i-Tree
Ecosystem Analysis

Roanoke

Urban Forest Effects and Values
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Acknowledgements

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Disclaimer:

Information about urban forest structure, function, and value in this report includes estimates based on statistical sampling, which has an associated margin of error. Therefore, all results should be interpreted with caution. To facilitate reading, statistical error rates are not reported for all forest attributes and model outputs in the main report.

Summary

Trees provide a long list of ecologic and economic benefits that improve environmental conditions and human well-being. Trees in urban settings are especially important. Understanding an urban forest's structure, function, and value can promote management decisions that will improve human health and environmental quality. An assessment of the urban forest in the City of Roanoke, Virginia was conducted during 2010 using i-Tree Eco sampling protocols and analysis tools. Data from 171 field plots located throughout Roanoke in three land-use classes (Forested Residential Use, Forested Mixed Use, and Urbanized Mixed Use) were analyzed using the Urban Forest Effects (UFORE) model developed by the U.S. Forest Service, Northern Research Station.

<u>Key findings</u>

- Number of trees: 2,586,202 (SE: 299,541)
- Tree canopy cover: 25% (SE: 0.46)
- Most common tree species: tree-of-heaven, flowering dogwood, and black cherry
- Percentage of trees less than 6" trunk diameter: 66%
- Carbon storage: 342,024 tons (valued at $6.3 million)
- Annual gross carbon sequestration: 20,943 tons (valued at $386 thousand)
- Annual avoided carbon emissions: 719 tons (valued at $13,241)
- Annual pollution removal: 304 tons (valued at $2.27 million)
- Annual building energy savings: $511 thousand
- Structural value of trees: $2.17 billion (SE: 2.17 million)

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

Carbon storage: the amount of carbon bound up in the above-ground and below-ground parts of woody vegetation

Carbon sequestration: the removal of carbon dioxide from the air by plants through photosynthesis

Structural value: value based on the physical resource itself (e.g., the cost of having to replace a tree with a similar tree)

Monetary values ($) reported in US Dollar throughout report except where noted

SE: standard error of the total

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Assessment Methods

UFORE Model and Field Measurements

UFORE is designed to use standardized field data from randomly located plots and local hourly air pollution and meteorological data to quantify urban forest structure (e.g., species composition, tree health, leaf area, etc.) and its numerous effects[5], including:

- Amount of pollution removed hourly by the urban forest and its associated percent air quality improvement throughout a year. Pollution removal is calculated for ozone (O_3), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), and particulate matter <10 microns (PM_{10}).
- Total carbon stored and net carbon annually sequestered by the urban forest.
- Effects of trees on building energy use and consequent effects on carbon dioxide emissions from power plants.
- Structural value of the forest as well as the value for air pollution removal and carbon storage and sequestration.
- Potential impact of infestations by Asian longhorned beetle, emerald ash borer, gypsy moth, and Dutch elm disease.

In the City of Roanoke, 171 one-tenth-acre plots were sampled using a stratified random sampling method across four land use types: commercial (14 plots), industrial (40 plots), residential (83), and underdeveloped (34 plots). Plots were assigned proportionate to tree canopy cover and land area within each stratum based on existing canopy data and land use zoning. Plots on both public and private property were assessed. All field data were collected during the 2010 leaf-on season to properly assess tree canopies. At each field plot, two to four crew members collected data on ground and tree cover, individual tree attributes of species, stem diameter, height, crown width, crown canopy missing and dieback, and distance and direction to residential buildings[11].

To calculate current **carbon storage**, biomass for each tree was calculated using equations from the literature and measured tree data. Open-grown, maintained trees tend to have less biomass than predicted by forest-derived biomass equations[12]. To adjust for this difference, biomass results for open-grown urban trees were multiplied by 0.8. No adjustment was made for trees found in natural stand conditions. Tree dry-weight biomass was converted to stored carbon by multiplying by 0.5.

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

Air pollution removal estimates were derived from calculated hourly tree-canopy resistances for ozone, sulfur dioxide, and nitrogen dioxide based on a hybrid of big-leaf and multi-layer canopy deposition models[13,14]. As the removal of carbon monoxide and particulate matter by vegetation is not directly related to transpiration, removal rates (deposition velocities) for these pollutants were based on average measured values from the literature[15,16] that were adjusted depending on leaf phenology and leaf area. Particulate removal incorporated a 50 percent re-suspension rate of particles back to the atmosphere[17]. Recent updates (2011) to air quality modeling are based on improved leaf area index simulations, weather and pollution processing and interpolation, and updated pollutant monetary values[27,28,29].

Seasonal effects of trees on **residential building energy use** were calculated based on procedures described in the literature[4] using distance and direction of trees from residential structures, tree height, and tree condition data.

Structural values were based on valuation procedures of the Council of Tree and Landscape Appraisers[8], which uses tree species, diameter, condition, and location information[18].

For modeling and analysis of urban forest structure, function, and value, Roanoke's human population was set at 97,032 as estimated by the U.S. Census Bureau in 2010 (http://quickfacts.census.gov/qfd/states/51/5168000.html).

Structure of Roanoke's Urban Forest

Tree Characteristics of the Urban Forest

The urban forest of Roanoke comprises about 2.6 million trees with a tree canopy cover of about 27 percent (see Appendix III for comparable values from other cities). The three most common tree species are tree-of-heaven (~11 percent), flowering dogwood (~9 percent), and black cherry (~8 percent) as shown in Figure 1. There were 106 unique taxa of woody plants catalogued in the field survey. With the exception of the top three species mentioned above (along with Virginia pine), all other species have relative abundance less than 5 percent – a positive indication of species diversity in the forest. A complete listing of tree abundance by species and land use is provided in Appendix I. The overall tree density in Roanoke averages about 95 trees per acre, which is very high relative to other localities along the East Coast (Appendix III). Among the land use strata, the highest tree densities occur in Underdeveloped lands followed by Residential lands and Commercial lands (Fig. 2). Trees that have diameters less than 6-inches constitute about 66 percent of the tree population (Fig. 3), which suggests that there are plentiful young trees to help sustain forest cover into the future.

