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Assessing Urban Forest Effects and Values: Toronto's Urban Forest

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Abstract

An analysis of trees in Toronto, Ontario, Canada, reveals that this city has about 10.2 million trees with a tree and shrub canopy that covers approximately 26.6 percent of the city. The most common tree species are eastern white-cedar, sugar maple, and Norway maple. The urban forest currently stores an estimated 1.1 million metric tons of carbon valued at CAD$25.0 million. In addition, these trees remove about 46,700 metric tons of carbon per year (CAD$1.1 million per year) and about 1,905 metric tons of air pollution per year (CAD$16.9 million per year). Trees in Toronto are estimated to reduce annual residential energy costs by CAD$9.7 million per year. The compensatory value is estimated at CAD$7.1 billion. Information on the structure and functions of the urban forest can be used to improve and augment support for urban forest management programs and to integrate urban forests within plans to improve environmental quality in the Toronto area.

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Cover Photo

Aerial shot of High Park and southwest end of Toronto. Photo by Urban Forestry, City of Toronto, used with permission.

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Aerial shot of High Park and the southwest end of Toronto.
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EXECUTIVE SUMMARY

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

In 2008, the i-Tree Eco model was used to survey and analyze Tononto's urban forest.

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

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

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

To help determine the vegetation structure, functions, and values of the urban forest in Toronto, a vegetation assessment was conducted during the summer of 2008. For this assessment, 0.04 hectare (one-tenth acre) field plots were sampled and analyzed using the i-Tree Eco model. This report summarizes results and values of (Table 1):

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

This study provides an update with more detailed information to the previous report "Every Tree Counts: A Portrait of Toronto's Urban Forest".[1]

Table 1.—Summary of urban forest features, Toronto, 2008

Feature	Measure
Number of trees	10,220,000
Tree and shrub cover	26.6 %
Most common species	eastern white-cedar, sugar maple, Norway maple
Trees <15.24 cm diameter	68.6%
Pollution removal	1,905 t/yr (CAD$16.9 million/yr)
Carbon storage	1.1 million t (CAD$25.0 million)
Carbon sequestration	46,700 t/yr (CAD$1.1 million/yr)
Building energy reduction	CAD$9.7 million/yr
Avoided carbon emissions	CAD$382,200/yr
Compensatory value	CAD$7.1 billion

t = metric ton

Benefits ascribed to urban trees include:

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

I-TREE ECO MODEL AND FIELD MEASUREMENTS

Though urban forests have many functions and values, currently only a few of these attributes can be assessed. To help assess the city's urban forest, data from 407 random field plots located throughout the city were analyzed using the i-Tree Eco (formerly known as UFORE) model.[2]

i-Tree Eco uses standardized field data from randomly located plots and local hourly air pollution and meteorological data to quantify urban forest structure and its numerous effects, including:

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

In the field, 0.04 hectare (one-tenth acre) plots were distributed on a randomized grid-based pattern at a density of approximately 1 plot for every 157 hectares (387 acres). In Toronto, land uses were used to divide the analysis into smaller zones based on city land-use map classifications.

The plots were divided among the following land uses:

- Parks (37 plots)—areas with parks and Toronto and Region Conservation Authority (TRCA) lands.
- Open space (19 plots)—areas with open space, including commercial, recreation, and agricultural.
- Commercial (30 plots)—areas with commercial land uses, including retail stores, shopping centers, etc.
- Industrial (44 plots)—areas with industrial land uses, including manufacturing and industrial parks.
- Institutional (25 plots)—areas with institutional land uses, including schools, hospitals, colleges, government buildings, etc.
- Utility and transportation (Utility & Trans; 14 plots)—areas with utility and transportation land uses, including power-generating facilities, sewage treatment facilities, limited access highways, railroad stations, shipyards, airports, etc.

Field Survey Data

Plot Information

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

Tree parameters

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

- Multi-family residential (MF residential; 23 plots)—areas with multi-family dwellings.
- Single family residential (SF residential; 181 plots)—areas with single family dwellings.
- Other (31 plots)—areas that are vacant or do not fall into one of the other land-use categories.
- Unknown (3 plots)—areas of no data on the land-use map.

Field data were collected for the Forest Service by city personnel; data collection occurred during the leaf-on season to properly assess tree canopies. Within each plot, data included land use, ground and tree cover, shrub characteristics, and individual tree attributes of species, stem diameter at breast height (d.b.h.; measured at 1.37 m [4.5 ft]), tree height, height to base of live crown, crown width, percentage crown canopy missing and dieback, and distance and direction to residential buildings.[3]

To estimate 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.[4] To adjust for this difference, biomass results for open-grown urban trees are multiplied by 0.8.[4] No adjustment is made for trees found in natural stand conditions. Tree dry-weight biomass was converted to stored carbon by multiplying by 0.5.

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

Air pollution removal estimates are derived from calculated hourly tree-canopy resistances for ozone, and sulfur and nitrogen dioxides based on a hybrid of big-leaf and multi-layer canopy deposition models.[5,6] 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[7, 8] that were adjusted depending on leaf phenology and leaf area. Particulate removal incorporated a 50 percent resuspension rate of particles back to the atmosphere.[9]

Seasonal effects of trees on residential building energy use was calculated based on procedures described in the literature[10] using distance and direction of trees from residential structures, tree height and tree condition data. As no Canadian city data are available on building energy effects from trees, data representing the buildings and climate zone of New York State were used.

Compensatory values were based on valuation procedures of the Council of Tree and Landscape Appraisers,[11] which uses tree species, diameter, condition, and location information.[2]

To learn more about i-Tree Eco methods[2] visit: http://nrs.fs.fed.us/tools/ufore/ or www.itreetools.org

There are an estimated 10.2 million trees in Toronto with tree and shrub canopy that covers 26.6% of the region.

TREE CHARACTERISTICS OF THE URBAN FOREST

The urban forest of Toronto has an estimated 10.2 million trees[a] (standard error [SE] = 952,000) with a tree and shrub cover of approximately 26.6 percent (SE = 0.4). This cover estimate is based on random point sampling of 10,000 points from leaf-on aerial imagery from 2009. The three most common species (by number of trees) in the urban forest are eastern white-cedar[b] (15.6 percent), sugar maple (10.2 percent), and Norway maple (6.5 percent) (Fig. 1). The 10 most common species account for 57.7 percent of all trees (Fig. 1). One hundred and fifteen tree species were sampled in Toronto (Appendix I). Trees that have diameters less than 15.24 centimeters account for 68.6 percent of the population (Figs. 2-3).

