4.2
Live oak	7,774,000	3.5
Cherrybark oak	5,342,000	2.4
Other species	13,436,000	6.1
Total	219,231,000	100.0

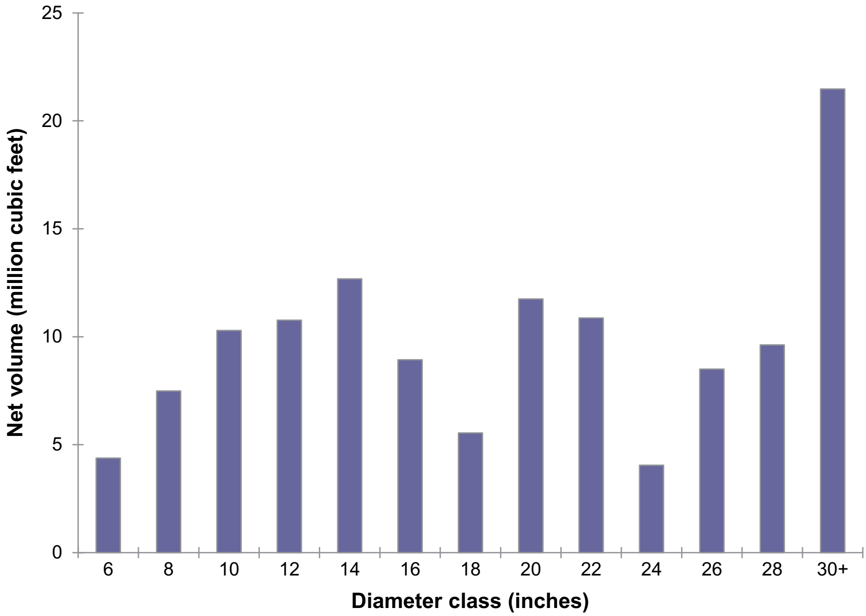

Figure 30—Net cubic-foot volume by tree diameter class, Houston, 2015. Diameter classes are designated by their midpoint (e.g., 6 is actually 5 to 6.9 inches). Diameter measurements were taken at breast height (d.b.h.).

Table 15—Annual energy savings[a] (MBTU, MWH, or tons) due to trees near residential buildings, Houston, 2015

Reduced energy use and emissions	Heating	Cooling	Total
MBTU[b]	319,000	N/a	319,000
MWH[c]	13,000	439,000	452,000
Carbon avoided (tons)[d]	12,000	97,000	109,000

N/a = Not applicable (MBTUs are not used to quantify cooling effects).

[a] Negative values indicate an increase in energy requirements.

[b] MBTU = Million British Thermal Units.

[c] MWH = Megawatt-hour.

[d] To convert carbon estimates to CO_2, multiply carbon value by 3.667.

this projected decrease in energy requirements is associated with a decrease in energy costs of $4.9 million per year (table 16). During the cooling season, energy requirements are projected to decrease by an estimated 439,000 MWHs with an associated value of $49.0 million per year. The net effect of trees on residential energy costs is a decrease of $53.9 million annually. Trees also provide an additional $14.4 million in value per year by reducing 109,000 tons of carbon emissions (398,000 tons of CO_2) from fossil-fuel-based power sources (tables 15 and 16).

Trees tend to reduce summertime energy consumption due to shading and evaporative cooling.

Table 16—Annual monetary savings[a,b] in residential energy expenditures during heating and cooling seasons, Houston, 2015

Reduced energy use and emissions	Heating	Cooling	Total
		U.S. dollars	
MBTU[c] ($)	3,446,000	N/a	3,446,000
MWH[d] ($)	1,444,000	49,040,000	50,484,000
Carbon avoided ($)	1,543,000	12,889,000	14,432,000

N/a = Not applicable (MBTUs are not used to quantify cooling effects).

[a] Based on 2012 statewide energy costs (U.S. Energy Information Administration 2012a, 2012b, 2014b, 2014c) and 2015 social cost of carbon (Interagency Working Group 2013, U.S. Environmental Protection Agency 2015).

[b] Negative values indicate an increase in energy requirements.

[c] MBTU = Million British Thermal Units.

[d] MWH = Megawatt-hour.

Structural and functional values—The city's forest has a structural value based on the tree itself that includes compensatory value and carbon storage value. The compensatory value is an estimate of the value of the forest as a structural asset (e.g., how much should one be compensated for the loss of the physical structure of the tree). The compensatory value (Nowak and others 2002a) of the trees in Houston is about $16.3 billion (fig. 31). For small trees, a replacement cost can be used; for larger trees, several estimation procedures are used (Nowak and others 2002a). The structural value of the forest resource tends to increase with an increase in the number and size of healthy trees. Note that some invasive tree species are listed with a high compensatory value (fig. 31) because the methods used to estimate compensatory value do not account for management preferences (e.g., noninvasive species). Additionally, despite their status as an invasive, these species still contribute ecosystem services (see table 6 and table 26 for importance values, abundance, and leaf area data by species).

Compensatory value varies across the plots in Houston (fig. 32). It is a function of the number and condition of trees, types of species, diameter of trees, and land use found on each plot. Compensatory value per acre is greater than $200,000 per acre for six plots in Houston. On these plots, the average tree diameter is 15 inches or greater. Forests also have functional values (either positive or negative) based on the functions the trees

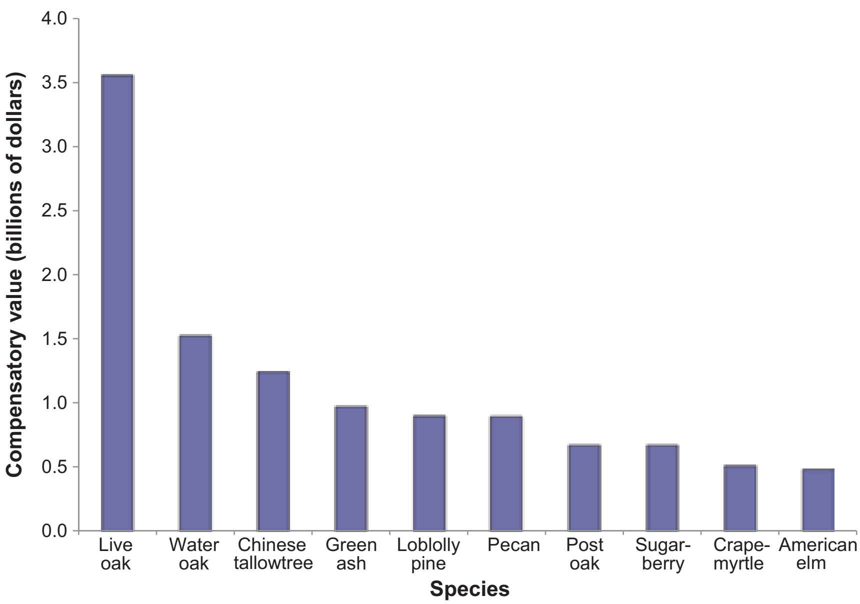

Figure 31—Tree species with the greatest collective compensatory value, Houston, 2015.

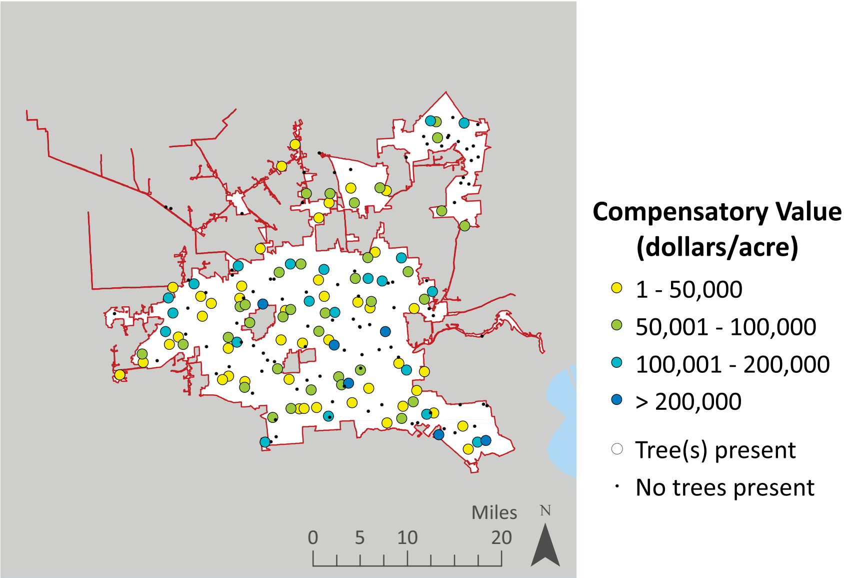

Figure 32—Average compensatory value per acre by plot, Houston, 2015.

perform, including sequestering carbon, removing air pollutants, and reducing the amount of energy used to heat or cool buildings. 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 forest, though they are not quantified here (e.g., reduction in ultraviolet radiation, aesthetics, and wildlife habitat). Thus, the functional estimates provided in this report represent only a portion of the total forest functional values. Through proper management, urban forest values can be increased. However, the values and benefits can also decrease as the amount of healthy tree cover declines. There are also various monetary costs associated with urban forest management, such as tree pruning, inspection, removal and disposal, which are not accounted for in this assessment (McPherson and others 2005).

Urban trees in Houston have the following structural values:

- Compensatory value: $16.3 billion
- Carbon storage: $272 million

Urban trees in Houston have the following annual functional values:

- Carbon sequestration: $18.6 million
- Pollution removal: $20.4 million
- Reduced energy costs: $53.9 million
- Stormwater runoff: $7.8 million
- Avoided emissions: $14.4 million

Urban Forest Health

A healthy urban forest will provide greater benefits to society than an unhealthy one. This report highlights tree damage variables, crown measurements, and the number of standing dead trees as indicators of urban forest health in Houston.

Crews were asked to note the presence or absence of seven different damage variables that are commonly seen among trees in urban areas. These urban forest health indicators are of specific interest to arborists and plant health specialists.

In addition to damage variables, field crews collected crown data for all trees > 1 inch in diameter (see U.S. Forest Service 2015 for details). The crown dieback variable helps illustrate tree health and is defined as recent mortality of small branches and twigs in the upper and outer portion of the tree's crown.

The number of standing dead trees is another measure of urban forest health and can be an indication of a specific problem, such as a pest or disease, within the urban forest. However, one must be cautious in interpreting health issues based on standing dead trees as removal rates vary among land use classes. That is, standing dead trees will likely remain standing long in low use areas (e.g., forests) and are removed more rapidly in high use areas (e.g., street trees, residential areas). Based on urban FIA protocols, all trees 5 inches or greater in diameter that were standing dead were recorded as such.

Although drought took its toll on trees in Memorial Park, it continues to be a highly used community greenspace.

Damage indicators of tree health—Urban FIA protocols were used to collect data on the following seven damage variables: (1) trunk bark inclusion, (2) root/stem girdling, (3) conflict with overhead wires, (4) topping/pruning, (5) sidewalk-root conflict, (6) excessive mulch, and (7) improper planting. For a detailed description and images of these variables, see U.S. Forest Service (2015). The presence or absence of these damage variables, along with the location of the damage, were recorded for all trees at least 1 inch in diameter. Damage at the root level or tree bole can potentially be more significant in terms of tree health as compared to damages in branches or upper bole. The severity of the damage was also recorded. All observed damages were recorded for each tree, with inspections starting at the roots and bole and progressing up to the crown (U.S. Forest Service 2015).

Trunk bark inclusions were the most common damage and occurred on 6.4 percent of the trees in Houston. Trunk bark inclusions are places where branches are not strongly attached to the tree. A weak union occurs when two or more branches grow so closely together that bark grows between the branches and inside the union. This ingrown, or included, bark does not have the structural strength of wood, and the union can become very weak. The inside bark may also act as a wedge and force the branch union to split apart. The FIA-designated land use with the greatest proportion of trees with trunk bark inclusions is Rights-of-way (table 17). Poor pruning practices can result in the formation of included trunk bark. Species with the highest percent of its population with trunk bark inclusions were callery pear, pecan, and sugarberry (table 18).