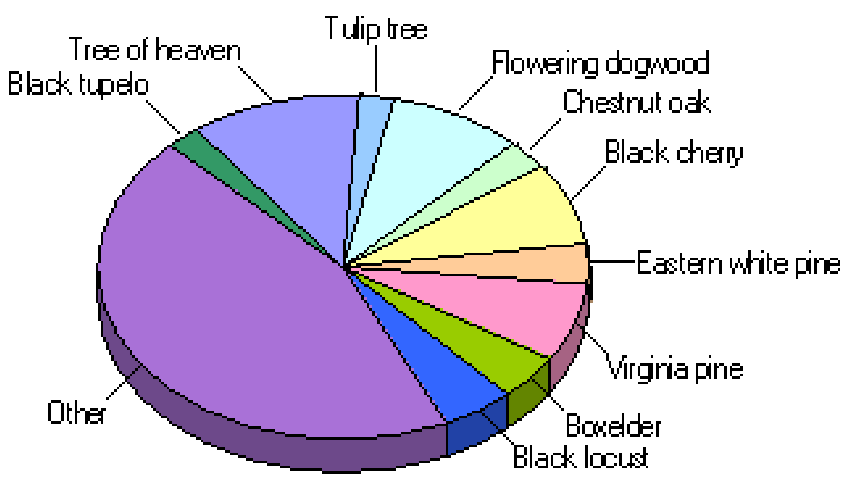

Figure 1. Tree species composition (percent of total) in City of Roanoke

Urban forests are composed of a mix of native and exotic tree species. Thus, urban forests often have higher species diversity than surrounding native landscapes. High species diversity helps minimize forest vulnerability to species-specific pests and disorders, but may also pose a risk to forest health if exotic species are invasive plants that can potentially out-compete and displace native species. In Roanoke, about 74 percent of the trees are species native to North America, while 73 percent are native to the state (Fig. 4). Species exotic to Virginia make up 26 percent of the population. Most of Roanoke's exotic tree species are indigenous to Asia (~19 percent of the species).

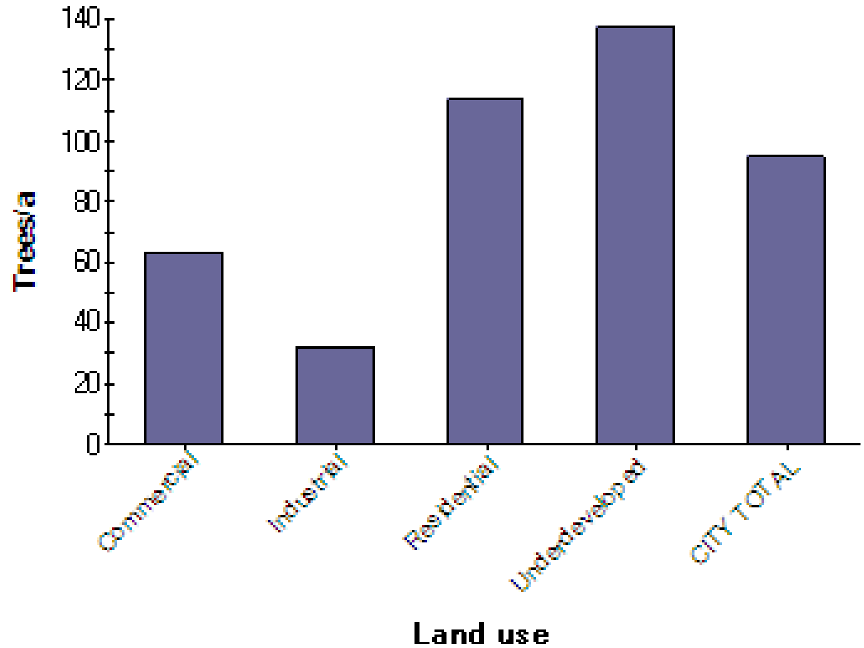

Figure 2. Trees per acre (a) in City of Roanoke by land use

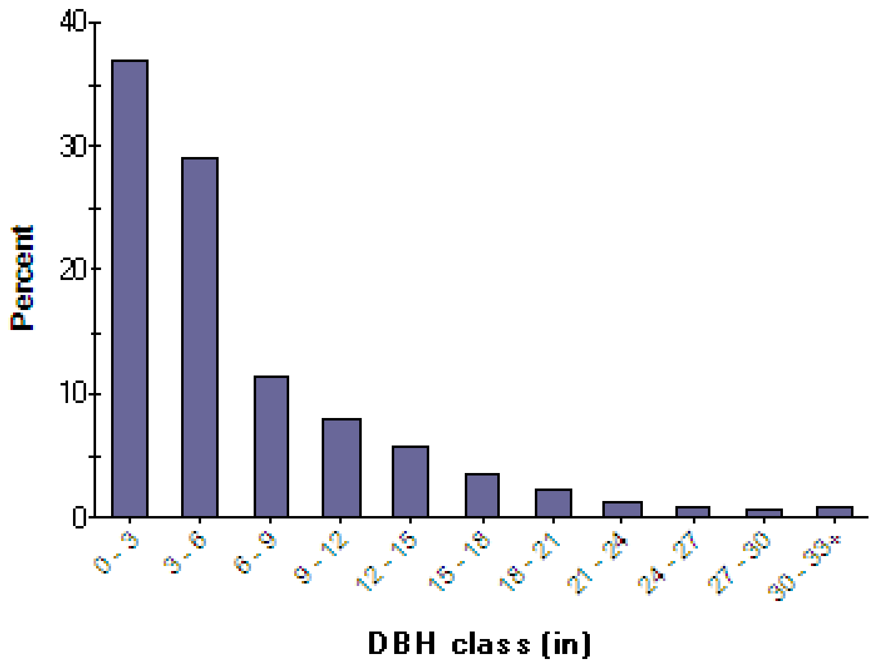

Figure 3. Trunk diameter distribution (DBH=stem diameter at 4.5 feet above ground line) of trees in City of Roanoke.