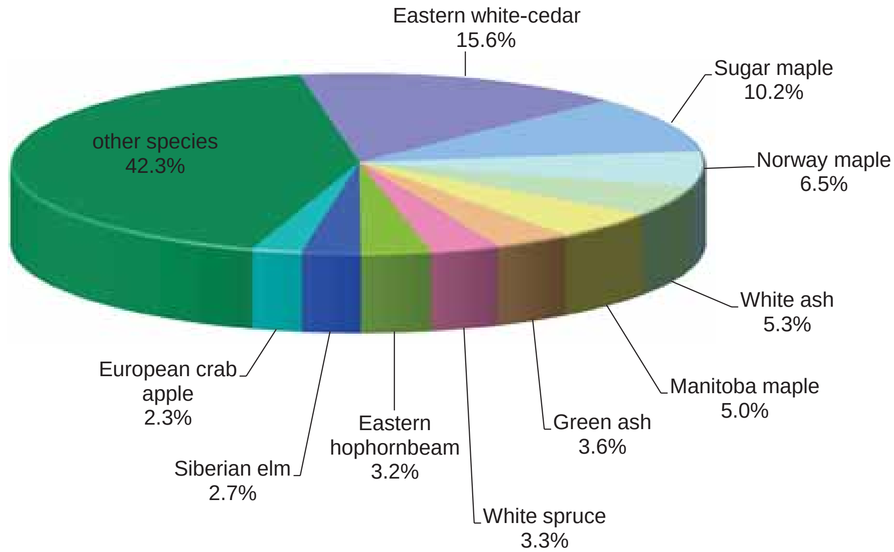

Figure 1.—Urban tree species composition, Toronto, 2008.

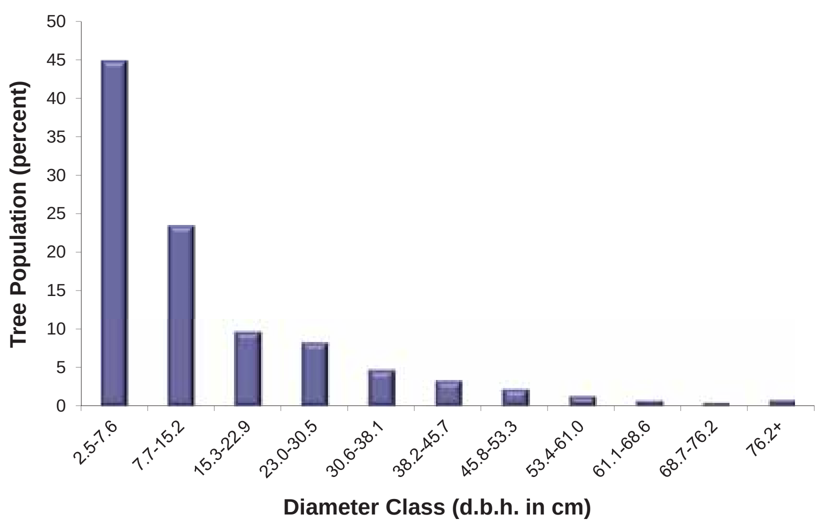

Figure 2.—Percent of tree population by diameter class, Toronto, 2008.

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[a] Includes cedar hedges >2.5 cm d.b.h. measured as trees as per the i-Tree Eco field data collection protocol.

[b] Canadian common name of *Thuja occidentalis*.

The highest density of trees occurs in the parks land-use category (501.5 trees/ha), followed by single family residential (180.9 trees/ha), and other land uses (152.2 trees/ha) (Fig. 4). The overall tree density in Toronto is 160.4 trees/ha, which is comparable to other city tree densities measured using this methodology (Appendix II) that range from 22.5 to 275.8 trees/hectare.

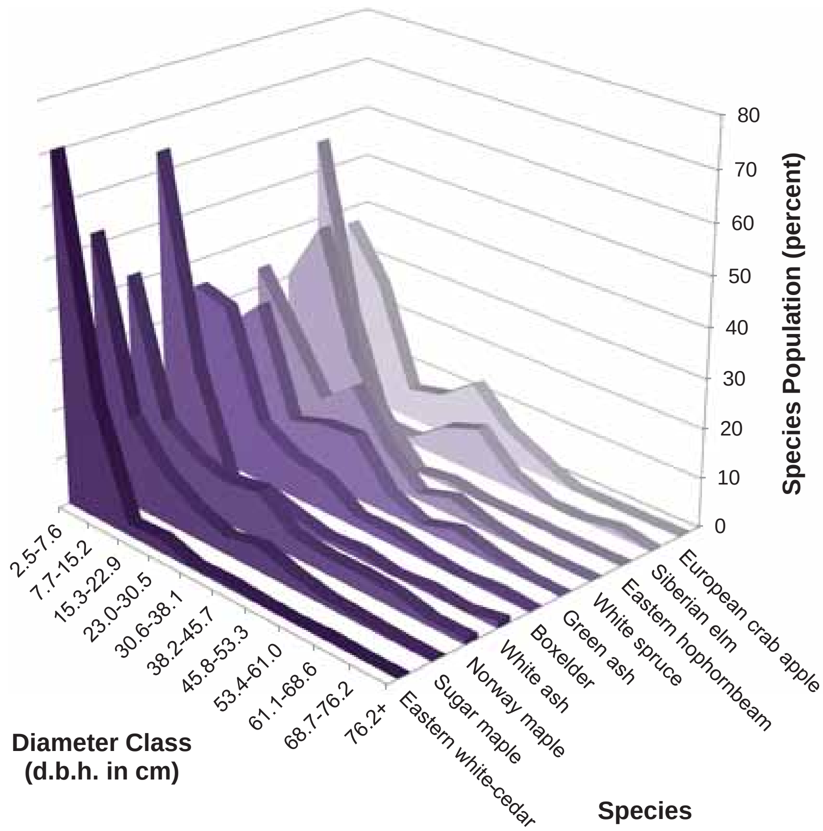


Figure 3.—Percent of species population by diameter class for 10 most common tree species, Toronto, 2008.