Table 17—Percentage of trees with various types of damage by land use, Houston, 2015
For example, 68.7 percent of trees in the Rights-of-way land use had trunk bark inclusion

Damage class	Land cover							
	Forest Land	Residential	Rights-of-way	Commercial	Other Developed	Multi-family Residential	Other Nonforest	Total
	percent							
Trunk bark inclusion	1.2	17.3	68.7	1.1	3.8	1.8	6.5	6.4
Topping/pruning	0.0	12.7	69.8	4.9	6.3	3.6	0.0	5.2
Sidewalk-root conflict	0.0	6.6	7.0	7.1	10.1	83.6	0.0	3.8
Overhead wires	0.0	11.4	4.6	1.1	15.7	0.0	12.5	2.2
Excess mulch	0.0	1.2	3.2	0.0	1.3	0.0	0.0	0.3
Root/stem girdling	0.1	0.6	0.0	0.0	1.7	0.0	0.0	0.2
Improper planting	0.0	0.6	0.0	0.0	1.3	0.0	0.0	0.1

Table 18—Species with greatest proportion of their population with damage, by damage type, Houston, 2015

For example, 97.5 percent of callery pear had trunk/bark inclusion

Damage type and species	Class	Damage type and species	Class
	percent		*percent*
Trunk bark inclusion		Sidewalk-root conflict	
Callery pear	97.5	Live oak	31.6
Pecan	32.3	Japanese privet	31.4
Sugarberry	28.4	Willow oak	14.9
Live oak	16.3	Water oak	9.5
Green ash	9.1	Pecan	6.6
Root/stem girdling[a]		Excess mulch[a]	
Chinaberry	5.8	Willow oak	4.3
Boxelder	2.5	Pecan	3.3
		Loblolly pine	2.5
Overhead wires		Live oak	1.7
Chinaberry	34.6		
Sugarberry	20.1	Improper planting[a]	
Pecan	9.7	Live oak	3.5
Water oak	9.5	Sugarberry	0.7
Post oak	8.0		
Topping/pruning			
Callery pear	96.2		
Chinaberry	23.2		
Live oak	20.4		
Pecan	19.8		
Crapemyrtle	18.3		

Note: Only species with minimum sample size of 10 live trees are included in this analysis to minimize effect of small sample size on percentage estimates. All species values are given in appendix 8.

[a] There were not five species having the specific damage type of root/stem girdling, excess mulch, or improper planting with a minimum sample size of 10 trees.

Topping/pruning was the second most common damage and occurred on 5.2 percent of the trees in Houston. Severe topping or poor pruning is the result of improper maintenance techniques where the stem or branches of the tree crown are removed or cut incorrectly and sometimes in excessive amounts. In Rights-of-way areas, topping/pruning was found on 69.8 percent of the trees (table 17). Callery pear, chinaberry, and live oak were the species with the highest proportion of their population exhibiting this damage (table 18).

Sidewalk-root conflicts were the third most common damage recorded. In 3.8 percent of the trees in Houston, tree root conflicts with sidewalks were observed. This conflict occurs when tree roots grow under sidewalks and asphalt and is noted where direct damage is readily apparent. The FIA-designated land use with the greatest proportion of trees with sidewalk conflicts was Multi-family Residential (table 17). Live oak, Japanese privet, and willow oak trees had the highest proportion of their population with sidewalk-root conflicts (table 18).

Crown indicators of tree health—Measurement of tree crowns can be used as an indicator of tree health. Large, dense crowns are often indicative of vigorously growing trees, while small, sparsely foliated crowns signal trees with little or no growth and possibly in a state of decline. One measurement of crown health used to estimate tree condition is dieback.

Trees with crown dieback >25 percent may be in decline, for both hardwoods and conifers (Steinman 1998). Based on the live tree population with at least 10 trees in the sample, species with the highest average dieback were boxelder and willow oak (table 19). Higher levels of dieback may indicate a potential insect, disease, or environmental problem associated with this species, and further evaluation is warranted.

Standing dead trees—Seven percent of the urban tree population 5 inches in diameter and greater was standing dead. Twenty-two plots had standing dead trees. Plot estimates range from 6.0 to 42.1 standing dead trees per acre. Most plots with the highest dead tree densities are located in the outer (more forested) areas of the city (fig. 33). The species with the highest percentage of its population in standing dead trees were Osage-orange,

Table 19—Species with greatest average dieback (minimum sample size = 10 trees), Houston, 2015

Species	Sample	Average dieback	Trees with >25% dieback
	number	- - - - - - *percent*	- - - - - -
Boxelder	18	5.6	2.5
Willow oak	22	4.5	6.9
Sweetgum	60	3.8	12.6
Chinese tallowtree	136	3.5	3.7
Sugarberry	69	2.5	1.6
Live oak	38	2.4	1.7
American elm	29	1.0	0.0

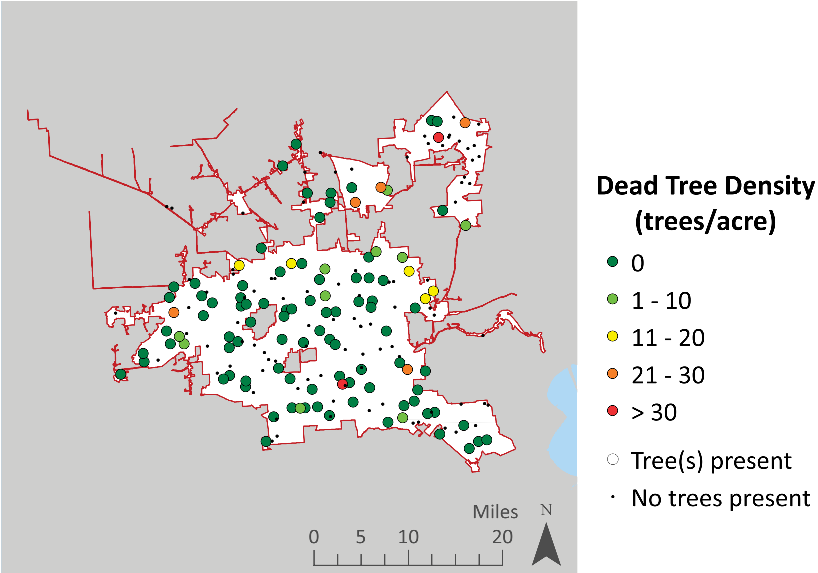

Figure 33—Number of standing dead trees per acre by plot, Houston, 2015.

southern red oak, willow oak, white mulberry, and loblolly pine (table 20). Of the standing dead tree population, 21.6 percent are loblolly pine, 14.5 percent are Chinese tallowtree, and 14.4 percent are sugarberry (table 21).

Higher proportions of standing dead trees may indicate potential insect, disease, or environmental problems associated with a specific species. In Houston, where droughts are a common concern, climate conditions may cause or exacerbate health problems among certain species. Further evaluation and monitoring of these species is warranted. A high percentage of dead trees does not necessarily indicate a health problem with the species; rather, it could be due to the fact that some trees will naturally remain standing as dead trees for longer periods, or that they might be left standing dead depending upon the land cover, risk associated with dead trees, and maintenance activities related to their removal. Thus, some species may have a higher proportion of dead trees as they are in locations where they are not immediately removed and therefore have a higher probability of being sampled as dead. For example, 100 percent of Osage-orange trees that were observed in the field were standing dead, but the species had a sample size of 4 trees, all of which were found in the Forest/Scrub land cover. Long-term monitoring of plots can help determine actual species mortality rates. Land covers with the highest estimated number of standing dead trees were Forest/Scrub, Developed–Low, and Developed–Open (table 22).

Table 20—Perentage of tree population classified as standing dead by species, Houston, 2015
For example, 100 percent of Osage-orange trees are standing dead

Common name	Sample[a]	Standing dead trees	
	- - - - *number* - - - -		*percent*
Osage-orange	4	53,000	100.0
Southern red oak	1	12,000	30.7
Willow oak	7	91,000	23.9
White mulberry	1	12,000	20.2
Loblolly pine	12	156,000	19.4
Cedar elm	1	13,000	16.4
Cherrybark oak	1	13,000	14.9
Sugarberry	8	104,000	11.5
Water oak	4	49,000	7.8
Chinese tallowtree	8	104,000	6.9
Sweetgum	4	53,000	6.8
Black willow	1	13,000	5.3
Crapemyrtle	1	12,000	4.1
Green ash	2	25,000	3.3
Live oak	1	12,000	1.8

[a] Sample is the number of dead trees sampled for each species.

Table 21—Species composition of standing dead trees, Houston, 2015
For example, 21.6 percent of standing dead trees are loblolly pine

Common name	Standing dead trees
	percent
Loblolly pine	21.6
Chinese tallowtree	14.5
Sugarberry	14.4
Willow oak	12.5
Sweetgum	7.3
Osage-orange	7.3
Water oak	6.8
Green ash	3.4
Cherrybark oak	1.8
Black willow	1.8
Cedar elm	1.8
White mulberry	1.7
Southern red oak	1.7
Live oak	1.7
Crapemyrtle	1.6

Table 22—Percentage of tree population classified as standing dead by land cover, Houston, 2015

Land cover	Standing dead trees	
	number	*percent*
Forest/Scrub	526,000	10.0
Developed–Low	87,000	5.8
Developed–Open	82,000	8.3
Developed–High	16,000	2.7
Developed–Medium	12,000	0.7
Grass/Herb/Crop	0	N/a
Water	0	N/a
Total	722,000	7.2

N/a = not applicable; percent not estimated for land covers with no standing dead trees.

MANAGEMENT IMPLICATIONS

The urban forest of Houston and its associated benefits vary across the city and inevitably will change over time. An important aspect of managing the urban forest for current and future residents is to understand how to sustain the benefits for all city residents. This report details urban forest benefits and provides a baseline for making decisions to improve forest management. Future monitoring is important as long-term urban forest plot data can be used to more accurately assess changes in species composition, size class distribution, and environmental benefits, in addition to assessing tree growth and mortality (Nowak and others 2004, 2013b).

Urban forest managers must consider prioritizing areas to protect or enhance the existing tree cover. An accepted paradigm is the "right tree in the right place" so that the trees can provide desired services and survive with minimal maintenance. While current tree cover for all of Houston is estimated at 18.4 percent, it ranges from 0.2 percent in the Water land areas to 53.6 percent in the Forest/Scrub lands. This tree-cover variability corresponds to variability in urban forest benefits across the city.

Houston's tree canopy frames Heritage Plaza.

Additional issues to consider in urban forest management are the forces that can cause species changes and alterations to the structure and composition of the urban forest over time and thus the provision of environmental benefits. Natural forces that could play a role in shaping the future urban forest include the current tree size distribution, nonnative invasive species, and potential pest infestations. Human activities, such as development and population growth, can have a large impact on the future urban forest as well. Other factors that will influence future forest structure include land cover changes, climate change, changing infrastructure, and natural resource management.

Current Size Distribution and Potential Species Changes

Change in species composition and tree size structure of Houston's urban forest may have a significant influence on the benefits provided by the urban forest for the next several decades. These changes are likely to require a different approach in forest management strategies that affect species composition. These strategies include pest management, regeneration, and restoration efforts.

The future urban forest will be determined, in part, by the structure and composition of today's urban forest. Younger trees will grow to larger sizes, and older trees will eventually decline and die. Houston has more small trees than large trees (this leads to an inverse J-shaped distribution of diameter structure; see fig. 13). This pattern is a favorable indication of long-term sustainability of tree cover. The shape of the diameter distribution curve is dependent on many factors such as mortality rates, growth rates, and influx rates (i.e., the number of trees being planted or naturally regenerating each year, which is not analyzed in this report).

By comparing the species composition of small trees (<5 inches diameter) with that of the large trees (15 inches diameter or greater), the future urban forest can be predicted. Several of the most common large diameter tree species, particularly live oak, pecan, post oak, and willow oak, are underrepresented among the small diameter trees (fig. 15). This indicates that there may not be enough regeneration and planting of these species to maintain the current species mix in the future. Species that dominate the small diameter class and appear to be regenerating well are Chinese tallowtree and American elm. Some other species dominating the small diameter class, such as Chinese privet and Japanese privet, do not attain a large stature at maturity. If these individual small trees are replacing large trees in the urban landscape, this could lead to lower canopy levels and altered size structure.