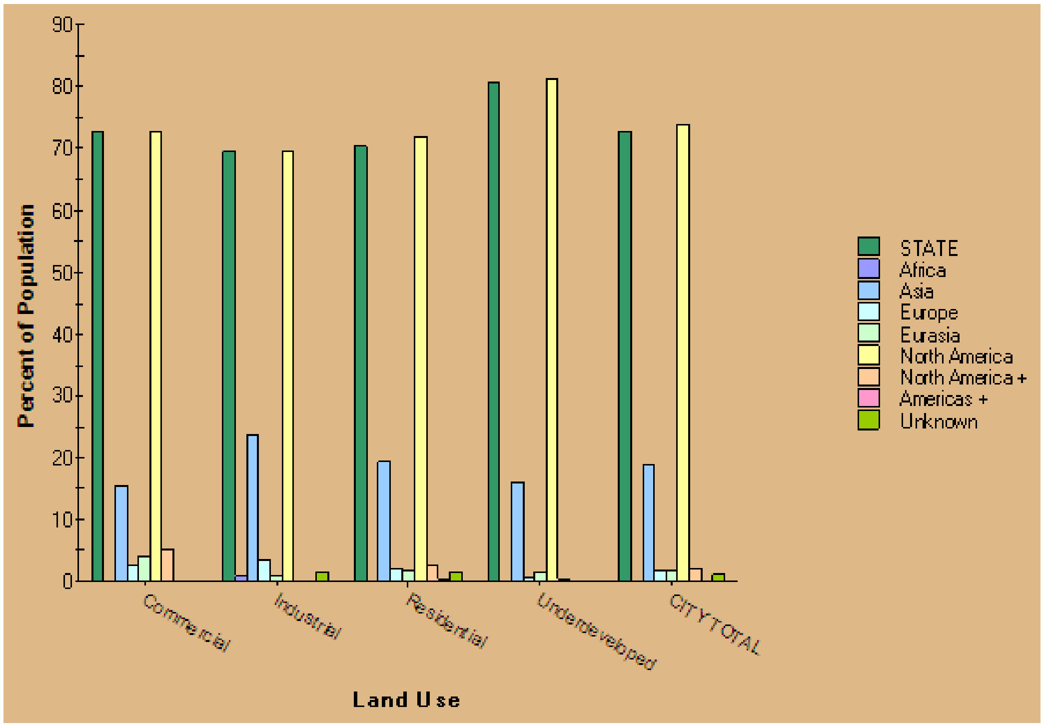

Figure 4. Species composition of live trees in City of Roanoke by geographic origin

"North America +" = native to North America and at least one other continent except South America

Urban Forest Cover and Leaf Area

Tree canopy covers about 25 percent of Roanoke's land area. Many tree benefits are directly proportional to the amount of healthy leaf surface area. In Roanoke, the three most dominant tree species in terms of leaf area are tulip-poplar, black walnut, and black cherry (Table 1). No single species accounts for more than 10 percent of total leaf area. Importance Value (IV) is a metric that documents species dominance by summing relative abundance and relative leaf area for each tree species. An IV over 10 may indicate that an urban forest is over-reliant on a particular species for structural and functional benefits, depending on the local ecosystem. Roanoke has five species with an IV exceeding 10. The most important species is tree-of-heaven with an IV of 17.7. Roanoke's ten most important species are listed in Table 1 below.

The two most dominant ground cover types in Roanoke are grass (37 percent) and duff/mulch (22 percent) as shown in Figure 5. The three impervious ground cover classes (Building, Cement, and Tar) make up 28 percent of total ground cover. Ground space permissible for tree planting (not covered by impervious surface and free of overhead obstructions such as existing tree canopy and utility lines) exists on about 27 percent of the land area (data not shown), which suggests moderate potential for increasing Roanoke's tree canopy cover.

Table 1. Ten most important tree species in City of Roanoke. Importance Value (IV) is the sum of relative abundance and relative leaf area.

Species Name	*Percent of Population*	*Percent of Leaf Area*	*Importance Value (IV)*
Tree of heaven	11.4	6.3	17.7
Black cherry	7.6	6.4	14.1
Flowering dogwood	9.0	3.8	12.8
Virginia pine	7.3	4.8	12.1
Tulip-poplar	2.3	7.8	10.1
Black walnut	1.8	7.7	9.4
Eastern white pine	3.7	5.3	9.0
Chestnut oak	2.9	4.8	7.7
Boxelder	4.3	3.3	7.6
Black locust	4.8	2.7	7.5

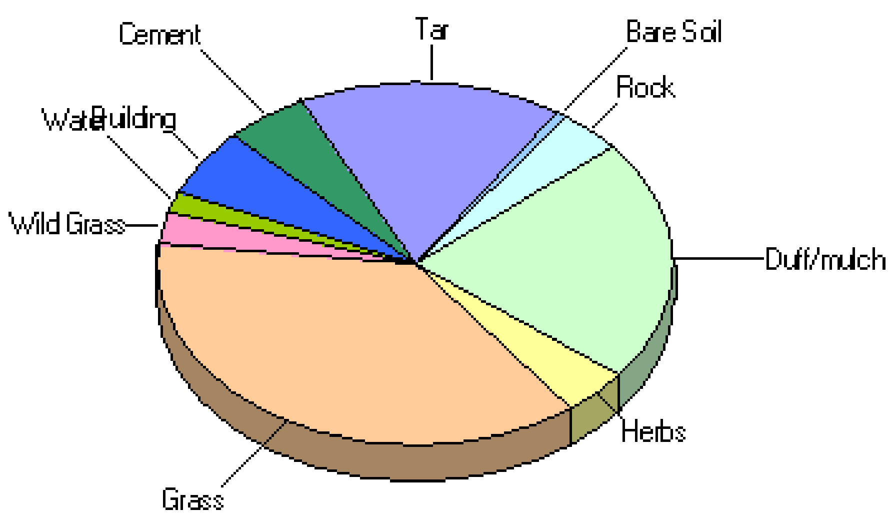

Figure 5. Ground cover composition (percent of total) in City of Roanoke

Structural and Functional Values of Roanoke's Urban Forest

Overview of Urban Forest Values

Urban forests have monetary value as structural assets much like any other infrastructure found in a municipality. This value is commonly calculated based on the cost that would be incurred to replace existing trees with trees of similar type and size. In addition, the carbon stored in woody tree parts has structural value as a carbon offset resource. Urban forests also have monetary value as functional assets based on the ecosystem services that they provide. These services (carbon sequestration, air pollution removal, and energy conservation) are rendered through tree interactions with the natural and built environment and may have positive or negative value depending on the nature of these interactions.

The structural and functional values of an urban forest tend to increase with an increase in the number and size of healthy trees[6]. However, inappropriate species selection, improper tree placement, and tree neglect can diminish both structural and functional values.

The structural value of Roanoke's urban forest exceeds $2 billion. The most valuable species in Roanoke's urban forest is eastern white pine at nearly $168 million (Fig. 6). The ten most valuable species alone have a combined value of over $1.2 billion. A summary of annual functional values are shown below and summarized in the subsequent sections of this report.