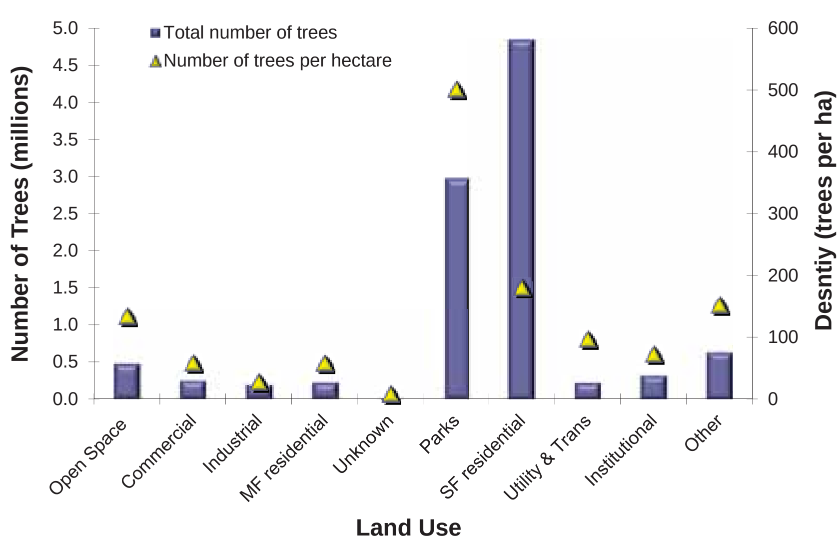


Figure 4.—Number of urban trees and tree density by land-use category, Toronto, 2008.

Urban forests are a mix of native tree species that existed prior to development and exotic species that were introduced by residents or other means. Thus, urban forests often have a tree diversity that is higher than surrounding native landscapes. Increased tree diversity can minimize the overall impact or destruction by a species-specific insect or disease, but the increase in the number of exotic plants can also pose a risk to native plants if some of the exotics are invasive plants that can potentially out-compete and displace native species. In Toronto, about 64 percent of the trees are species native to Ontario. Trees with an origin outside of North America are mostly from Eurasia (15.7 percent of the species) (Fig. 5).

Urban forests are a mix of native tree species that existed prior to development and exotic species that were introduced by residents or other means.

i-Tree

Invasive species such as the Norway maple have had a strong impact on the native species biodiversity of Toronto's natural areas (Fig. 6). To maintain the natural functions of habitat diversity and slope stability, certain areas within Toronto are being managed by invasive species removal and the replanting of native species.

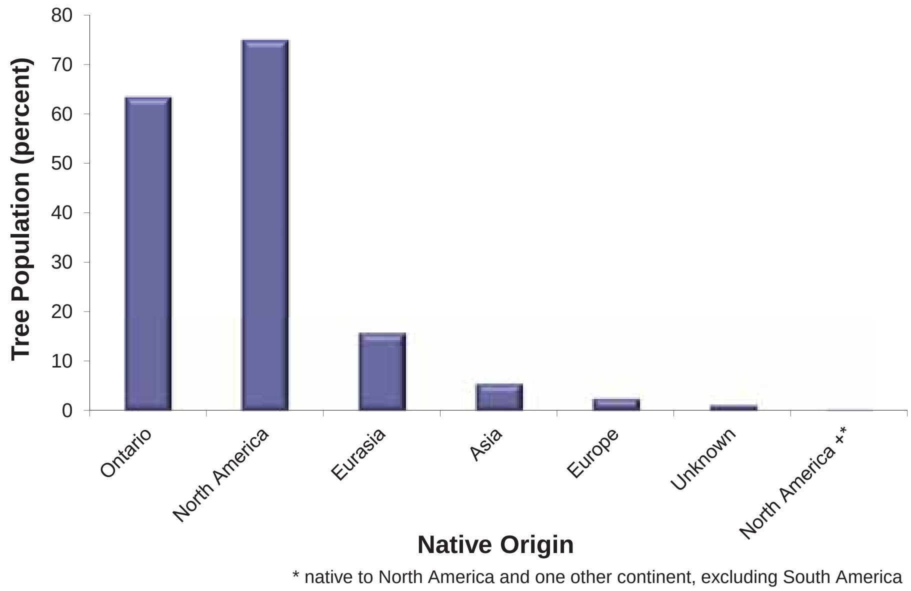


Figure 5.—Percent of total population by area of native origin, Toronto, 2008.

Figure 6.—Impact of invasive species in natural areas, Toronto. A) Norway maple dominated slope: little ground vegetation, slope vulnerable to erosion, and little structural or biological diversity. B) Same slope 5 years after removal of Norway maples and replanting with native species.
Photos by Ruthanne Henry, Toronto Parks, Forestry and Recreation.

URBAN FOREST COVER AND LEAF AREA

Trees and shrubs cover about 26.6 percent of Toronto, an estimate based on photo-interpretation of 10,000 random points for 2009 leaf-on aerial imagery.

Toronto was subdivided into neighborhoods (Fig. 7; Appendix III). In some neighborhoods, less than 30 points were sampled, so additional points were added and photo-interpreted in those neighborhoods to ensure a minimum of 30 points. These same points also were interpreted in 2005 (leaf-off imagery) and 1999 (leaf-off imagery) to determine temporal changes in tree cover.

Results from 2009 Imagery

Tree cover was highest in the Rosedale-Moore Park (#98 in Fig. 8; 61.8 percent), Bridle Path-Sunnybrooke-York Mills (#41; 55.6 percent) and Mount Pleasant East (#99; 54.8 percent) neighborhoods (Figs. 7-8; Appendix III). It is notable that the five neighborhoods with more than 50 percent canopy all overlap with a ravine or park (Fig. 9). The ravine areas have an estimated 60 percent tree cover, an estimate derived from geographic information system (GIS) analyses by city employees.