Nonnative Invasive Species

Nonnative invasive species are another concern in Houston (City of Houston 2010, U.S. Forest Service 2014b). Invasive tree species account for 11.1 million live trees with a leaf area of 77,000 acres. The invasive species observed in Houston can alter the urban forest composition through time as they spread into the surrounding landscape, potentially displacing native species and altering local ecosystems (Pimentel and others 2000). Management of invasive species (i.e., eradication) must consider loss of environmental services and the subsequent need for increased management of desirable species to offset losses.

Insect and Disease Impacts

Insects and diseases can infest urban forests, potentially killing trees and reducing the health, value, and sustainability of the urban forest. Various pests have different tree hosts, so the potential damage or risk of each pest will differ. We evaluated 20 exotic insects/diseases for their potential impact using range maps of the pests in the coterminous United States and host species information (U.S. Forest Service 2013, 2014a; Worrall 2007). For a complete list of the 20 exotic insects/diseases, see appendix 9.

In Houston, concerns about insect and disease impacts are compounded by the local climate. During periods of prolonged droughts, trees can become distressed, making them more vulnerable to pest infestations and diseases. Texas has historically experienced intense droughts, most notably the drought that lasted from 1950 to 1957. In more recent years, the State recorded one of its most extreme 12-month precipitation deficits from October 2010 to September 2011 (Nielsen-Gammon 2011).

Although there are additional pests that could impact Houston's urban forest, gypsy moth (GM), Asian longhorned beetle (ALB), oak wilt (OW), Dutch elm disease (DED), and emerald ash borer (EAB) pose the most serious threats, each putting more than 1 million trees at risk to infestation (table 23). At the time of this study (2015), OW and DED were confirmed present in Harris, Fort Bend, and Montgomery Counties where Houston is located. Potential loss from OW is 2.6 million trees with an associated compensatory value of $6.7 billion, while DED could impact 1.7 million trees ($616 million compensatory value). EAB, which was detected in Harrison County, TX, in April 2016, is located within 250 miles of Harris, Fort Bend, and Montgomery Counties. Potential loss of

Table 23—Potential risk to trees by insect or disease, Houston, 2015

Code	Scientific name	Common name	Trees at risk	As proportion of all trees	Compensatory value
			number	*percent*	*$ millions*
GM	*Lymantria dispar*	Gypsy moth	5,866,000	17.6	7,537
ALB	*Anoplophora glabripennis*	Asian longhorned beetle	3,701,000	11.1	2,122
OW	*Ceratocystis fagacearum*	Oak wilt[a]	2,566,000	7.7	6,683
DED	*Ophiostoma novo-ulmi*	Dutch elm disease[a]	1,747,000	5.3	616
EAB	*Agrilus planipennis*	Emerald ash borer	1,207,000	3.6	1,435
SPB	*Dendroctonus frontalis*	Southern pine beetle	988,000	3.0	912
PSB	*Tomicus piniperda*	Pine shoot beetle[a]	988,000	3.0	912
SW	*Sirex noctilio*	Sirex woodwasp	988,000	3.0	912
LAT	*Choristoneura conflictana*	Large aspen tortrix	260,000	0.8	82
AL	*Phyllocnistis populiella*	Aspen leafminer	237,000	0.7	63
SOD	*Phytophthora ramorum*	Sudden oak death	28,000	0.1	323

[a] Confirmed present in Harris, Fort Bend, and/or Montgomery Counties.

trees from EAB is 1.2 million ($1.4 billion compensatory value). GM and ALB have not been found within 750 miles of Harris, Fort Bend, and Montgomery Counties, but the impacts of these two pests could be devastating. Potential loss of trees from GM is 5.9 million ($7.5 billion in compensatory value) and ALB is 3.7 million ($2.1 billion in compensatory value).

Oak wilt has posed a threat to the large population of oak trees in Houston over the last few decades. Efforts to prevent the spread of oak wilt are motivated by the fact that oak is a significant tree in Houston. There were eight different oak species sampled in Houston though water oak, live oak, and willow oak make up more than 83 percent of the total number of oak trees. Citywide, oaks account for 7.7 percent of the trees in the urban forest and more than a quarter of the carbon stored and sequestered there. It is found in five of the seven land cover categories.

In more recent years, emerald ash borer has become a greater threat to Houston's urban forest. The pest's detection in Harrison County, TX, in April 2016 and ability to spread rapidly have spurred the call for mitigation and preparedness planning in the Houston area (Texas A&M Forest Service 2016). The ash population in Houston consists of five different ash species, a total number of 1.2 million live trees (table 24), and is found in five of the seven land cover categories (table 25). With a contribution of 7.2 percent of the city's leaf area (table 24), ash trees are providing a moderate amount of the urban forest's ecosystem services. Ash species are most prominent in Forest/Scrub areas, comprising 18.8 percent of the total tree population in that land cover. On a plot basis, ash tree density ranged from 6.0 to 147.2 trees per acre, though ash trees were only observed on 20 plots in Houston (fig. 34). However, only 2 of the 200 plots sampled had densities equivalent to more than 100 ash trees per acre. These higher ash density plots occurred on the western side of the city.

Table 24—Ash estimates, Houston, 2015

Estimate type	Units	Estimate	Proportion of all trees
Population	Number	1,207,000	3.6%
Density	Trees per acre	3.0	N/a
Carbon stored	Tons	183,000	9.0%
Carbon sequestered	Tons per year	11,000	7.6%
Leaf area	Acres	30,000	7.2%
Leaf biomass	Tons	9,000	5.0%
Trees, diameter <5 inches[a]	Number	328,000	27.1%[b]
Trees, diameter ≥ 15 inches[a]	Number	173,000	14.4%[b]

N/a = not applicable; density cannot be described as a proportion of all trees.

[a] Diameter measurements were taken at breast height (d.b.h.) or root collar (d.r.c.) for woodland species.

[b] Percentage of all ash trees.

Table 25—Ash trees by land cover, Houston, 2015

Land cover[a]	Ash trees	Ash tree density	Proportion of trees in land cover that are ash
	number	*trees per acre*	*percent*
Forest/Scrub	985,000	18.8	4.8
Developed–Medium	142,000	1.3	3.2
Developed–Low	37,000	0.5	1.4
Developed–High	31,000	0.4	2.7
Developed–Open	12,000	0.2	0.3
Houston	1,207,000	3.0	3.6

[a] No ash trees were found on Grass/Herb/Crop land cover; no trees were found on Water land cover.

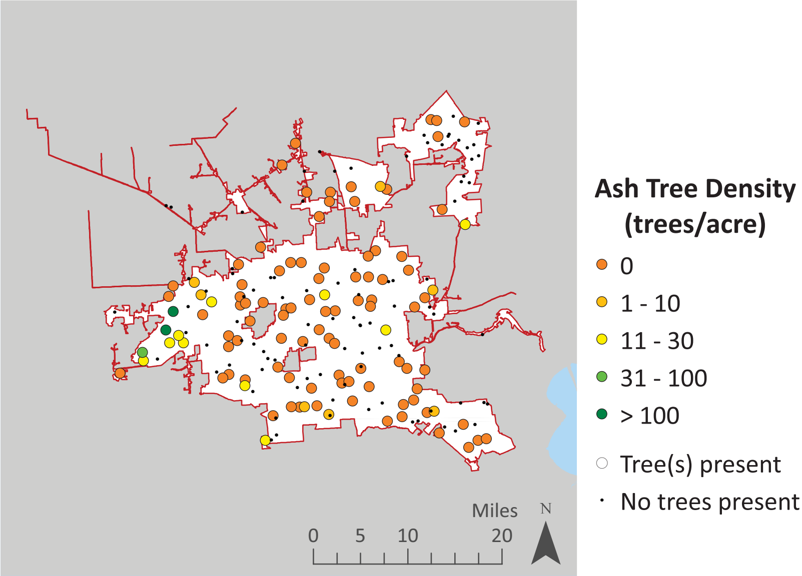

Figure 34—Number of ash trees per acre by plot, Houston, 2015.

Population Growth

One anthropogenic force that could shape Houston's future urban forest is population growth. In 2015, Houston's population reached 2,296,000 people, an increase of 8.9 percent from 2010 (U.S. Census Bureau 2010). Continued population growth in Houston can have many implications for the urban forest. Most notably, development of land to support growing housing and economic needs could impact the land cover composition of the city and change local infrastructure.

CONCLUSION

The Houston urban forest contributes significantly to the environment, the economy, and residents' well-being. Throughout the city, an estimated 33.3 million trees, representing more than 63 species, provide a canopy cover of 18.4 percent. That canopy, particularly leaf surface area, provides a wide range of important environmental benefits including air pollution removal, reduced carbon emissions, carbon storage and sequestration, reduced energy use for buildings, stormwater capture, and many others.

There are a number of change forces that will impact Houston's forest structure and health, as well as the environmental benefits provided to the city's residents in the future. Some of these forces include insect and disease infestations, invasive trees and other plants, aging and loss of larger trees, expansion of opportunistic species, changes in the management and use of the forest, and human population growth.

This analysis provides a baseline for future monitoring. While data from this report captures the current urban forest resource and the ecosystem services and values provided by it, future monitoring will be necessary to identify how the forest is changing over time. One-fifth of the plots established in the city of Houston will be remeasured every year as part of the continuing urban FIA program. Future analyses of the city's forest can be used to determine the role that natural and human forces play in shaping forest structure and composition.

For now, managers can use these data to inform long-term management plans and policies to sustain a healthy urban tree population and ecosystem services for future generations. Planning and management of the urban forest resource can help sustain vital ecosystem services and values for current and future generations in Houston. In the future, change analyses can be used to evaluate the success of urban forest management programs.

More information on trees in Houston can be found at: FIA Tools (http://www.fia.fs.fed.us/tools-data/) or My City's Trees (www.mycitystrees.com).

Houston's urban forest helps manage stormwater runoff.

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APPENDIX 1—URBAN FIA

Sampling Design

The FIA program maintains a systematic grid of permanent plots (FIA core plots) across the United States that is used to inventory and monitor the Nation's forests (Reams and others 2005). The urban FIA inventory uses the same sampling frame as the core FIA program and data are used to produce estimates of the quantity, health, composition, and benefits of urban trees. The urban FIA protocol follows a city-based model where urban inventory plots are located in the U.S. Census-defined urban areas and urban clusters (UAUC), within a chosen core-based statistical area (CBSA). Houston city limits are defined by the 2010 U.S. Census.

There are two zones of interest in the urban FIA sample design (fig. 35). Urban FIA plots within the CBSA-confined UAUC boundaries are established at the same location as the FIA core plots, and tree measurements are taken at all sample sites regardless of whether they are forested or not. Collocated urban plots are measured at the same intensity and on the same timeline as the rest of the FIA core plots in the region.

The second zone of interest in the urban FIA sample design is the city boundary that is associated with the chosen CBSA. Urban plots within the city boundary may include

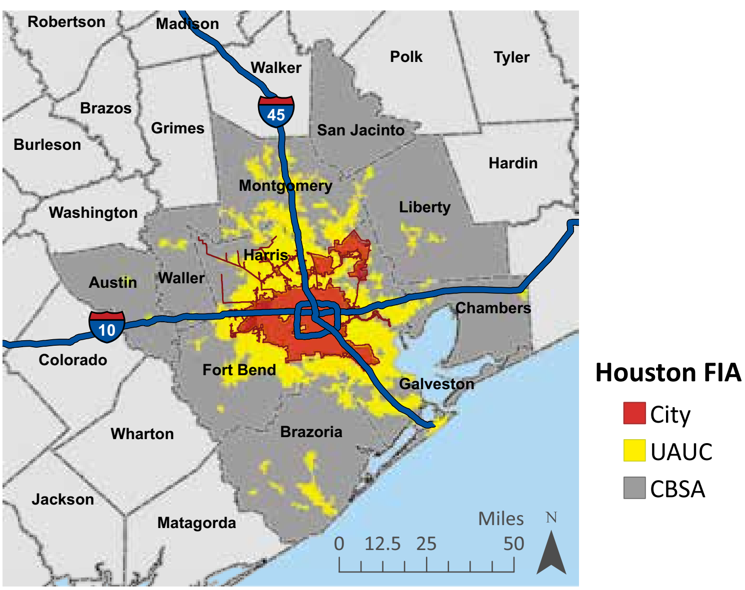

Figure 35—Location of Houston city boundary and urban areas and urban clusters (UAUC), within the Houston core-based statistical area (CBSA).

some plots that are collocated with established core FIA plots, but also consist of an intensified set of urban-design only plots. In general, sampling within the target city will be intensified to the point of reaching a total of approximately 200 plots.