<u>Structural values of trees in Roanoke's urban forest:</u>

- Structural value: $2.17 billion
- Carbon storage: $6.30 million

<u>Functional values of trees in Roanoke's urban forest (annual basis):</u>

- Carbon sequestration (removal): $386 thousand
- Pollution removal: $2.27 million
- Energy savings and carbon emission reductions: $524 thousand

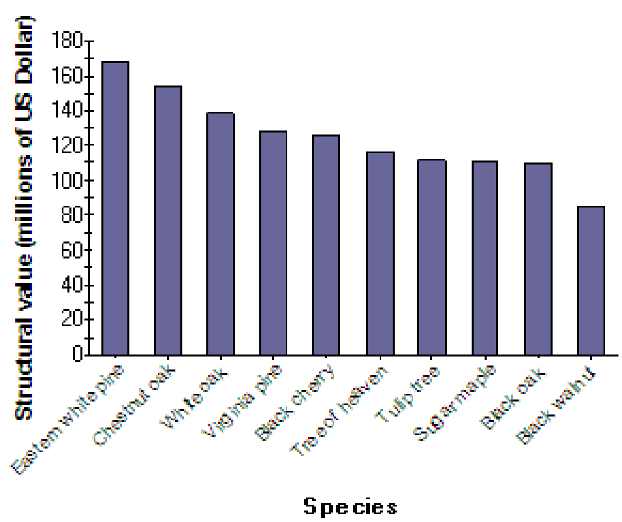

Figure 6. Structural value of the ten most valuable tree species in City of Charlottesville

Carbon Storage and Sequestration

Climate change is an issue of global concern. Urban trees can help mitigate climate change by sequestering (removing) atmospheric carbon (as carbon dioxide through photosynthesis) in tissue and by altering energy use in buildings, and consequently altering carbon dioxide emissions from fossil-fuel based power plants[3].

Trees reduce the amount of carbon in the atmosphere by sequestering carbon in new growth every year. The amount of carbon annually sequestered increases with the size and health of the trees. The gross sequestration of Roanoke's trees is about 20,900 tons of carbon per year with an associated value of $386,000. Net carbon sequestration (accounting for losses from carbon dioxide release through tree respiration) in Roanoke's urban forest is about 15,900 tons annually. Tree-of-heaven sequesters the most carbon annually (~1,584 tons), which accounts for about 10% of all sequestered carbon in the urban forest (Fig. 7).

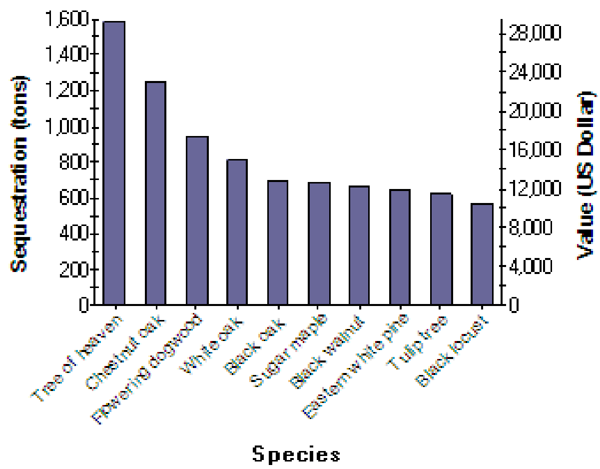

Figure 7. Annual carbon sequestration quantity and value for top ten tree species in Charlottesville

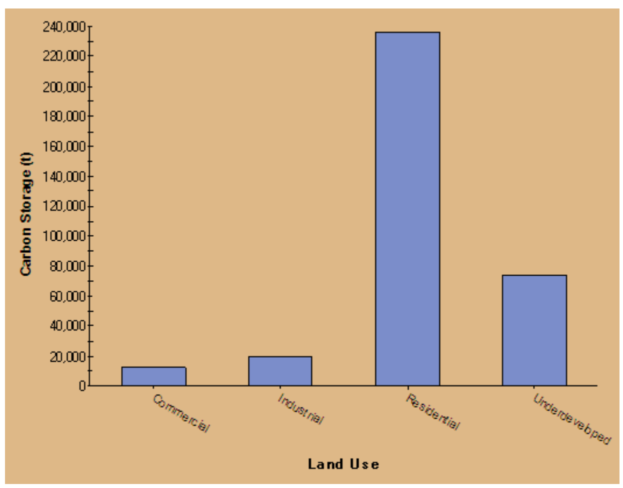

Figure 8. Carbon storage in Charlottesville's urban forest by land use

As trees grow, they accumulate carbon as wood. As trees die and decay, they release much of the stored carbon back to the atmosphere. Thus, carbon storage is an indication of the amount of carbon that can be lost if trees are allowed to die and decompose. Trees in Roanoke are estimated to store 342,000 tons of carbon, which is valued at $6.30 million (Fig. 8). Of all the species sampled, black cherry stores the most carbon (~11% of the total; data not shown).

Air Pollution Removal by Urban Trees

Poor air quality is a common problem in many urban areas. It can lead to decreased human health, damaged landscape plants and ecosystem processes, and reduced visibility. The urban forest can help improve air quality by directly removing pollutants from the air, reducing ambient air temperature, and reducing energy consumption in buildings, which consequently reduces air pollutant emissions from the power plants. Trees also emit volatile organic compounds (VOCs) that can contribute to ground-based ozone formation. However, integrative studies have revealed that an increase in tree cover leads to reduced ozone formation overall despite VOC emissions[1].

Pollution removal by trees in Roanoke was estimated using field data and recent pollution and weather data available. Pollution removal is greatest for ozone (O_3) as shown in Figure 9. It is estimated that Roanoke's trees remove 304 tons of air pollution (CO, NO_2, O_3, PM_{10}, and SO_2) per year with an associated value of $2.27 million (based on estimated national median externality costs associated with pollutants[2]).