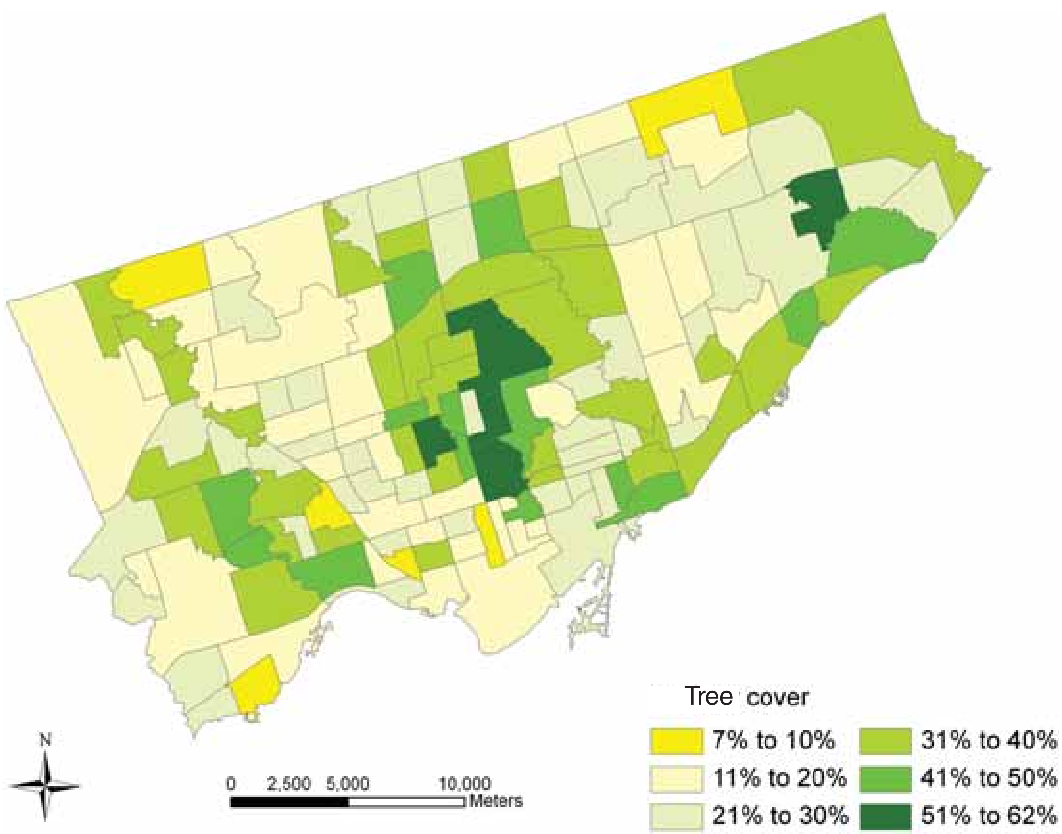


Figure 7.—Tree cover (percent) in Toronto neighborhoods, 2009.

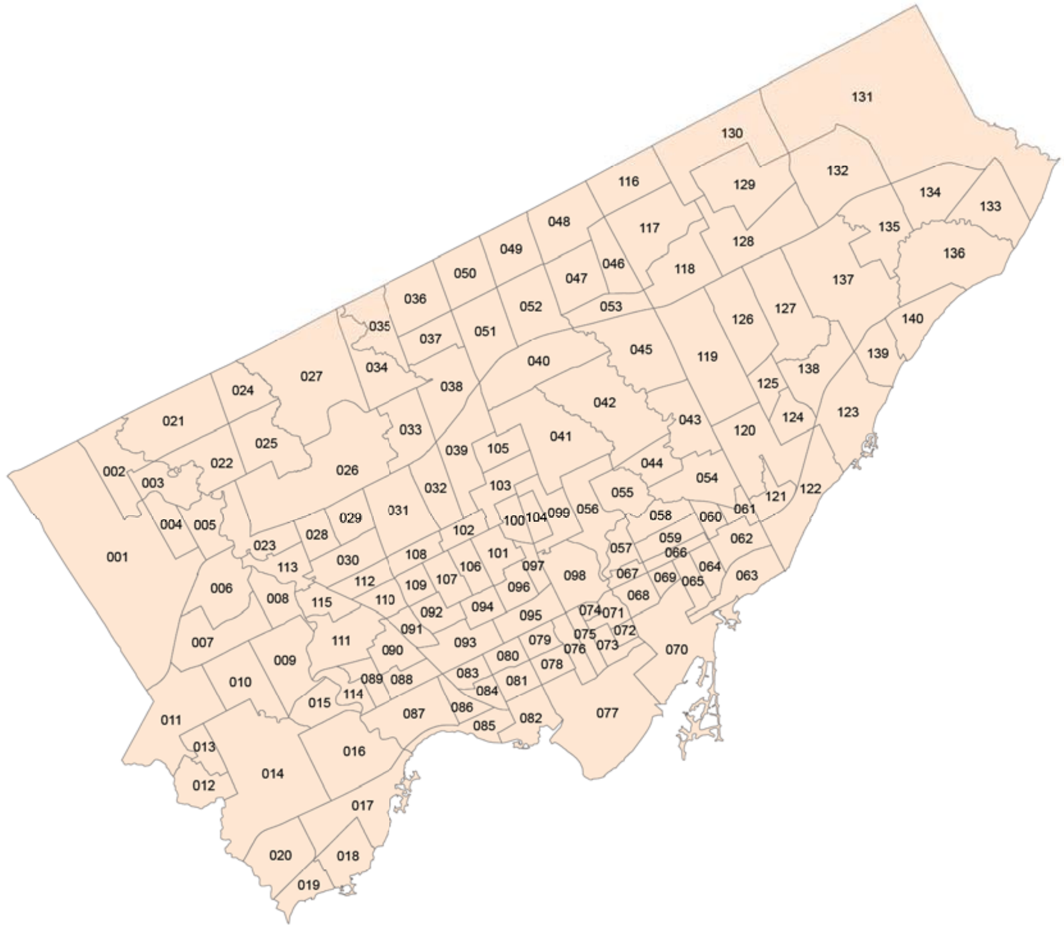


Figure 8.—Toronto neighborhoods, 2008. See Appendix III for numbering key.