In Houston, there were 38 established FIA core plots within the CBSA-confined UAUC boundary that were being sampled in the year of the study (i.e., 2015 field season), but only 11 were located in the Houston city boundaries. Intensification within Houston city boundaries added 198 additional urban plots, bringing the total number of urban FIA plots to 209. The estimates contained within this report are based only on that sample of 200 accessible plots in the city boundaries of Houston.

Data Collection

With support from State and city cooperators, data collection on the intensified plots in Houston was accelerated so that all data collection took place during the 2015 field season. Ordinarily, under the standard urban FIA protocol, the intensified plots within the city limits are measured on the same timeline as core FIA plots in the State, using the FIA panel system (Reams and others 2005). The proportion of the total sample plots measured in a given year is related to the cycle length. States with a cycle length of 5 years will have 1/5th of the total number of plots sampled each year, and remeasurement will begin in the 6th year. The Houston urban plots will be remeasured on a 5-year cycle, as are the FIA core plots in eastern Texas.

As data collection continues annually, there will be additional data collected in the CBSA-confined UAUC boundary, and analysis and reporting will be expanded to include this new urban zone. Also, annual plot remeasurements will begin on a portion of intensified plots within the city beginning in the 2016 field season, allowing for urban monitoring and analyses of change in future reports.

Plot Layout

Each urban forest inventory plot consisted of one circular plot 1/6 acre in size with a radius of 48 feet. Each plot contained four nested microplots; each 1/300 acre in size, with a radius of 6.8 feet and offset 12 feet horizontal in each cardinal direction from the plot center. Urban FIA and core FIA plot layouts are the same in total sampled area but differ in configuration. The single circular urban plot has the same total area as the FIA core plot consisting of a cluster of four subplots. The urban nested microplots are the equivalent of the nested microplots of an FIA core plot, with each being the same diameter. For more details on the FIA core plot layout, see Bechtold and Scott (2005).

APPENDIX 2—SPECIES SAMPLED IN THE HOUSTON URBAN FOREST

Table 26—Scientific and common names of tree species sampled in the urban forest, with estimated metrics for species, Houston, 2015

Genus	Species	Common name	Live trees		Leaf area	IV[a]	Diameter[b] Median	Diameter[b] Average	Basal area[c]	Structural value
			number	*%*	*%*		*inches*	*inches*	*ft²*	*$ millions*
Acer	*negundo*	Boxelder	533,000	1.6	1.8	3.4	3.8	6.3	167,000	185
Betula	*nigra*	River birch	24,000	0.1	0.0	0.1	7.4	7.4	7,000	19
Carpinus	*caroliniana*	American hornbeam	186,000	0.6	0.6	1.2	4.9	5.4	30,000	27
Carya	*aquatica*	Water hickory	53,000	0.2	0.1	0.3	7.0	7.1	15,000	10
Carya	*illinoinensis*	Pecan	376,000	1.1	4.1	5.3	11.0	12.8	405,000	901
Carya	*ovata*	Shagbark hickory	24,000	0.1	0.4	0.5	26.0	26.0	93,000	174
Celtis	*laevigata*	Sugarberry	1,585,000	4.8	10.4	15.2	5.0	5.5	488,000	669
Celtis	*occidentalis*	Hackberry	88,000	0.3	0.7	1.0	9.6	11.4	75,000	155
Citrus	*sinensis*	Sweet orange	781,000	2.3	0.9	3.3	3.5	3.1	45,000	122
Crataegus	species	Hawthorn spp.	668,000	2.0	0.2	2.2	3.0	2.7	30,000	27
Cupressus	*sempervirens*	Italian cypress	147,000	0.4	0.0	0.5	1.3	1.3	1,000	8
Cupressus	species	Cypress	12,000	0.0	0.1	0.2	15.0	15.0	14,000	12
Diospyros	*virginiana*	Common persimmon	468,000	1.4	0.2	1.6	1.5	1.6	9,000	11
Fraxinus	*americana*	White ash	26,000	0.1	0.2	0.2	13.1	10.5	16,000	21
Fraxinus	*berlandieriana*	Berlandier ash	59,000	0.2	0.6	0.8	14.0	14.6	85,000	217
Fraxinus	*caroliniana*	Carolina ash	12,000	0.0	0.2	0.2	22.4	22.4	34,000	80
Fraxinus	*pennsylvanica*	Green ash	1,063,000	3.2	5.5	8.7	7.0	8.5	708,000	977
Fraxinus	*velutina*	Velvet ash	47,000	0.1	0.7	0.9	13.4	14.1	58,000	139
Gleditsia	*triacanthos*	Honeylocust	154,000	0.5	0.0	0.5	1.1	1.1	1,000	4
Ilex	*vomitoria*	Yaupon	7,610,000	22.9	9.5	32.4	1.5	1.6	116,000	143
Juniperus	*pinchotii*	Pinchot juniper	12,000	0.0	0.1	0.1	8.5	8.5	5,000	15
Juniperus	*virginiana*	Eastern redcedar	220,000	0.7	0.6	1.3	3.8	4.9	33,000	79
Lagerstroemia	*indica*	Crapemyrtle	279,000	0.8	1.2	2.1	9.4	11.1	229,000	510
Ligustrum	*amurense*	Amur privet	12,000	0.0	0.0	0.0	5.3	5.3	2,000	7
Ligustrum	*japonicum*	Japanese privet[d]	1,897,000	5.7	3.1	8.8	2.3	3.9	270,000	332
Ligustrum	*sinense*	Chinese privet[d]	2,293,000	6.9	1.9	8.8	2.2	2.3	77,000	74
Liquidambar	*styraciflua*	Sweetgum	1,353,000	4.1	3.8	7.9	5.3	6.1	477,000	451
Maclura	*pomifera*	Osage-orange[d,e]	0	0.0	0.0	0.0	n/a	n/a	10,000	0
Magnolia	*grandiflora*	Southern magnolia	49,000	0.1	0.3	0.4	10.4	8.9	22,000	59
Melia	*azedarach*	Chinaberry[d]	204,000	0.6	1.5	2.1	8.8	11.0	168,000	264
Morus	*alba*	White mulberry[d]	49,000	0.1	0.5	0.6	31.5	18.8	142,000	209
Morus	*rubra*	Red mulberry	12,000	0.0	0.1	0.1	5.4	5.4	2,000	7
Nyssa	*sylvatica*	Blackgum	12,000	0.0	0.2	0.2	22.0	22.0	31,000	25
Ostrya	*virginiana*	Eastern hophornbeam	12,000	0.0	0.1	0.1	5.3	5.3	2,000	2
Phoenix	*dactylifera*	Date palm	12,000	0.0	0.2	0.3	22.6	22.6	35,000	17
Pinus	*palustris*	Longleaf pine	12,000	0.0	0.0	0.1	5.2	5.2	2,000	7
Pinus	*taeda*	Loblolly pine	976,000	2.9	6.0	9.0	6.9	8.9	828,000	905
Planera	*aquatica*	Water-elm	12,000	0.0	0.1	0.1	6.9	6.9	3,000	3
Platanus	*mexicana*	Mexican sycamore	12,000	0.0	0.1	0.2	31.5	31.5	64,000	150

continued

Table 26 (continued)—Scientific and common names of tree species sampled in the urban forest, with estimated metrics for species, Houston, 2015

Genus	Species	Common name	Live trees		Leaf area	IV[a]	Diameter[b]		Basal area[c]	Structural value
							Median	Average		
			number	*%*	*%*		*inches*	*inches*	*ft²*	*$ millions*
Platanus	*occidentalis*	American sycamore	35,000	0.1	0.8	1.0	14.9	19.7	96,000	184
Poncirus	*trifoliata*	Hardy orange[d]	12,000	0.0	0.0	0.1	5.4	5.4	2,000	7
Pyrus	*calleryana*	Callery pear[d]	931,000	2.8	0.8	3.6	3.5	3.3	65,000	193
Pyrus	*communis*	Common pear	12,000	0.0	0.0	0.1	5.1	5.1	2,000	6
Quercus	*falcata*	Southern red oak	28,000	0.1	0.7	0.8	29.9	30.2	165,000	323
Quercus	*lyrata*	Overcup oak	13,000	0.0	0.1	0.1	18.9	18.9	26,000	25
Quercus	*nigra*	Water oak	1,171,000	3.5	6.0	9.5	3.8	8.3	855,000	1,531
Quercus	*pagoda*	Cherrybark oak	75,000	0.2	0.9	1.1	16.1	15.6	126,000	155
Quercus	*phellos*	Willow oak	288,000	0.9	2.2	3.0	12.3	12.4	366,000	384
Quercus	*shumardii*	Shumard oak	167,000	0.5	0.8	1.3	1.9	3.3	31,000	33
Quercus	*stellata*	Post oak	148,000	0.4	2.3	2.7	15.4	18.7	316,000	670
Quercus	*virginiana*	Live oak	676,000	2.0	8.4	10.5	13.6	15.7	1,171,000	3,562
Sabal	*mexicana*	Mexican palmetto	49,000	0.1	0.1	0.3	13.5	15.7	67,000	35
Salix	*nigra*	Black willow	237,000	0.7	0.8	1.5	7.6	7.4	79,000	63
Samanea	*saman*	Raintree	47,000	0.1	0.7	0.8	10.1	10.9	35,000	85
Tilia	*americana*	Carolina basswood	12,000	0.0	0.1	0.1	11.5	11.5	8,000	20
Triadica	*sebifera*	Chinese tallowtree[d]	5,693,000	17.1	9.9	27.0	2.3	3.7	880,000	1,245
Ulmus	*alata*	Winged elm	308,000	0.9	1.1	2.1	4.3	5.5	55,000	56
Ulmus	*americana*	American elm	1,032,000	3.1	5.4	8.5	2.9	5.0	269,000	483
Ulmus	*crassifolia*	Cedar elm	394,000	1.2	0.6	1.8	2.6	2.9	48,000	54
Ulmus	*parvifolia*	Chinese elm[d]	63,000	0.2	1.0	1.2	8.0	8.8	27,000	78
Ulmus	*rubra*	Slippery elm	12,000	0.0	0.3	0.4	13.4	13.4	12,000	23
Vaccinium	*arboreum*	Farkleberry	328,000	1.0	0.1	1.1	1.2	1.2	2,000	5
Zanthoxylum	*clava-herculis*	Hercules' club	190,000	0.6	0.6	1.2	4.8	4.8	24,000	20

N/a = not applicable; median and average diameter cannot be estimated for species that have no live trees.

[a] IV = importance value (% live population + % leaf area).

[b] Diameter measurements were taken at breast height (d.b.h.) or root collar (d.r.c.) for woodland species. Median and average diameter measurements are estimated for live trees only.

[c] Basal area is the cross sectional area of the tree stems measured at the diameter. This is estimated for live and dead trees.

[d] Invasive species.

[e] Osage-orange was the only species sampled for which there were no live trees.