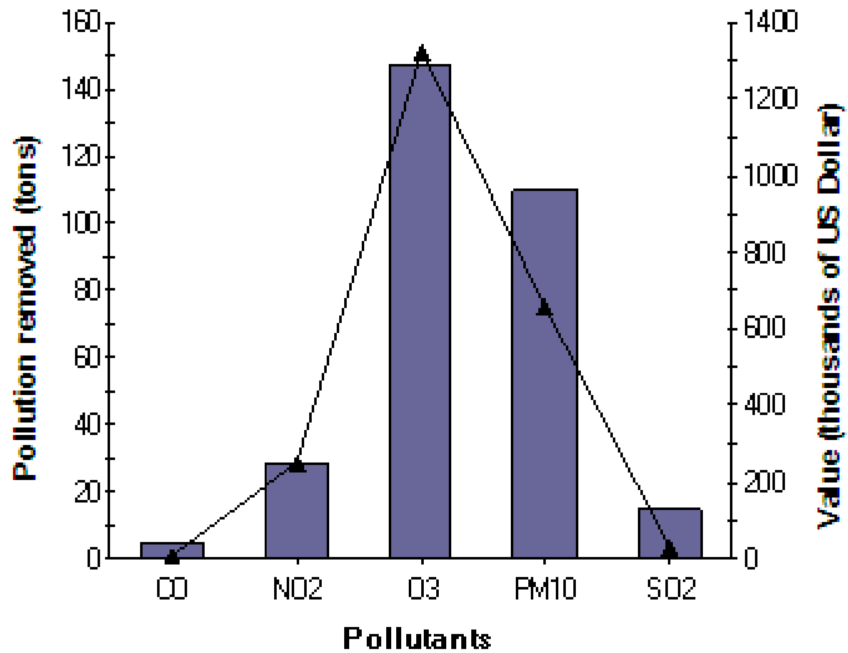

Figure 9. Pollution removal (bars) and associated monetary value (line) for trees in City of Roanoke

Trees and Building Energy Use

Trees affect energy consumption by shading buildings, providing evaporative cooling, and blocking winter winds. Trees tend to reduce building energy consumption in the summer months and can either increase or decrease building energy use in the winter months, depending on the location of trees around the building. Estimates of tree effects on energy use are based on field measurements of tree distance and direction to space conditioned residential buildings[4].

Based on 2002 prices, trees in Roanoke are estimated to reduce energy-related costs from residential buildings by $511 thousand annually (Tables 2 and 3). Trees also provide an additional $13,241 in value[5] by reducing the amount of carbon released by fossil-fuel based power plants (a reduction of 719 tons of carbon emissions).

Table 2. Annual energy conservation and carbon avoidance due to trees near residential buildings. Note: negative numbers indicate an increased energy use or carbon emission.

	Heating	*Cooling*	*Total*
MBTU[1]	7,732	n/a	7,732
MWH[2]	133	3,792	3,925
Carbon avoided (tons)	146	573	719

[1]One million British Thermal Units
[2]Megawatt-hour

Table 3. Annual savings[1] in residential energy expenditure during heating and cooling seasons. Note: negative numbers indicate a cost due to increased energy use or carbon emission.

	Heating ($)	*Cooling ($)*	*Total ($)*
MBTU[2]	94,794	n/a	94,794
MWH[3]	14,111	402,331	416,443
Carbon avoidance	2,689	10,552	13,241

[1]Based on state-wide energy costs for Virginia.
[2]One million British Thermal Units
[3]Megawatt-hour

Potential Pest Impacts

Various insects and diseases can infest trees, potentially killing trees and reducing the health, value, and sustainability of the urban forest. As pests tend to have differing tree hosts, the potential risk of each pest will differ. Four exotic pests were analyzed for their potential impact (Fig. 10): Asian longhorned beetle (ALB), gypsy moth (GM), emerald ash borer (EAB), and Dutch elm disease (DED).

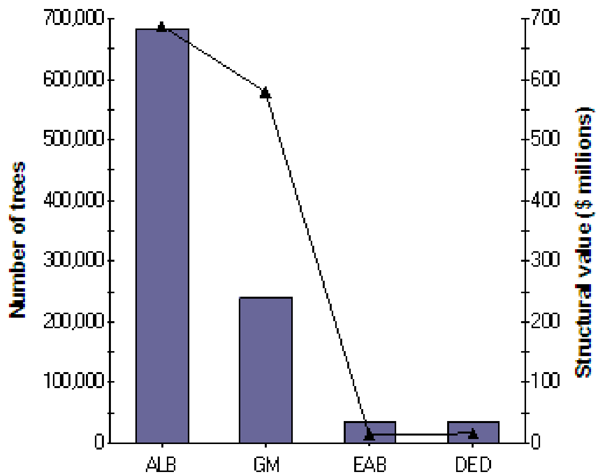

Figure 10. Susceptible trees (bars) and potential structural value loss (line) by pest for City of Roanoke's urban forest

The Asian longhorned beetle (ALB)[7] is an insect that bores into and kills a wide range of hardwood tree species. ALB poses a threat to about 26 percent of Roanoke's urban forest, which represents a potential loss of $687 million in structural value of the urban forest.

The gypsy moth (GM)[8] caterpillar is an insect that feeds on many tree species, causing widespread defoliation and tree death if outbreak conditions persist over several years. This pest threatens about 9 percent of the tree population, representing a potential loss of $579 million in structural value.

Emerald ash borer (EAB)[9] is a wood-boring insect has killed thousands of native ash trees in parts of the United States. EAB has the potential to affect about 1.3 percent of Roanoke's tree population ($12.1 million in potential structural value loss).

American elm, one of the most important street trees in the twentieth century, has been devastated by the Dutch elm disease (DED)[10]. Since the 1930s, DED has killed over 50 percent of the native elm population in the United States. Although some elm species have shown varying degrees of resistance, Roanoke could possibly lose 1.3 percent of its trees to this pest ($14.6 million in structural value).