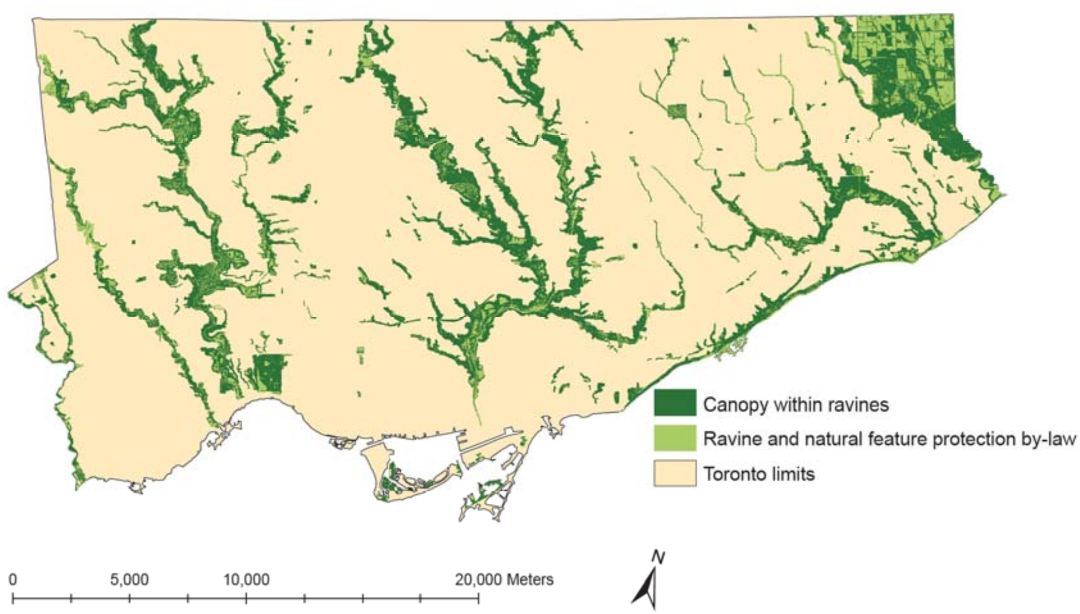


Figure 9.—Tree cover in ravines, Toronto. Ravines make up 11,097 hectares of land, or 17.5 percent of city land. Ravines under canopy make up 6,503 hectares, or 59 percent of the ravine area.

Toronto's dominant ground-cover includes herbaceous (e.g., grass, gardens; 37.9 percent), impervious surfaces (e.g., driveways, sidewalks, parking lots, but excluding buildings; 26.7 percent), and buildings (20.6 percent; Fig. 10).

Benefits from trees are linked to the amount of healthy leaf surface area of the plant. In Toronto, trees that dominate in terms of leaf area are Norway maple, sugar maple, and Manitoba maple (Fig. 11).

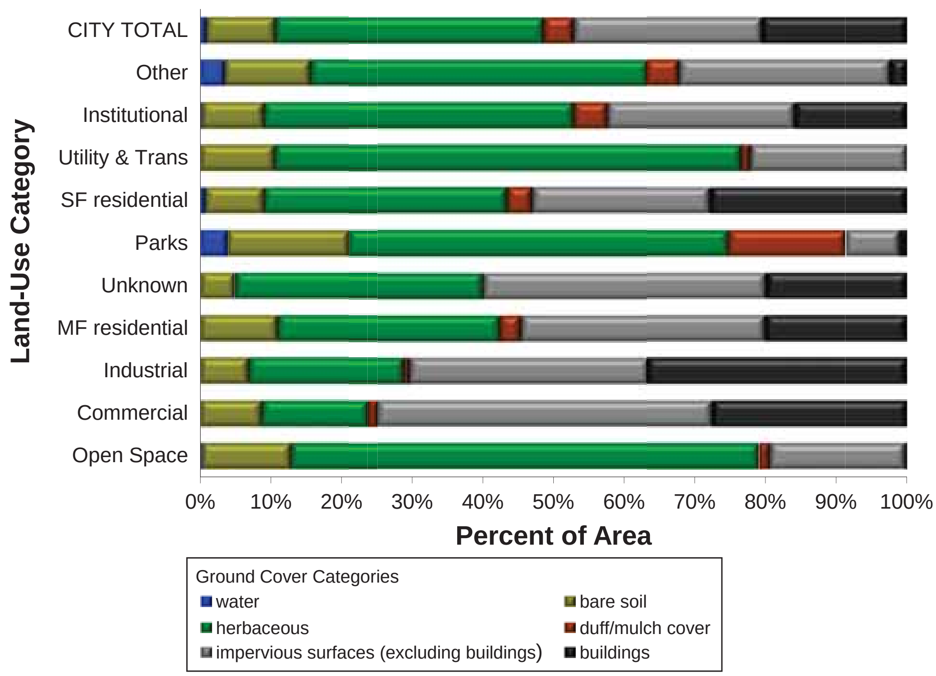


Figure 10.—Percent of area covered by various ground-cover classes, by land-use class and city total, Toronto, 2008.

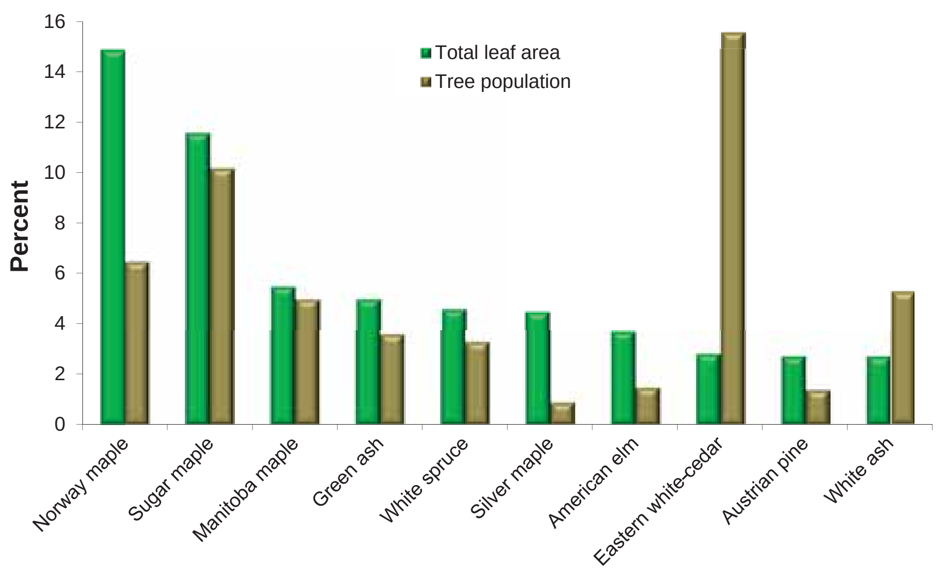


Figure 11.—Percent of total tree population and total leaf area for the 10 most common tree species, Toronto, 2008.