APPENDIX 3—LAND COVER CATEGORY DESCRIPTIONS

Table 27—Land cover categories and descriptions, based on aggregation of the 2011 National Land Cover classes (Homer and others 2015)

Land cover category	NLCD code	NLCD class	Land cover description
Water	11	Open Water	Areas of open water, generally with <25 percent cover of vegetation or soil.
Developed–Open	21	Developed, Open Space	Areas with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses. Impervious surfaces account for <20 percent of total cover. These areas most commonly include large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes.
Developed–Low	22	Developed, Low Intensity	Areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 20 to 49 percent of total cover. These areas most commonly include single-family housing units.
Developed–Medium	23	Developed, Medium Intensity	Areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 50 percent to 79 percent of the total cover. These areas most commonly include single-family housing units.
Developed–High	24	Developed, High Intensity	Highly developed areas where people reside or work in high numbers. Examples include apartment complexes, row houses and commercial/industrial. Impervious surfaces account for 80 percent to 100 percent of the total cover.
Grass/Herb/Crop	31	Barren Land	Areas of bedrock, desert pavement, scarps, talus, slides, volcanic material, glacial debris, sand dunes, strip mines, gravel pits and other accumulations of earthen material. Generally, vegetation accounts for less than 15 percent of total cover.

continued

Table 27 (continued)—Land cover categories and descriptions, based on aggregation of the 2011 National Land Cover classes (Homer and others 2015)

Land cover category	NLCD code	NLCD class	Land cover description
Grass/Herb/Crop (continued)	71	Grassland/ Herbaceous	Areas dominated by gramanoid or herbaceous vegetation, generally greater than 80 percent of total vegetation. These areas are not subject to intensive management such as tilling, but can be utilized for grazing.
	81	Pasture/Hay	Areas of grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops, typically on a perennial cycle. Pasture/hay vegetation accounts for greater than 20 percent of total vegetation.
Forest/Scrub	41	Deciduous Forest	Areas dominated by trees generally greater than 5 meters tall, and greater than 20 percent of total vegetation cover. More than 75 percent of the tree species shed foliage simultaneously in response to seasonal change.
	42	Evergreen Forest	Areas dominated by trees generally greater than 5 meters tall, and greater than 20 percent of total vegetation cover. More than 75 percent of the tree species maintain their leaves all year. Canopy is never without green foliage.
	43	Mixed Forest	Areas dominated by trees generally greater than 5 meters tall, and greater than 20 percent of total vegetation cover. Neither deciduous nor evergreen species are greater than 75 percent of total tree cover.
	52	Shrub/Scrub	Areas dominated by shrubs; less than 5 meters tall with shrub canopy typically greater than 20 percent of total vegetation. This class includes true shrubs, young trees in an early successional stage or trees stunted from environmental conditions.
	90	Woody Wetlands	Areas where forest or shrubland vegetation accounts for greater than 20 percent of vegetative cover and the soil or substrate is periodically saturated with or covered with water.

APPENDIX 4—TREE SPECIES DISTRIBUTION

This appendix illustrates various species distributions for the Houston urban forest. During field data collection, sampled trees are identified to the most specific classification possible. Some trees have been identified to the species or genus level.

The species distributions for each land cover are illustrated for the 20 most common species or all species if there are less than 20 species in the land cover category. The Water land cover category has 0 trees and is not depicted.

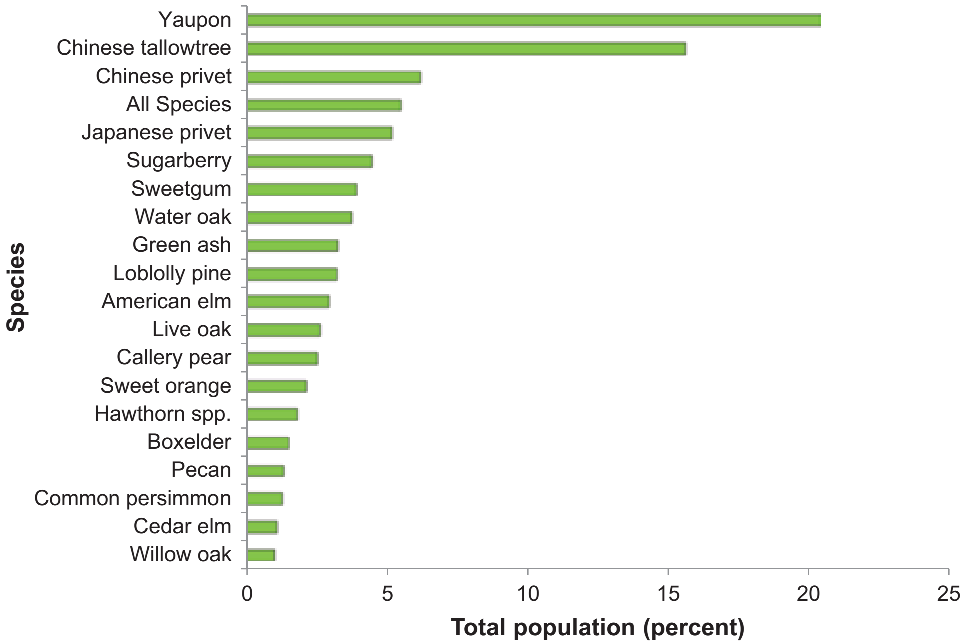

Figure 36—The 20 most common tree species as a percent of the total urban tree population, Houston, 2015.

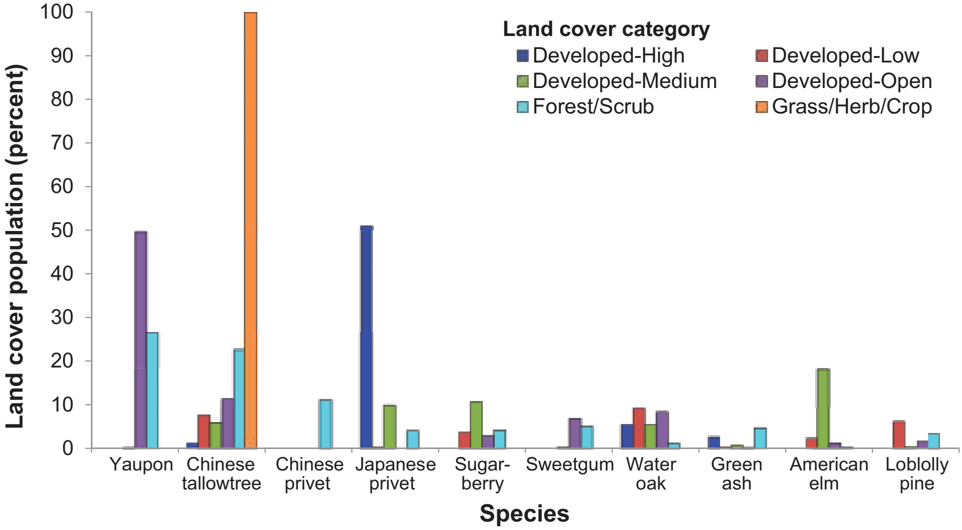

Figure 37—Proportion of the total tree population found in each land cover category for the 10 most common species, Houston, 2015. For example, yaupon comprises 49.7 percent of the tree population in the Developed–Open land cover.

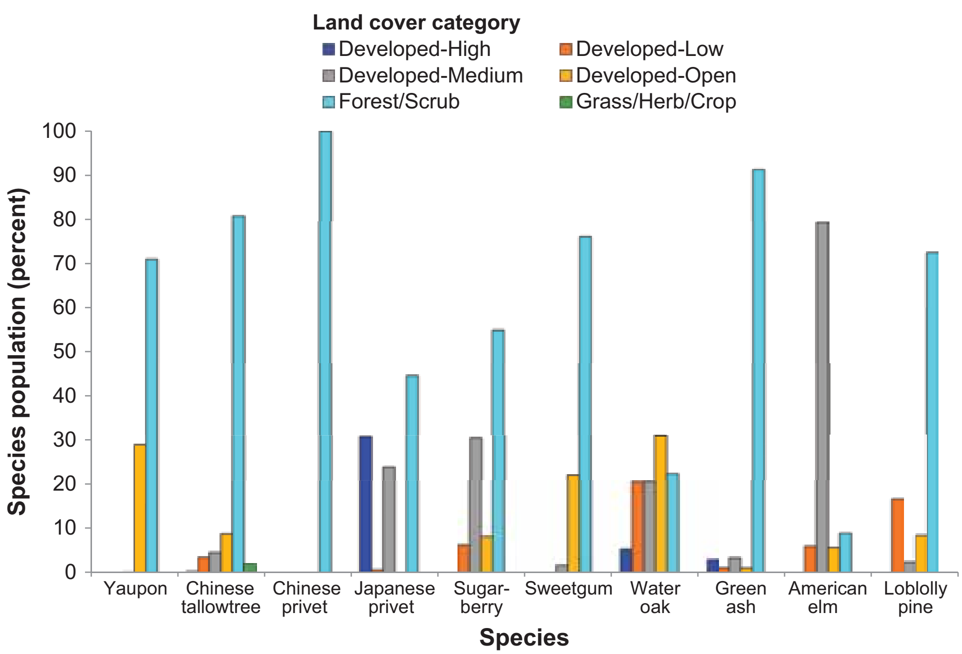

Figure 38—Distribution of each species' total citywide population among each land cover category for the 10 most common species, Houston, 2015. For example, 100 percent of Chinese privet in Houston is located in the Forest/Scrub land cover.

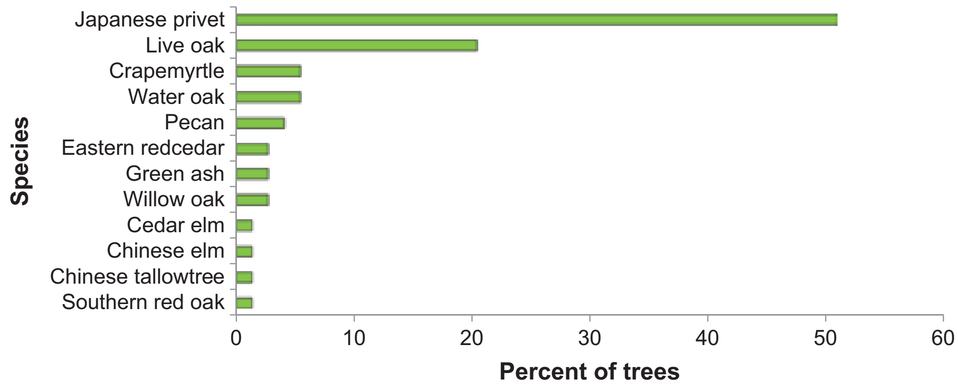

Figure 39—Percentage of trees in Developed–High land cover category, Houston, 2015.

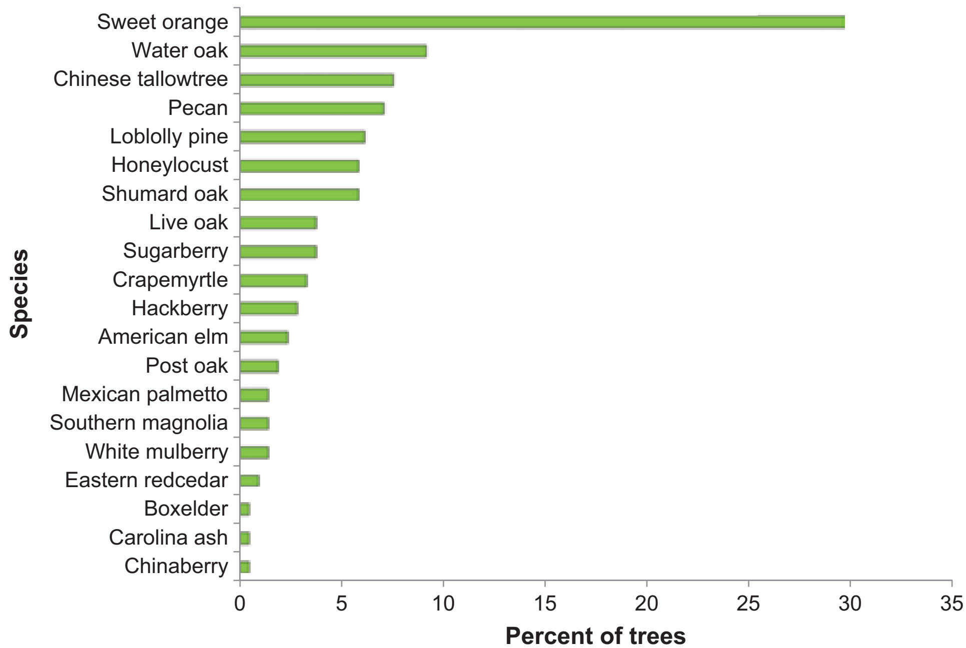

Figure 40—Percentage of trees in Developed–Low land cover category, Houston, 2015.