Appendix I. Tree count and structural value by land use and tree species

		Number of Trees		Structural Values ($)	
Land Use	**Species**	**Value**	**SE**	**Value**	**SE**
Commercial	Mockernut hickory	24,518	24,511	4,088,125	4,087,041
Commercial	Black cherry	16,974	16,969	5,600,882	5,599,397
Commercial	Eastern white pine	15,088	13,188	16,819,036	13,788,614
Commercial	Eastern red cedar	13,202	13,198	1,519,531	1,519,128
Commercial	Virginia pine	11,316	9,471	10,745,199	10,574,026
Commercial	Black locust	7,544	7,542	7,992,780	7,990,661
Commercial	Black walnut	7,544	7,542	2,785,931	2,785,193
Commercial	Flowering dogwood	7,544	7,542	434,570	434,455
Commercial	Hackberry spp	7,544	7,542	1,551,339	1,550,928
Commercial	Siberian elm	7,544	7,542	10,828,569	10,825,698
Commercial	White oak	7,544	7,542	1,270,706	1,270,369
Commercial	American elm	5,658	5,656	4,491,081	4,489,890
Commercial	Lagerstroemia spp	5,658	5,656	4,955,437	4,954,123
Commercial	Norway maple	5,658	5,656	727,140	726,947
Commercial	Tree of heaven	5,658	5,656	190,641	190,590
Commercial	Black oak	3,772	3,771	1,768,598	1,768,129
Commercial	Callery pear	3,772	2,562	6,163,479	6,129,879
Commercial	Sweet cherry	3,772	3,771	255,240	255,172
Commercial	Pignut hickory	1,886	1,885	19,417,056	19,411,908
Commercial	Queens crapemyrtle	1,886	1,885	1,946,216	1,945,700
Commercial	Red mulberry	1,886	1,885	738,463	738,267
Commercial	**Total**	**165,966**	**101,460**	**104,290,019**	**53,666,145**
Industrial	Virginia pine	37,860	26,439	33,199,626	23,341,704
Industrial	Tree of heaven	36,345	21,442	9,646,115	8,981,750
Industrial	Flowering dogwood	24,230	12,033	10,508,453	5,830,238
Industrial	Black cherry	19,687	10,925	15,448,809	10,239,475
Industrial	American elm	12,115	12,111	1,887,457	1,886,834
Industrial	White oak	6,058	4,750	532,477	420,630
Industrial	Boxelder	4,543	3,350	1,054,104	1,016,331
Industrial	Eastern hemlock	4,543	4,542	2,281,313	2,280,560
Industrial	Eastern white pine	4,543	3,350	2,757,712	2,601,365
Industrial	Queens crapemyrtle	4,543	4,542	1,794,995	1,794,402
Industrial	Autumn olive	3,029	3,028	211,810	211,740
Industrial	Chinese holly	3,029	3,028	3,909,351	3,908,060
Industrial	Lagerstroemia spp	3,029	3,028	749,015	748,768
Industrial	Red maple	3,029	2,113	30,706	30,696
Industrial	Tulip tree	3,029	3,028	19,045,308	19,039,019
Industrial	American basswood	1,514	1,514	19,165,764	19,159,435
Industrial	Atlas cedar	1,514	1,514	3,112,272	3,111,244

Industrial	Black haw	1,514	1,514	37,400	37,387
Industrial	Black locust	1,514	1,514	75,642	75,617
Industrial	Black walnut	1,514	1,514	60,651	60,631
Industrial	Callery pear	1,514	1,514	9,335,874	9,332,791
Industrial	Crabapple	1,514	1,514	1,785,113	1,784,524
Industrial	Deodar cedar	1,514	1,514	4,953,315	4,951,679
Industrial	Kousa dogwood	1,514	1,514	215,399	215,328
Industrial	Norway maple	1,514	1,514	95,901	95,870
Industrial	Norway spruce	1,514	1,514	663,637	663,418
Industrial	Shagbark hickory	1,514	1,514	650,449	650,234
Industrial	Siberian elm	1,514	1,514	5,096,441	5,094,758
Industrial	Sweet cherry	1,514	1,514	123,050	123,009
Industrial	Sweetbay	1,514	1,514	296,818	296,720
Industrial	Taiwanese photinia	1,514	1,514	89,602	89,572
Industrial	Umbrella pine	1,514	1,514	290,442	290,346
Industrial	**Total**	**195,355**	**70,208**	**149,105,020**	**43,096,984**
Residential	Tree of heaven	175,972	55,436	62,783,947	24,348,029
Residential	Flowering dogwood	162,170	54,694	44,197,461	11,995,216
Residential	Black cherry	151,819	40,199	80,873,597	26,320,773
Residential	Black locust	110,414	52,363	47,488,990	19,675,895
Residential	Virginia pine	96,612	67,164	60,387,254	30,892,137
Residential	Eastern white pine	63,833	30,279	84,924,987	37,481,780
Residential	Black haw	50,031	26,251	6,470,067	4,440,060
Residential	Boxelder	46,581	19,494	8,474,758	5,529,491
Residential	Shagbark hickory	43,130	41,408	11,198,108	8,622,433
Residential	White mulberry	37,955	13,682	31,952,644	12,660,295
Residential	Tulip tree	36,230	14,276	57,586,726	25,052,611
Residential	Black walnut	32,779	9,915	81,899,387	32,489,966
Residential	Hackberry spp	31,054	12,996	3,416,438	1,683,063
Residential	Mockernut hickory	31,054	18,857	6,179,045	3,933,583
Residential	Eastern redbud	29,329	19,595	6,067,875	4,612,927
Residential	Norway maple	29,329	8,765	41,471,288	16,045,709
Residential	Black oak	27,603	13,319	76,980,312	42,706,306
Residential	Black tupelo	27,603	16,177	6,632,470	4,141,770
Residential	Northern hackberry	27,603	18,275	2,621,994	1,781,596
Residential	Siberian elm	25,878	14,339	19,160,153	11,179,085
Residential	Chestnut oak	24,153	12,225	56,093,185	32,931,625
Residential	Sugar maple	22,428	7,556	105,590,520	44,359,802
Residential	White oak	22,428	10,550	100,903,918	65,726,651
Residential	Chinese holly	20,703	17,375	2,822,464	1,756,332
Residential	Pignut hickory	15,527	9,508	9,591,949	5,912,932
Residential	Red maple	13,802	6,311	11,024,432	8,620,161
Residential	Royal paulownia	13,802	10,002	431,346	304,697
Residential	Sweet cherry	13,802	5,271	7,088,233	3,812,558