Table 2.—Percent of population, percent of leaf area, and importance values of species with the greatest importance values, Toronto, 2008

Common Name	%Pop[a]	%LA[b]	IV[c]
Sugar maple	10.2	11.6	21.8
Norway maple	6.5	14.9	21.4
Eastern white-cedar	15.6	2.8	18.4
Manitoba maple	5.0	5.5	10.5
Green ash	3.6	5.0	8.6
White ash	5.3	2.7	8.0
White spruce	3.3	4.6	7.9
Eastern hophornbeam	3.2	2.4	5.6
Silver maple	0.9	4.5	5.4
American elm	1.5	3.7	5.2

[a] %Pop = percent of population
[b] %LA = percent of leaf area
[c] IV = %Pop + %LA

Tree species with relatively large individuals contributing leaf area to the population (species with percent of leaf area much greater than their percent of the total population) are American elm (8.4 percent of its population greater than 76.2 cm d.b.h.), Norway maple (1.2 percent > 76.2 cm), and white oak (3.7 percent > 76.2 cm). A species must constitute at least 1 percent of the total population to be considered as relatively large or small trees in the population. Silver maple comprises only about 0.9 percent of the population, but 15.6 percent of its population has a diameter greater than 76.2 cm.

Species with smaller individuals contributing to leaf area (species with percent of leaf area much less than their percent of total population) are Port-Orford-cedar (100 percent of population less than 7.6 cm d.b.h.), eastern white-cedar (70.3 percent < 7.6 cm), and European buckthorn (65.8 percent < 7.6 cm).

The most important species in Toronto's urban forest are sugar maple, Norway maple, and eastern white-cedar.

A species' contribution to the urban forest can be described with an importance value (IV), which is calculated from a formula using the species' relative leaf area and abundance (Fig. 11). The most important species in Toronto's urban forest, according to calculated IVs, are sugar maple, Norway maple, and eastern white-cedar (Table 2).

Tree Cover Map

In addition to the photo-interpreted data (1999, 2005, and 2009), a high-resolution (0.6 m) map of tree and impervious cover was developed for Toronto using 2007 imagery (Fig. 12).[12] This map delimited eight land-cover classes (e.g., tree, impervious surfaces, etc.) and identified potential locations to plant trees to be used by the City of Toronto for urban forest management. The data from this map cannot be directly compared to the photo-interpreted data to estimate change in cover due to the differences in methodology, but the results are similar. Tree cover from photo-interpreted data is estimated at 25.5 percent (SE = 0.4 percent) in 2005 and 26.6 percent (SE = 0.4 percent) in 2009. The tree cover estimate from the 2007 high-resolution map is 28.0 percent, but the error from the map estimation is unknown, though likely small.

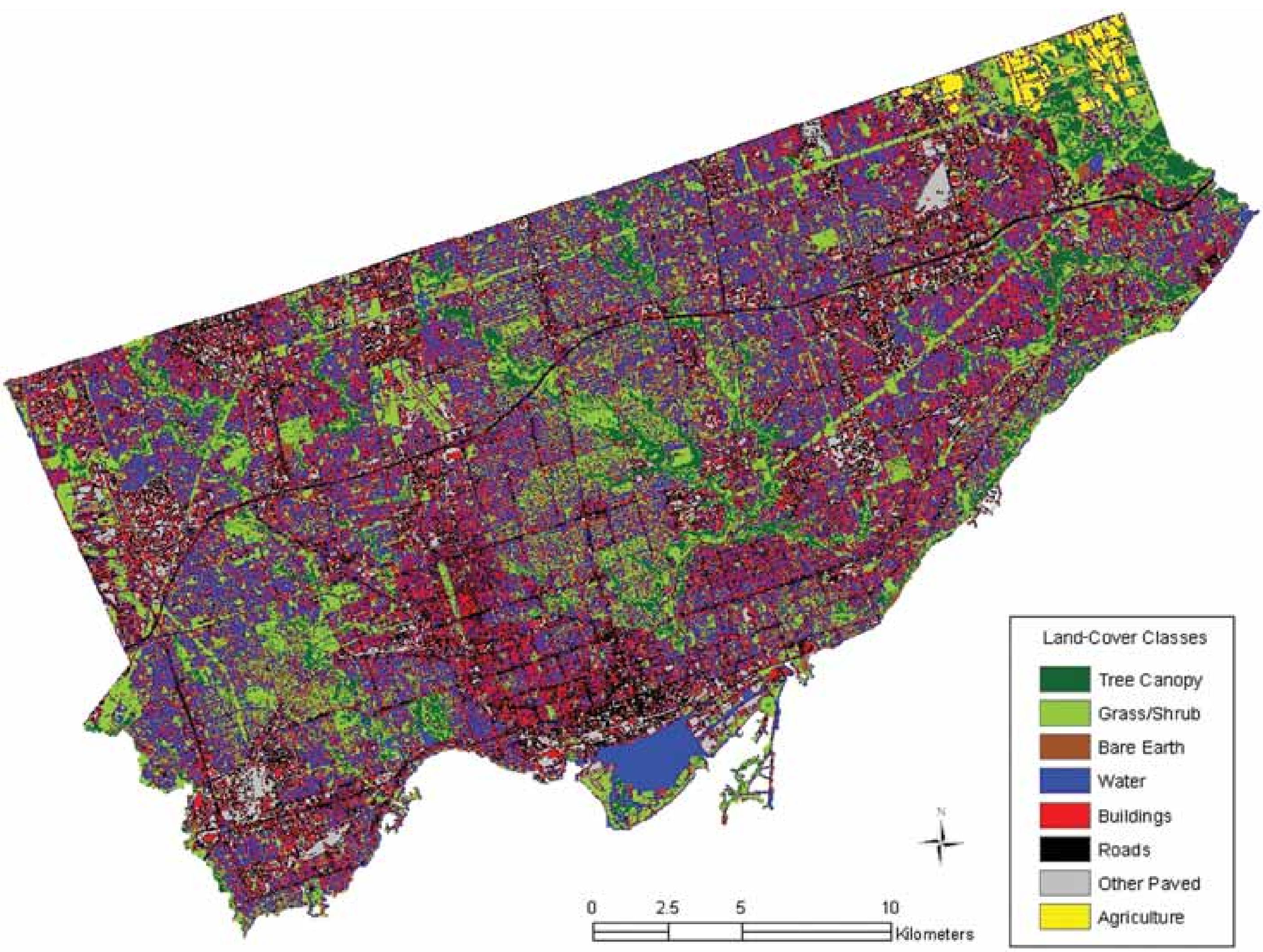


Figure 12.—Land cover based on 2007 imagery, Toronto.

Tree Cover Change

Aerial view of a Toronto ravine.
Photo by Urban Forestry, City of Toronto, used with permission.