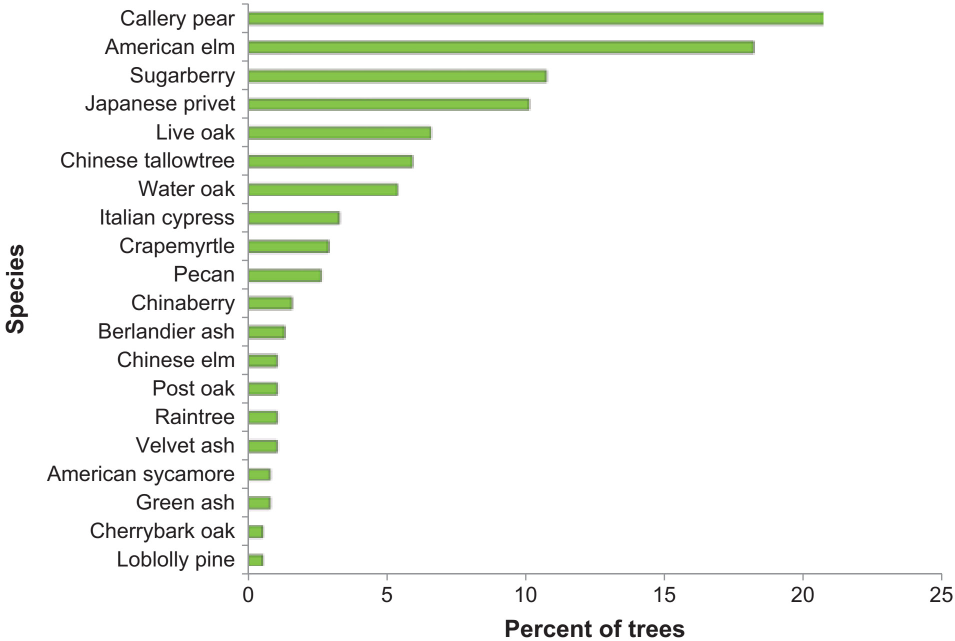

Figure 41—Percentage of trees in Developed–Medium land cover category, Houston, 2015.

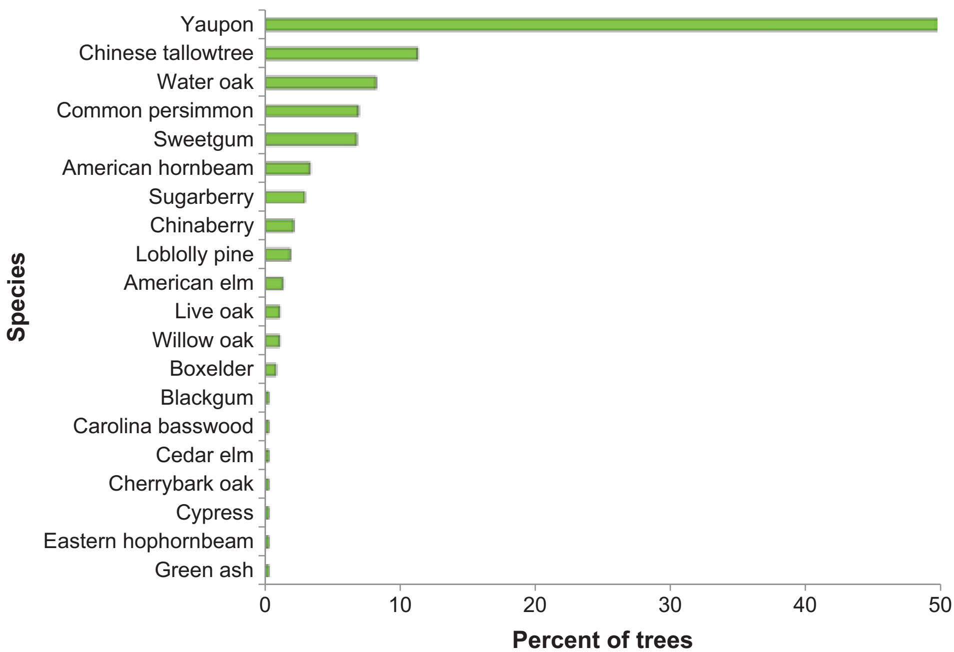

Figure 42—Percentage of trees in Developed–Open land cover category, Houston, 2015.

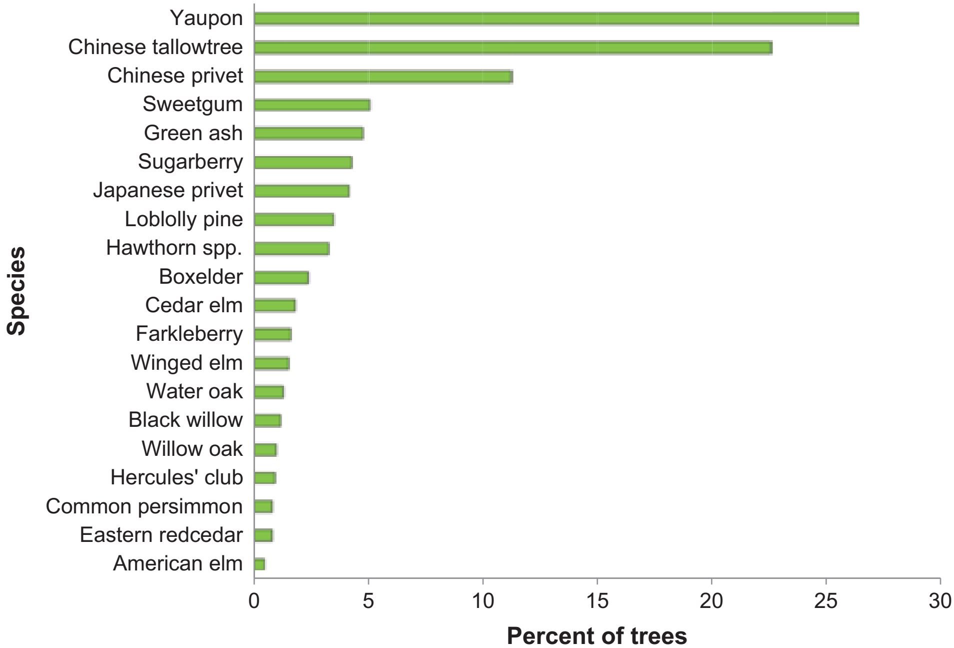

Figure 43—Percentage of trees in Forest/Scrub land cover category, Houston, 2015.

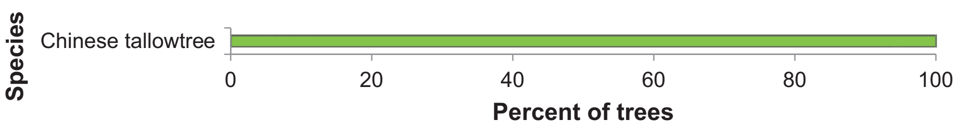

Figure 44—Percentage of trees in Grass/Herb/Crop land cover category, Houston, 2015.

APPENDIX 5—RELATIVE TREE EFFECTS

The urban forest in Houston provides benefits that include carbon storage, carbon sequestration, and air pollutant removal. These benefits vary across diameter classes (table 28). The relative value of tree benefits is calculated to show how carbon storage and sequestration, and air pollutant removal vary by tree size and equates to municipal carbon emissions, passenger automobile emissions, and household emissions.

Table 28—Average tree effects by tree diameter class, Houston, 2015

Diameter[a]	Carbon storage			Carbon sequestration			Pollution removal	
inches	*Lbs.*	*$*	*miles*[b]	*lbs/yr.*	*$/yr.*	*miles*[b]	*lbs/yr.*	*$/yr.*
2	4	0.29	17	1.7	0.12	7	0.04	0.18
4	25	1.69	101	3.5	0.23	14	0.07	0.29
6	53	3.52	212	7.3	0.48	29	0.16	0.69
8	114	7.59	457	11.5	0.77	46	0.25	1.05
10	197	13.09	788	19.2	1.28	77	0.36	1.50
12	341	22.71	1,367	23.8	1.58	95	0.41	1.74
14	470	31.27	1,883	29.9	1.99	120	0.45	1.90
16	593	39.46	2,376	34.6	2.30	139	0.58	2.45
18	635	42.22	2,541	39.5	2.62	158	0.57	2.39
20	1,045	69.53	4,186	64.3	4.28	257	0.89	3.76
22	1,142	75.97	4,573	60.2	4.01	241	0.83	3.52
24	1,253	83.38	5,019	64.8	4.31	260	1.04	4.38
26	2,054	136.67	8,227	97.8	6.51	392	1.23	5.18
28	2,431	161.72	9,735	124.7	8.30	499	1.55	6.55
30+	2,986	198.66	11,959	119.5	7.95	479	1.32	5.57

[a] Diameter classes are designated by their midpoint (e.g., 2 is actually 1 to 2.9 inches). Diameter measurements were taken at breast height (d.b.h.) or root collar (d.r.c.) for woodland species.

[b] Miles = number of automobile miles driven that produces emissions equivalent to tree effect.

<u>General tree information</u>:

Number of live trees sampled = 882

Number of species sampled, including Osage-orange for which only dead trees were observed = 63

Municipal carbon emissions are based on 2010 U.S. per capita carbon emissions (World Bank 2010). Per capita emissions were multiplied by city population to estimate total city carbon emissions.

Light duty vehicle emission rates (grams per mile) for carbon monoxide (CO), nitrogen oxides (NO_X), VOCs, particulate matter less than 10 microns (PM_{10}), SO_2 for 2010

(Heirigs and others 2004, U.S. Bureau of Transportation Statistics 2010), and CO_2 for 2011 (U.S. Environmental Protection Agency 2010) were multiplied by average miles driven per vehicle in 2011 (U.S. 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 Btu usage, and wood Btu usage per household in 2009 (U.S. Energy Information Administration 2013, 2014a).

CO_2, SO_2, and NO_X power plant emission per kWh are from Leonardo Academy 2011. CO emission per kWh assumes one-third of 1 percent of C emissions (U.S. Energy Information Administration 1994).

CO_2, NO_X, 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) (Leonardo Academy 2011).

CO_2 emissions per Btu of wood (U.S. Energy Information Administration 2014a).

CO, NO_X, and sulfur oxides (SO_X) emission per Btu based on total emissions and wood burning (tons) (British Columbia Ministry 2005, Georgia Forestry Commission 2009).

Total annual pollution removal per pollutant was contrasted with annual emissions per city, vehicle, and household to determine offset equivalents of urban forests versus city, vehicle, and household emissions.