Residential	Common box	12,077	7,029	7,353,613	4,749,478
Residential	Northern red oak	12,077	7,839	51,228,145	32,317,682
Residential	Common persimmon	10,351	5,901	2,978,633	2,447,381
Residential	Green ash	10,351	5,901	414,266	266,702
Residential	Northern white cedar	10,351	7,675	901,795	643,133
Residential	Silver maple	10,351	4,773	78,654,598	39,986,211
Residential	American elm	8,626	5,676	2,119,172	1,446,276
Residential	Osage orange	8,626	8,624	1,736,993	1,736,489
Residential	American sycamore	6,901	4,182	44,863,469	29,498,171
Residential	Pin oak	6,901	3,386	50,065,448	37,263,147
Residential	Sassafras	6,901	3,386	295,802	155,255
Residential	American holly	5,176	2,951	6,140,182	3,662,764
Residential	Callery pear	5,176	3,838	16,185,404	13,339,396
Residential	Japanese maple	5,176	3,838	9,181,244	8,050,367
Residential	Mimosa	5,176	2,951	670,018	420,550
Residential	Privet spp	5,176	2,951	1,800,983	1,473,530
Residential	Rose-of-sharon	5,176	3,838	734,855	574,956
Residential	Shore juniper	5,176	5,174	558,598	558,436
Residential	Sourwood	5,176	5,174	1,454,428	1,454,006
Residential	White ash	5,176	5,174	99,563	99,534
Residential	Amur privet	3,450	2,424	6,659,407	5,448,265
Residential	Apple spp	3,450	2,424	87,249	87,224
Residential	Ash spp	3,450	2,424	7,193,759	5,478,365
Residential	Catalpa spp	3,450	2,424	255,697	223,387
Residential	Kousa dogwood	3,450	3,449	379,751	379,641
Residential	Kwanzan cherry	3,450	3,449	346,046	345,945
Residential	Lagerstroemia spp	3,450	2,424	2,501,153	2,175,434
Residential	Lilac spp	3,450	2,424	4,696,830	3,700,635
Residential	Plum spp	3,450	2,424	1,632,452	1,570,260
Residential	Red mulberry	3,450	2,424	321,430	226,304
Residential	Rhododendron spp	3,450	3,449	1,187,470	1,187,126
Residential	Viburnum spp	3,450	2,424	1,474,902	1,290,832
Residential	American basswood	1,725	1,725	210,248	210,187
Residential	American hornbeam	1,725	1,725	419,886	419,764
Residential	Apple	1,725	1,725	34,305	34,295
Residential	Cherry plum	1,725	1,725	2,273,117	2,272,459
Residential	Chinese chestnut	1,725	1,725	6,022,715	6,020,969
Residential	Cucumber tree	1,725	1,725	375,596	375,487
Residential	Deodar cedar	1,725	1,725	14,978,430	14,974,088
Residential	Dogwood spp	1,725	1,725		
Residential	Downy serviceberry	1,725	1,725	1,781,448	1,780,932
Residential	Eastern hemlock	1,725	1,725	191,816	191,760
Residential	Eastern red cedar	1,725	1,725	290,488	290,404
Residential	Evergreen euonymus	1,725	1,725	545,306	545,148

Residential	Ha'a	1,725	1,725	109,061	109,030
Residential	Heavenly bamboo	1,725	1,725	196,310	196,253
Residential	Holly spp	1,725	1,725	348,996	348,895
Residential	Mulberry spp	1,725	1,725	136,327	136,287
Residential	Pawpaw	1,725	1,725	196,310	196,253
Residential	Pear spp	1,725	1,725	3,246,053	3,245,112
Residential	Pecan	1,725	1,725	251,952	251,879
Residential	Queens crapemyrtle	1,725	1,725	2,492,555	2,491,833
Residential	Red cedar spp	1,725	1,725	77,635	77,612
Residential	Scarlet oak	1,725	1,725	4,001,096	3,999,936
Residential	Shingle oak	1,725	1,725	4,569,605	4,568,280
Residential	Showy forsythia	1,725	1,725	545,306	545,148
Residential	Smooth sumac	1,725	1,725	461,547	461,413
Residential	Southern red oak	1,725	1,725	263,461	263,385
Residential	White spruce	1,725	1,725	193,544	193,488
Residential	Willow oak	1,725	1,725	11,689,696	11,686,307
Residential	Winged burningbush	1,725	1,725	545,306	545,148
Residential	Winged elm	1,725	1,725	2,835,747	2,834,926
Residential	**Total**	**1,626,880**	**240,005**	**1,397,770,766**	**177,354,411**
Underdeveloped	Tree of heaven	78,112	41,851	43,524,910	20,015,415
Underdeveloped	Boxelder	60,184	38,979	16,082,051	7,782,289
Underdeveloped	Chestnut oak	49,940	28,651	98,245,443	54,427,372
Underdeveloped	Sweetgum	43,538	43,521	3,270,507	3,269,229
Underdeveloped	Virginia pine	42,257	19,574	23,050,626	11,237,624
Underdeveloped	Flowering dogwood	38,416	23,297	6,327,069	2,867,307
Underdeveloped	Sourwood	34,574	19,426	14,512,579	9,131,332
Underdeveloped	Black tupelo	30,732	21,626	10,505,018	6,353,236
Underdeveloped	Red maple	29,452	18,893	27,794,428	15,777,191
Underdeveloped	Tulip tree	19,208	9,756	34,212,918	20,285,785
Underdeveloped	Siberian elm	16,647	9,372	2,223,358	1,520,055
Underdeveloped	Eastern redbud	12,805	11,552	1,752,314	1,598,968
Underdeveloped	Eastern white pine	12,805	6,239	62,848,674	30,633,151
Underdeveloped	Green ash	12,805	9,641	807,833	570,917
Underdeveloped	White oak	11,525	6,446	35,446,051	19,791,918
Underdeveloped	Sassafras	10,244	6,110	1,048,438	687,947
Underdeveloped	Black cherry	8,964	4,017	23,922,455	11,764,486
Underdeveloped	Norway maple	8,964	7,748	788,343	690,909
Underdeveloped	Black oak	7,683	4,674	30,991,989	21,399,453
Underdeveloped	American elm	6,403	5,240	3,313,993	2,624,069
Underdeveloped	Pignut hickory	5,122	5,120	551,166	550,951
Underdeveloped	Red mulberry	5,122	4,011	1,209,067	957,952
Underdeveloped	Black locust	3,842	2,827	10,752,400	8,352,003
Underdeveloped	Black walnut	3,842	2,827	782,779	632,409
Underdeveloped	Eastern hophornbeam	3,842	2,827	4,179,459	4,115,848