To estimate tree and other surface cover changes in Toronto, photo-interpreted data from 1999 (leaf-off), 2005 (leaf-off) and 2009 (leaf-on) aerial photos were compared. This analysis of tree-cover change compared changes on a point-by-point basis using information from all images. Each point in each year was classified into one of the following eight land-cover classes: tree/shrub, grass or herbaceous, agricultural (herbaceous or soil depending upon time of year), soil, water, buildings, roads, or other impervious materials.

Tree cover in Toronto increased 1.2 percent over the 10-year period (Table 3), from 25.3 percent in 1999 to 26.6 percent in 2009. This change represents 2.7 percent (SE=0.16) in "new tree cover" offset by a 1.5 percent loss of previously existing tree cover. This 10-year net change is statistically significant from zero (McNemars test; $\alpha < 0.0001$) and equates to an average annual increase of about 0.12 percent per year.

Table 3.—Tree cover and impervious cover by land use, Toronto

	Tree Cover (%)			Impervious Cover (%)		
Land Use	1999	2009	Sig.[a]	1999	2009	Sig.[a]
Commercial	8.5	8.9		77.2	80.9	**
Industrial	5.2	6.3	*	73.0	76.4	**
Institutional	19.0	20.5	*	49.7	50.1	
MF residential	23.4	23.1		58.4	61.3	**
Parks	53.8	56.9	**	9.9	10.1	
Open Space	31.1	31.8		16.2	16.9	
Other	20.0	21.4		24.1	31.7	**
SF residential	30.4	31.4	**	47.7	49.7	**
Utility & Transportation	11.6	14.9	**	38.2	39.4	
Unknown	12.0	14.1		26.6	29.7	*
Toronto	25.3	26.6	**	45.6	47.9	**

[a] Sig. = statistically significant difference in cover between 1999 and 2009 where * = $\alpha < 0.05$ and ** = $\alpha < 0.01$

Impervious cover also increased from 45.6 percent in 1999 to 47.9 percent in 2009, a statistically significant increase (McNemars test; $\alpha < 0.0001$) (average annual increase of about 0.23 percent per year).

Tree cover increased in all land uses between 1999 and 2009, except for multi-family residential.

Past trends do not predict future conditions as environmental and management activities (e.g., development and tree planting trends) may change over time. Future monitoring is needed to track how current and future city activities will affect Toronto's tree cover changes.

Surface Cover by Land Use (1999-2009)

Tree/shrub cover in 2009 was greatest on parks (56.9 percent of land), open space (31.8 percent) and single family residential land (31.4 percent; Table 4). Tree cover increased in all land uses between 1999 and 2009, except for multi-family residential where it decreased from 23.4 to 23.1 percent (Tables 4-5). Five land-use classes exhibited statistically significant increases in tree cover (α <0.05): utility/transportation (3.3 percent), parks (3.1 percent), institutional (1.5 percent), industrial (1.1 percent) and single family residential (1.0 percent).

Impervious cover in 2009 was greatest on commercial (80.9 percent), industrial (76.4 percent) and multi-family residential (61.3 percent) land-use classes (Table 4). Impervious cover increased in all classes between 1999 and 2009 (Tables 4-5). Six land-use classes had statistically significant increases in impervious cover (α <0.05): other (7.6 percent), commercial (3.7 percent), industrial (3.4 percent), unknown (3.1 percent), multi-family residential (2.9 percent) and single family residential (2.0 percent).

Nearly half (49.9 percent) of Toronto's tree cover is found on single family residential land, followed by parks (19.0 percent) and open space (7.3 percent) (Table 6). Single family residential land is the most common land use in Toronto (42.2 percent of area)

Table 4.—Land cover by land use (1999, 2005, and 2009), Toronto								
			1999		2005		2009	
Land Use	n[a]	Cover type	% cover	SE[b]	% cover	SE[b]	% cover	SE[b]
Commercial	684	Grass	12.9	1.3	10.4	1.2	10.2	1.2
		Tree/Shrub	8.5	1.1	8.6	1.1	8.9	1.1
		Building	26.9	1.7	27.6	1.7	28.4	1.7
		Road	13.6	1.3	14.3	1.3	14.3	1.3
		Impervious other	36.7	1.8	37.9	1.9	38.2	1.9
		Water	0.0	0.0	0.0	0.0	0.0	0.0
		Soil	1.5	0.5	1.2	0.4	0.0	0.0
		Agriculture	0.0	0.0	0.0	0.0	0.0	0.0
Industrial	1,089	Grass	18.2	1.2	16.5	1.1	14.2	1.1
		Tree/Shrub	5.2	0.7	5.0	0.7	6.3	0.7
		Building	32.2	1.4	33.1	1.4	33.1	1.4
		Road	6.7	0.8	6.8	0.8	6.8	0.8
		Impervious other	34.1	1.4	35.6	1.5	36.5	1.5
		Water	0.0	0.0	0.0	0.0	0.0	0.0
		Soil	3.1	0.5	2.9	0.5	3.0	0.5
		Agriculture	0.5	0.2	0.1	0.1	0.0	0.0
Institutional	664	Grass	29.7	1.8	27.9	1.7	26.7	1.7
		Tree/Shrub	19.0	1.5	20.2	1.6	20.5	1.6
		Building	17.5	1.5	17.5	1.5	17.9	1.5
		Road	8.0	1.1	8.0	1.1	8.0	1.1
		Impervious other	24.2	1.7	24.7	1.7	24.2	1.7
		Water	0.0	0.0	0.0	0.0	0.0	0.0
		Soil	1.7	0.5	1.8	0.5	2.7	0.6
		Agriculture	0.0	0.0	0.0	0.0	0.0	0.0
MF residential	589	Grass	16.6	1.5	15.8	1.5	14.8	1.5
		Tree/Shrub	23.4	1.7	22.4	1.7	23.1	1.7
		Building	23.8	1.8	25.5	1.8	26.3	1.8
		Road	13.4	1.4	13.6	1.4	13.2	1.4
		Impervious other	21.2	1.7	21.4	1.7	21.7	1.7
		Water	0.0	0.0	0.0	0.0	0.0	0.0
		Soil	1.5	0.5	1.4	0.5	0.8	0.4
		Agriculture	0.0	0.0	0.0	0.0	0.0	0.0
Parks	611	Grass	29.6	1.5	29.1	1.5	27.6	1.5
		Tree/Shrub	53.8	1.7	54.7	1.7	56.9	1.7
		Building	0.9	0.3	1.0	0.3	1.0	0.3
		Road	4.7	0.7	4.8	0.7	5.0	0.7
		Impervious other	4.3	0.7	4.1	0.7	4.1	0.7
		Water	3.8	0.6	3.8	0.6	3.8	0.6
		Soil	2.3	0.5	1.9	0.5	1.4	0.4
		Agriculture	0.6	0.3	0.6	0.3	0.2	0.2