The trees in Houston provide:

<u>Carbon storage equivalent to</u>:

Amount of carbon (C) emitted in region in 67 days, or
Annual C emissions from 1,446,000 automobiles, or
Annual C emissions from 592,500 single family homes

<u>Nitrogen dioxide removal equivalent to</u>:

Annual nitrogen dioxide emissions from 53,800 automobiles, or
Annual nitrogen dioxide emissions from 24,300 single family homes

<u>Sulfur dioxide removal equivalent to</u>:

Annual sulfur dioxide emissions from 373,000 automobiles, or
Annual sulfur dioxide emissions from 1,000 single family homes

<u>Annual carbon sequestration equivalent to</u>:

Amount of C emitted in region in 5 days, or
Annual C emissions from 98,900 automobiles, or
Annual C emissions from 40,500 single family homes

APPENDIX 6—TREE SPECIES STATISTICS BY LAND COVER

Table 29—Tree statistics by land cover and species, Houston, 2015

Land cover and species	Trees	Basal[a] area	Diameter[b] Average	Median
	number	*ft²/acre*	*inches*	
Developed–High				
Cedar elm	15,600	0.1	9.9	9.9
Chinese elm	15,600	0.1	10.5	10.5
Chinese tallowtree	15,600	0.2	12.1	12.1
Crapemyrtle	62,600	0.3	8.2	8.0
Eastern redcedar	31,300	0.1	6.6	6.6
Green ash	31,300	0.2	8.5	8.5
Japanese privet	584,400	0.3	2.4	2.3
Live oak	234,600	5.5	16.4	14.4
Pecan	46,900	0.2	7.5	6.4
Southern red oak	15,600	1.0	29.9	29.9
Water oak	62,600	0.8	12.8	12.4
Willow oak	31,300	0.6	16.1	16.1
Developed–Low				
American elm	62,000	1.2	15.1	11.8
Boxelder	12,400	0.3	19.5	19.5
Carolina ash	12,400	0.4	22.4	22.4
Chinaberry	12,400	0.0	7.0	7.0
Chinese tallowtree	198,500	3.0	12.7	13.3
Crapemyrtle	86,900	0.9	12.1	13.9
Date palm	12,400	0.4	22.6	22.6
Eastern redcedar	24,800	0.2	9.8	9.8
Green ash	12,400	0.6	25.8	25.8
Hackberry	74,400	0.8	11.1	9.5
Hardy orange	12,400	0.0	5.4	5.4
Honeylocust	153,800	0.0	1.1	1.1
Japanese privet	12,400	0.0	6.1	6.1
Live oak	99,300	2.7	15.2	13.4
Loblolly pine	161,300	2.2	12.9	10.6
Mexican palmetto	37,200	0.6	14.8	13.5
Pecan	186,100	2.3	12.8	12.9
Pinchot juniper	12,400	0.1	8.5	8.5
Post oak	49,600	1.7	21.6	21.8

continued

Table 29 (continued)—Tree statistics by land cover and species, Houston, 2015

Land cover and species	Trees	Basal[a] area	Diameter[b] Average	Median
	number	*ft²/acre*	*inches*	
Developed–Low (continued)				
Shumard oak	153,800	0.0	1.9	1.9
Southern magnolia	37,200	0.3	9.9	10.4
Southern red oak	12,400	1.1	30.5	30.5
Sugarberry	99,300	0.8	7.8	6.0
Sweet orange	781,400	0.6	3.1	3.5
Water oak	240,600	2.8	9.2	3.3
Water-elm	12,400	0.0	6.9	6.9
White ash	12,400	0.1	7.8	7.8
White mulberry	37,200	1.8	23.1	31.5
Willow oak	12,400	0.0	7.2	7.2
Developed–Medium				
American elm	819,500	0.7	3.4	2.9
American sycamore	35,500	0.9	19.7	14.9
Amur privet	11,800	0.0	5.3	5.3
Berlandier ash	59,100	0.8	14.6	14.0
Callery pear	931,400	0.6	3.3	3.5
Cherrybark oak	23,600	0.4	18.0	18.0
Chinaberry	70,900	0.5	10.6	10.0
Chinese elm	47,300	0.2	8.3	7.9
Chinese tallowtree	265,600	1.2	7.1	2.5
Common pear	11,800	0.0	5.1	5.1
Crapemyrtle	130,000	1.2	11.8	10.4
Green ash	35,500	1.6	29.5	31.5
Italian cypress	147,300	0.0	1.3	1.3
Japanese privet	453,900	0.3	3.3	3.6
Live oak	295,600	4.8	16.0	13.2
Loblolly pine	23,600	0.2	12.5	12.5
Longleaf pine	11,800	0.0	5.2	5.2
Mexican palmetto	11,800	0.2	18.4	18.4
Mexican sycamore	11,800	0.6	31.5	31.5
Pecan	118,200	1.5	14.4	11.7
Post oak	47,300	0.7	16.2	15.2
Raintree	47,300	0.3	10.9	10.1
Red mulberry	11,800	0.0	5.4	5.4
River birch	23,600	0.1	7.4	7.4
Shagbark hickory	23,600	0.9	26.0	26.0
Slippery elm	11,800	0.1	13.4	13.4

continued

Table 29 (continued)—Tree statistics by land cover and species, Houston, 2015

Land cover and species	Trees	Basal[a] area	Diameter[b] Average	Median
	number	*ft²/acre*	*inches*	
Developed–Medium (continued)				
Sugarberry	483,900	0.9	4.9	2.8
Sweetgum	23,600	0.4	17.8	17.8
Velvet ash	47,300	0.5	14.1	13.4
Water oak	241,900	2.5	9.6	1.8
White mulberry	11,800	0.0	5.3	5.3
Yaupon	11,800	0.1	9.3	9.3
Developed–Open				
American elm	58,700	1.1	12.1	8.7
American hornbeam	146,200	0.4	4.9	4.9
Blackgum	11,700	0.6	22.0	22.0
Boxelder	35,200	0.3	8.7	8.6
Carolina basswood	11,700	0.2	11.5	11.5
Cedar elm	11,700	0.1	6.8	6.8
Cherrybark oak	11,700	0.1	7.9	7.9
Chinaberry	93,900	1.0	9.5	8.8
Chinese tallowtree	497,400	0.5	2.8	2.6
Common persimmon	304,200	0.2	1.9	1.8
Cypress	11,700	0.3	15.0	15.0
Eastern hophornbeam	11,700	0.0	5.3	5.3
Green ash	11,700	1.3	19.5	19.5
Live oak	47,000	0.7	11.3	9.7
Loblolly pine	82,200	3.1	13.7	10.0
Pecan	11,700	0.8	25.1	25.1
Post oak	11,700	0.5	20.5	20.5
Southern magnolia	11,700	0.0	5.9	5.9
Sugarberry	129,100	1.0	8.3	7.5
Sweetgum	298,900	2.1	6.2	5.7
Water oak	362,900	1.5	4.0	3.8
Willow oak	47,000	1.3	12.7	11.4
Yaupon	2,193,500	0.6	1.6	1.6
Forest/Scrub				
American elm	92,000	0.8	8.8	8.5
American hornbeam	39,400	0.2	7.2	7.2
Black willow	236,700	1.5	7.4	7.6
Boxelder	485,400	2.4	5.8	3.8
Cedar elm	367,000	0.7	2.4	2.6

continued

Table 29 (continued)—Tree statistics by land cover and species, Houston, 2015

Land cover and species	Trees	Basal[a] area	Diameter[b]	
			Average	Median
	number	*ft²/acre*	*inches*	
Forest/Scrub (continued)				
Cherrybark oak	39,400	1.5	16.4	16.1
Chinaberry	26,300	1.2	19.5	19.5
Chinese privet	2,293,100	1.5	2.3	2.2
Chinese tallowtree	4,615,800	9.1	3.3	2.2
Common persimmon	163,800	0.0	1.1	1.1
Eastern redcedar	163,800	0.2	3.8	3.8
Farkleberry	327,600	0.0	1.2	1.2
Green ash	971,900	7.8	7.3	6.5
Hackberry	13,100	0.2	13.2	13.2
Hawthorn spp.	668,300	0.6	2.7	3.0
Hercules' club	190,100	0.5	4.8	4.8
Japanese privet	846,400	4.1	5.3	2.2
Loblolly pine	708,900	7.7	7.3	5.4
Overcup oak	13,100	0.5	18.9	18.9
Pecan	13,100	0.1	7.4	7.4
Post oak	39,400	1.6	17.5	12.3
Shumard oak	13,100	0.5	19.7	19.7
Sugarberry	872,700	5.3	5.1	3.3
Sweetgum	1,030,500	6.1	5.8	5.0
Water hickory	52,600	0.3	7.1	7.0
Water oak	263,000	4.2	11.3	11.8
White ash	13,100	0.2	13.1	13.1
Willow oak	197,200	4.7	12.1	11.3
Winged elm	308,400	1.1	5.5	4.3
Yaupon	5,405,100	1.5	1.6	1.5
Grass/Herb/Crop				
Chinese tallowtree	99,800	0.0	1.0	1.0

[a] Basal area is the cross-sectional area of the tree stems measured at the diameter. This is estimated for live and dead trees.

[b] Diameter measurements were taken at breast height (d.b.h.) or root collar (d.r.c.) for woodland species. Median and average diameter measurements are estimated for live trees only.

APPENDIX 7—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:

1. **T**emperature reduction and other microclimatic effects
2. **R**emoval of air pollutants
3. **E**mission of volatile organic compounds (VOC) and tree maintenance emissions
4. **E**nergy conservation on buildings and consequent power plant emissions

The cumulative and interactive effects of trees on climate, pollution removal, 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	Increases pollution removal
Sustain existing tree cover	Maintains 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	Reduces long-term pollutant emissions from planting and removal
Use low maintenance trees	Reduces pollutant emissions from maintenance activities
Reduce fossil fuel use in maintaining vegetation	Reduces pollutant emissions
Plant trees in energy conserving locations	Reduces pollutant emissions from power plants
Plant trees to shade parked cars	Reduces vehicular VOC emissions
Supply ample water to vegetation	Enhances pollution removal and temperature reduction
Plant trees in polluted or heavily populated areas	Maximizes tree air quality benefits
Avoid pollutant-sensitive species	Improves tree health
Utilize evergreen trees for particulate matter	Provides year-round removal of particles

APPENDIX 8—DAMAGE TYPE AND MAINTENANCE OR SITE ISSUE STATISTICS

Table 30—Percent of live trees identified with damage or maintenance or site issues, Houston, 2015

Species	Sample	Damage variable						
		Trunk bark inclusion	Root/ stem girdling	Overhead wires	Topping/ pruning	Sidewalk-root conflict	Excess mulch	Improper planting
	n	- - - - - - - - - -	- - - - - -	- - - - -	*percent*	- - - - -	- - - - - -	- - - - - - - - - -
American elm	29	2.3	0.0	3.4	3.4	0.0	0.0	0.0
American hornbeam	4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
American sycamore	3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Amur privet	1	0.0	0.0	0.0	100.0	0.0	0.0	0.0
Berlandier ash	5	100.0	0.0	0.0	80.0	0.0	0.0	0.0
Black willow	18	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Blackgum	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Boxelder	18	0.0	2.5	0.0	0.0	0.0	0.0	0.0
Callery pear	10	97.5	0.0	0.0	96.2	1.3	0.0	0.0
Carolina ash	1	100.0	0.0	0.0	100.0	0.0	0.0	0.0
Carolina basswood	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cedar elm	7	44.5	4.0	0.0	0.0	4.0	0.0	0.0
Cherrybark oak	6	0.0	0.0	15.8	31.6	0.0	0.0	0.0
Chinaberry	17	5.8	5.8	34.6	23.2	5.8	0.0	0.0
Chinese elm	5	0.0	0.0	0.0	0.0	0.0	75.1	0.0
Chinese privet	14	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Chinese tallowtree	136	0.0	0.0	0.4	0.4	0.5	0.0	0.0
Common pear	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Common persimmon	4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Crapemyrtle	22	0.0	0.0	0.0	18.3	4.2	0.0	0.0
Cypress	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Date palm	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Eastern hophornbeam	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Eastern redcedar	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Farkleberry	5	0.0	0.0	0.0	14.2	0.0	0.0	0.0
Green ash	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hackberry	58	9.1	0.0	0.0	2.3	0.0	0.0	0.0
Hardy orange	7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hawthorn spp.	1	100.0	0.0	0.0	0.0	100.0	0.0	0.0

continued

Table 30 (continued)—Percent of live trees identified with damage or maintenance or site issues, Houston, 2015