Underdeveloped	Southern catalpa	3,842	2,827	104,804	73,625
Underdeveloped	Eastern red cedar	2,561	2,560	145,900	145,843
Underdeveloped	Honeylocust	2,561	2,560	5,181,531	5,179,507
Underdeveloped	Mockernut hickory	2,561	2,560	150,632	150,573
Underdeveloped	Post oak	2,561	2,560	4,462,173	4,460,430
Underdeveloped	Sugar maple	2,561	1,783	5,048,233	4,951,232
Underdeveloped	Sweet cherry	2,561	1,783	166,807	122,641
Underdeveloped	Table mountain pine	2,561	2,560	4,894,152	4,892,241
Underdeveloped	White ash	2,561	1,783	3,534,823	3,474,573
Underdeveloped	American basswood	1,281	1,280	39,013	38,998
Underdeveloped	American chestnut	1,281	1,280	48,019	48,001
Underdeveloped	American sycamore	1,281	1,280	44,636	44,618
Underdeveloped	Balsam poplar	1,281	1,280	6,037,442	6,035,084
Underdeveloped	Black haw	1,281	1,280	60,612	60,588
Underdeveloped	Common persimmon	1,281	1,280	4,611,655	4,609,854
Underdeveloped	Hackberry spp	1,281	1,280	258,579	258,478
Underdeveloped	Japanese tree lilac	1,281	1,280	1,084,249	1,083,825
Underdeveloped	Mimosa	1,281	1,280	3,716,640	3,715,189
Underdeveloped	Northern hackberry	1,281	1,280	949,680	949,309
Underdeveloped	Northern red oak	1,281	1,280	15,273,902	15,267,937
Underdeveloped	Southern red oak	1,281	1,280		
Underdeveloped	White mulberry	1,281	1,280	60,612	60,588
Underdeveloped	**Total**	**598,002**	**129,996**	**514,017,963**	**103,752,771**
CITY TOTAL	**Total**	**2,586,202**	**299,541**	**2,165,183,767**	**216,694,785**

Appendix II. Relative Tree Effects

The urban forest in City of Roanoke provides benefits that include carbon storage, carbon sequestration, and air pollutant removal. To estimate the relative value of these benefits, tree benefits were compared to estimates of average municipal carbon emissions[19], average passenger automobile emissions[20], and average household emissions[21].

Carbon storage is equivalent to:
- Amount of carbon emitted in Roanoke in 212 days
- Annual carbon (C) emissions from 205,000 automobiles
- Annual C emissions from 103,000 single-family houses

Carbon monoxide removal is equivalent to:
- Annual carbon monoxide emissions from 18 automobiles
- Annual carbon monoxide emissions from 74 single-family houses

Nitrogen dioxide removal is equivalent to:
- Annual nitrogen dioxide emissions from 1,770 automobiles
- Annual nitrogen dioxide emissions from 1,180 single-family houses

Sulfur dioxide removal is equivalent to:
- Annual sulfur dioxide emissions from 21,200 automobiles
- Annual sulfur dioxide emissions from 356 single-family houses

Particulate matter less than 10 micron (PM10) removal is equivalent to:
- Annual PM10 emissions from 292,000 automobiles
- Annual PM10 emissions from 28,200 single-family houses

Annual carbon sequestration is equivalent to:
- Amount of carbon emitted in Roanoke in 13 days
- Annual C emissions from 12,600 automobiles
- Annual C emissions from 6,300 single-family houses

Note: estimates above are partially based on the user-supplied information on human population total for study area

Appendix III. Comparison of Urban Forests

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

I. City totals for trees

City	*% Tree Cover*	*Number of trees*	*Carbon storage (tons)*	*Carbon Sequestration (tons/yr)*	*Pollution removal (tons/yr)*	*Pollution Value (USD)*
Calgary, Canada	7.2	11,889,000	445,000	21,422	326	1,611,000
Atlanta, GA	36.8	9,415,000	1,345,000	46,433	1,662	2,534,000
Toronto, Canada	20.5	7,542,000	992,000	40,345	1,212	6,105,000
New York, NY	21.0	5,212,000	1,351,000	42,283	1,677	8,071,000
Baltimore, MD	21.0	2,627,000	596,000	16,127	430	2,129,000
Philadelphia, PA	15.7	2,113,000	530,000	16,115	576	2,826,000
Washington, DC	28.6	1,928,000	523,000	16,148	418	1,956,000
Boston, MA	22.3	1,183,000	319,000	10,509	284	1,426,000
Woodbridge, NJ	29.5	986,000	160,000	5561.00	210	1,037,000
Minneapolis, MN	26.5	979,000	250,000	8,895	305	1,527,000
Syracuse, NY	23.1	876,000	173,000	5,425	109	268,000
Morgantown, WV	35.9	661,000	94,000	2,940	66	311,000
Moorestown, NJ	28.0	583,000	117,000	3,758	118	576,000
Jersey City, NJ	11.5	136,000	21,000	890	41	196,000
Freehold, NJ	34.4	48,000	20,000	545	21	133,000

II. Per-acre values of tree effects

City	No. of trees	Carbon storage (tons)	Carbon sequestration (lbs/yr)	Pollution removal (lbs/yr)	Pollution Value (USD)
Calgary, Canada	66.7	2.5	0.120	3.6	9.0
Atlanta, GA	111.6	15.9	0.550	39.4	30.0
Toronto, Canada	48.3	6.4	0.258	15.6	39.1
New York, NY	26.4	6.8	0.214	17.0	40.9
Baltimore, MD	50.8	11.5	0.312	16.6	41.2
Philadelphia, PA	25.0	6.3	0.190	13.6	33.5
Washington, DC	49.0	13.3	0.410	21.2	49.7
Boston, MA	33.5	9.0	0.297	16.0	40.4
Woodbridge, NJ	66.5	10.8	0.375	28.4	70.0
Minneapolis, MN	26.2	6.7	0.238	16.4	40.9
Syracuse, NY	54.5	10.8	0.338	13.6	16.7
Morgantown, WV	119.7	17.0	0.532	23.8	56.3
Moorestown, NJ	62.0	12.5	0.400	25.2	61.3
Jersey City, NJ	14.3	2.2	0.094	8.6	20.7
Freehold, NJ	38.5	16.0	0.437	33.6	106.6

Appendix IV. General Recommendations for Air Quality Improvement

Urban vegetation can directly and indirectly affect local and regional air quality by altering the urban atmosphere environment. Four main ways that urban trees affect air quality are[22]:

- Temperature reduction and other microclimate effects
- Removal of air pollutants
- Emission of volatile organic compounds (VOC) and tree maintenance emissions
- Energy effects on buildings

The cumulative and interactive effects of trees on climate, pollution removal, and VOC and power plant emissions determine the 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[23]. Local urban management decisions also can help improve air quality.

Urban forest management strategies to help improve air quality include[24]:

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

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