Species	Sample	Damage variable						
		Trunk bark inclusion	Root/ stem girdling	Overhead wires	Topping/ pruning	Sidewalk-root conflict	Excess mulch	Improper planting
	n	- - - - - - - - - - -	- - - - - - -	- - - - - - -	*percent*	- - - - - - -	- - - - - - -	- - - - - - -
Hercules' club	5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Honeylocust	3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Italian cypress	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Japanese privet	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Live oak	38	0.0	0.0	0.0	0.0	31.4	0.0	0.0
Loblolly pine	52	16.3	0.0	3.6	20.4	31.6	1.7	3.5
Longleaf pine	53	0.0	0.0	0.0	0.0	2.5	2.5	0.0
Mexican palmetto	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mexican sycamore	4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Overcup oak	1	0.0	0.0	100.0	100.0	100.0	0.0	0.0
Pecan	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pinchot juniper	30	32.3	0.0	9.7	19.8	6.6	3.3	0.0
Post oak	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Raintree	12	0.0	0.0	8.0	16.0	0.0	0.0	0.0
Red mulberry	4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
River birch	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Shagbark hickory	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Shumard oak	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Slippery elm	1	0.0	100.0	0.0	0.0	100.0	0.0	0.0
Southern magnolia	4	50.7	0.0	25.3	25.3	25.3	0.0	0.0
Southern red oak	2	0.0	0.0	0.0	0.0	55.8	0.0	0.0
Sugarberry	69	28.4	0.0	20.1	8.3	3.0	0.0	0.7
Sweet orange	6	0.0	0.0	1.6	0.0	0.0	0.0	0.0
Sweetgum	60	0.0	0.0	0.0	0.9	0.0	0.0	0.0
Velvet ash	4	100.0	0.0	0.0	100.0	100.0	0.0	0.0
Water hickory	4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Water oak	49	4.3	0.0	9.5	5.2	9.5	0.0	0.0
Water-elm	1	100.0	0.0	0.0	0.0	0.0	0.0	0.0
White ash	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
White mulberry	4	0.0	0.0	24.1	0.0	0.0	0.0	0.0
Willow oak	22	0.0	0.0	0.0	5.4	14.9	4.3	0.0
Winged elm	12	4.3	0.0	0.0	0.0	0.0	0.0	0.0
Yaupon	49	0.0	0.0	0.0	0.0	0.2	0.0	0.0
All trees	882	6.4	0.2	2.2	5.2	3.8	0.3	0.1

This table includes only the live tree population in Houston. Osage-orange is not included as it is the only the species for which only standing dead trees were sampled.

APPENDIX 9—POTENTIAL INSECT AND DISEASE IMPACTS

We evaluated 20 insects and diseases, along with their tree hosts in the Houston area, to quantify their potential impact on the urban forest. The number of trees at risk (table 31) reflects only the known host tree species that could experience mortality due to the pest.

Pest range maps (U.S. Forest Service 2013, 2014a; Worrall 2007) were used to determine the proximity of each pest to the area. For Houston, proximity was classified for insects

Table 31—Selected insect or disease threats and the potential risk to Houston trees, 2015

Code	Scientific name	Common name	Trees at risk	Compensatory value
			number	*$ millions*
AL	*Phyllocnistis populiella*	Aspen leafminer	237,000	63
ALB	*Anoplophora glabripennis*	Asian longhorned beetle	3,701,000	2,122
BBD	*Cryptococcus fagisuga*	Beech bark disease	0	0
BC	*Sirococcus clavigignenti-juglandacearum*	Butternut canker	0	0
CB	*Cryphonectria parasitica*	Chestnut blight	0	0
DA	*Discula destructive*	Dogwood anthracnose	0	0
DED	*Ophiostoma novo-ulmi*	Dutch elm disease	1,747,000	616
DFB	*Dendroctonus pseudotsugae*	Douglas-fir beetle	0	0
EAB	*Agrilus planipennis*	Emerald ash borer	1,207,000	1,435
FR	*Cronartium fusiforme*	Fusiform rust	0	0
GSOB	*Agrilus auroguttatus*	Goldspotted oak borer	0	0
GM	*Lymantria dispar*	Gypsy moth	5,866,000	7,537
LAT	*Choristoneura conflictana*	Large aspen tortrix	260,000	82
LWD	*Raffaelea lauricola*	Laurel wilt	0	0
OW	*Ceratocystis fagacearum*	Oak wilt	2,566,000	6,683
PSB	*Tomicus piniperda*	Pine shoot beetle	988,000	912
SOD	*Phytophthora ramorum*	Sudden oak death	28,000	323
SPB	*Dendroctonus frontalis*	Southern pine beetle	988,000	912
SW	*Sirex noctilio*	Sirex woodwasp	988,000	912
TCD	*Pityophthorus juglandis* and *Geosmithia* spp.	Thousand canker disease	0	0

and diseases in Harris, Fort Bend, and Montgomery Counties; within 250 miles of any of these three counties; between 250 and 750 miles of the counties; or greater than 750 miles away. Since there are no pest range maps for Dutch elm disease and chestnut blight, the ranges of these pests were based on known occurrence and the known host range, respectively (U.S. Forest Service 2013, 2014a; Worrall 2007).

Proximity data for 11 insects and diseases, along with the numbers of trees potentially affected and their compensatory values, are illustrated in fig. 45.

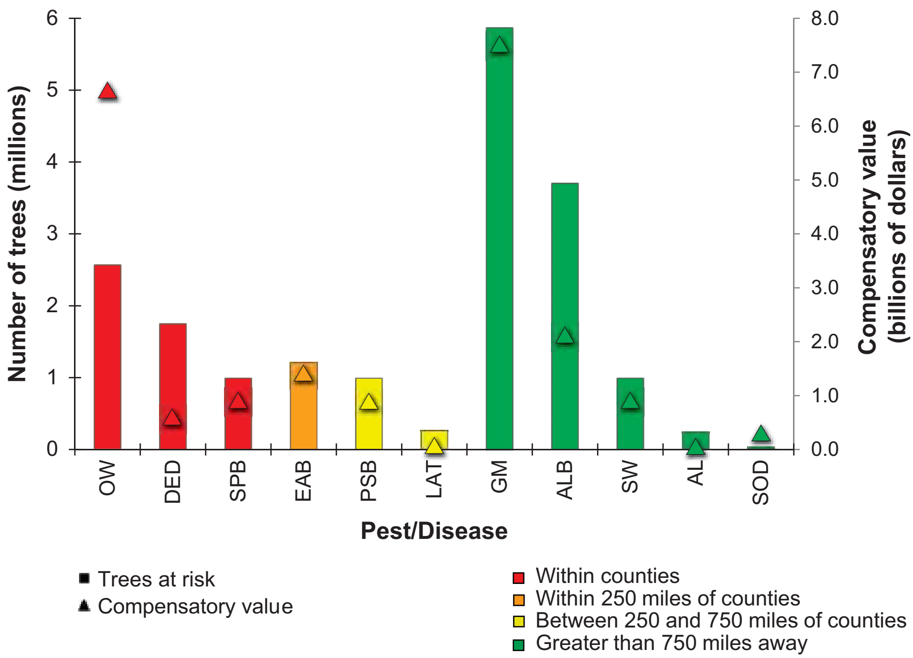

Figure 45—Number of trees at risk of insect and disease and the associated compensatory value, Houston, 2015. This figure does not include the pests and diseases that were not a threat to any of the species sampled in the city. For a complete list of the pests and diseases assessed, see table 31.

Based on the host tree species for each pest and the current range of the pest, it is possible to estimate the risk of attack by one of these insects or diseases for each tree species sampled in Houston. In table 32, species risk is designated as one of the following:

- Red—tree species is at risk to at least one pest within counties
- Orange—tree species has no risk to pests within counties, but has a risk to at least one pest within 250 miles from the counties
- Yellow—tree species has no risk to pests within 250 miles of counties, but has a risk to at least one pest that is 250 to 750 miles from the counties
- Green—tree species has no risk to pests within 750 miles of counties, but has a risk to at least one pest that is greater than 750 miles from the counties.

Tree species that were sampled in Houston, but are not listed in this matrix, are not known to be hosts to any of the 20 insects and diseases evaluated. This table also excludes the pests and diseases that were not a threat to any of the species sampled in the city. For a complete list of the pests and diseases assessed, see table 31. Tree species groups with the greatest risk to existing pest infestations in Houston are pines, oaks, and elms.

The majority of observed trees were in maintained areas such as lawns, rights-of-way, and parks.

Table 32—Potential insect and disease risk for tree species, Houston, 2015

Spp. risk[a]	Risk weight[b]	Common name	Pests[c]										
			OW	DED	SPB	EAB	PSB	LAT	GM	ALB	SW	AL	SOD
Red	7	Loblolly pine			Red		Yellow				Green		
Red	7	Longleaf pine			Red		Yellow				Green		
Red	6	Southern red oak	Red						Green				Green
Red	5	Water oak	Red						Green				
Red	5	American elm		Red						Green			
Red	5	Live oak	Red						Green				
Red	5	Cedar elm		Red						Green			
Red	5	Winged elm		Red						Green			
Red	5	Willow oak	Red						Green				
Red	5	Shumard oak	Red						Green				
Red	5	Post oak	Red						Green				
Red	5	Cherrybark oak	Red						Green				
Red	5	Overcup oak	Red						Green				
Red	5	Slippery elm		Red						Green			
Orange	4	Green ash				Orange				Green			
Orange	3	Berlandier ash				Orange							
Orange	3	Velvet ash				Orange							
Orange	3	White ash				Orange							
Orange	3	Carolina ash				Orange							
Yellow	5	Black willow						Yellow	Green	Green		Green	
Yellow	4	River birch						Yellow	Green	Green			
Green	2	**Chinese elm**[d]							Green	Green			
Green	1	Sweetgum							Green				
Green	1	**Callery pear**[d]							Green				
Green	1	Hawthorn spp.							Green				
Green	1	Boxelder								Green			
Green	1	American sycamore								Green			
Green	1	Eastern hophornbeam							Green				
Green	1	Carolina basswood							Green				

[a] Species risk: Red indicates that the tree species is at risk to at least one pest within Harris County, Fort Bend County, or Montgomery County. Orange indicates that the tree species has no risk to pests within Harris County, Fort Bend County, or Montgomery County, but has a risk to at least one pest within 250 miles of the county. Yellow indicates that the tree species has no risk to pests within 250 miles of Harris County, Fort Bend County, or Montgomery County, but has a risk to at least one pest that is 250 to 750 miles from the county. Green indicates that the tree species has no risk to pests within 750 miles of Harris County, Fort Bend County, or Montgomery County, but has a risk to at least one pest that is greater than 750 miles from the county.

[b] Risk weight: Numerical scoring system based on sum of points assigned to pest risks for species. Each pest that could attack tree species is scored as 4 points if red, 3 points if orange, 2 points if yellow, and 1 point if green.

[c] Pest color codes: Red indicates pest is within Harris County, Fort Bend County, or Montgomery County. Orange indicates pest is within 250 miles of Harris County, Fort Bend County, or Montgomery County. Yellow indicates pest is within 750 miles of Harris County, Fort Bend County, or Montgomery County. Green indicates pest is outside of these ranges.

[d] Species in bold text indicate that species is on the local invasive species list.

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An analysis of the urban forest in Houston, Texas, reveals that this area has an estimated 33.3 million live trees with tree canopy that covers 18.4 percent of the city. Roughly 19.2 million of the city's trees are located on private lands. The most common tree species are yaupon, Chinese tallowtree, Chinese privet, Japanese privet, and sugarberry. Trees in Houston currently store about 2.0 million tons of carbon (7.5 million tons of carbon dioxide [CO_2]); valued at $272 million. In addition, these trees remove about 126,000 tons of carbon per year (462,000 tons CO_2 per year) ($16.8 million per year) and about 2,400 tons of air pollution per year ($20.4 million per year). Houston's urban forest is also estimated to provide 126 million cubic feet of net wood volume and to reduce annual residential energy costs by $54.6 million per year. Reduction in runoff provided by the trees in Houston is estimated at 173 million cubic feet per year with an associated value of $7.8 million per year. The compensatory value of the trees is estimated at $16.3 billion. The information presented in this report can be used to improve and augment support for urban forest management programs and to inform policy and planning to improve environmental quality and human health in Houston. The analysis also provides a basis for monitoring changes in the urban forest over time.

Keywords: Air pollution removal, carbon sequestration, ecosystem services, tree value, urban forestry inventory**.**

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