continued

Table 4.—continued

Land Use	n[a]	Cover type	1999 % cover	1999 SE[b]	2005 % cover	2005 SE[b]	2009 % cover	2009 SE[b]
Open Space	660	Grass	33.9	1.9	34.4	1.9	34.4	1.9
		Tree/Shrub	31.1	1.9	31.3	1.9	31.8	1.9
		Building	3.0	0.7	3.1	0.7	3.1	0.7
		Road	5.2	0.9	5.2	0.9	5.2	0.9
		Impervious other	8.0	1.1	8.0	1.1	8.5	1.1
		Water	1.8	0.5	1.6	0.5	1.5	0.5
		Soil	2.1	0.6	2.3	0.6	2.6	0.6
		Agriculture	14.8	1.4	14.1	1.4	12.9	1.4
Other	192	Grass	34.5	1.9	32.0	1.8	28.5	1.8
		Tree/Shrub	20.0	1.6	20.2	1.6	21.4	1.6
		Building	2.3	0.6	2.3	0.6	5.8	0.9
		Road	10.0	1.2	9.8	1.2	10.6	1.2
		Impervious other	11.8	1.3	13.0	1.3	15.3	1.4
		Water	8.3	1.1	8.3	1.1	8.2	1.1
		Soil	5.8	0.9	9.1	1.1	5.9	0.9
		Agriculture	7.3	1.0	5.3	0.9	4.4	0.8
SF residential	4,215	Grass	20.8	0.6	19.7	0.6	18.6	0.6
		Tree/Shrub	30.4	0.7	30.4	0.7	31.4	0.7
		Building	24.6	0.7	25.7	0.7	25.8	0.7
		Road	10.0	0.5	10.2	0.5	10.2	0.5
		Impervious other	13.1	0.5	13.5	0.5	13.6	0.5
		Water	0.1	0.0	0.1	0.1	0.1	0.1
		Soil	0.6	0.1	0.3	0.1	0.1	0.1
		Agriculture	0.4	0.1	0.0	0.0	0.0	0.0
Utility & Transportation	409	Grass	43.8	2.5	40.6	2.4	38.9	2.4
		Tree/Shrub	11.6	1.6	13.4	1.7	14.9	1.8
		Building	1.5	0.6	1.5	0.6	1.5	0.6
		Road	7.1	1.3	7.1	1.3	7.1	1.3
		Impervious other	29.6	2.3	29.8	2.3	30.6	2.3
		Water	0.5	0.3	0.5	0.3	0.5	0.3
		Soil	0.7	0.4	1.7	0.6	1.2	0.5
		Agriculture	5.2	1.1	5.4	1.1	5.4	1.1
Unknown	887	Grass	31.8	3.4	30.2	3.3	26.0	3.2
		Tree/Shrub	12.0	2.3	12.5	2.4	14.1	2.5
		Building	5.2	1.6	6.3	1.7	7.3	1.9
		Road	9.9	2.2	10.9	2.3	11.5	2.3
		Impervious other	11.5	2.3	10.4	2.2	10.9	2.3
		Water	27.6	3.2	27.6	3.2	27.6	3.2
		Soil	1.6	0.9	2.1	1.0	2.6	1.1
		Agriculture	0.5	0.5	0.0	0.0	0.0	0.0
Toronto	10,000	Grass	24.0	0.4	22.6	0.4	21.3	0.4
		Tree/Shrub	25.3	0.4	25.5	0.4	26.6	0.4

continued

Table 4.—continued

Land Use	n[a]	Cover type	1999 % cover	1999 SE[b]	2005 % cover	2005 SE[b]	2009 % cover	2009 SE[b]
		Building	18.8	0.4	19.6	0.4	20.1	0.4
		Road	9.1	0.3	9.3	0.3	9.3	0.3
		Impervious other	17.7	0.4	18.2	0.4	18.5	0.4
		Water	1.6	0.1	1.6	0.1	1.6	0.1
		Soil	1.7	0.1	1.7	0.1	1.4	0.1
		Agriculture	1.9	0.1	1.5	0.1	1.3	0.1

[a] n = sample size
[b] SE = standard error

Table 5.—Matrix of change in land cover, Toronto, 1999 to 2009

1999 Land Cover Classes	2009 Land Cover Classes: Grass/ herb	Tree/ shrub	Imp. Bldg.	Imp. Road	Imp. Other	Water	Soil/Bare Ground	Agri.	1999 Total	1999 SE
Grass/herb	19.4%	2.0%	0.7%	0.1%	1.4%	0.0%	0.4%	0.0%	24.0%	0.4%
Tree/shrub	0.7%	23.8%	0.2%	0.1%	0.4%	0.0%	0.1%	0.0%	25.3%	0.4%
Imp. Bldg.	0.1%	0.1%	18.5%	0.0%	0.2%	0.0%	0.1%	0.0%	18.8%	0.4%
Imp. Road	0.0%	0.1%	0.0%	8.9%	0.0%	0.0%	0.0%	0.0%	9.1%	0.3%
Imp. Other	0.4%	0.4%	0.4%	0.1%	16.2%	0.0%	0.2%	0.0%	17.7%	0.4%
Water	0.0%	0.0%	0.0%	0.0%	0.0%	1.6%	0.0%	0.0%	1.6%	0.1%
Soil/Bare Ground	0.3%	0.1%	0.2%	0.1%	0.4%	0.0%	0.5%	0.0%	1.7%	0.1%
Agriculture	0.3%	0.0%	0.1%	0.0%	0.1%	0.0%	0.1%	1.3%	1.9%	0.1%
2009 Total	21.3%	26.6%	20.1%	9.3%	18.5%	1.6%	1.4%	1.3%		
2009 SE	0.4%	0.4%	0.4%	0.3%	0.4%	0.1%	0.1%	0.1%		
Net Change (1999-2009)	-2.7%	1.3%	1.3%	0.2%	0.8%	0.0%	-0.3%	-0.6%		

Table 6.—Distribution of tree cover and available growing space by land use, Toronto, 2009

Land Use	% of City	Tree Cover (% of Total Cover)	AGS[a] (% of Total AGS)	Tree Cover (% of City)	AGS[a] (% of City)
Single family Residential	42.2	49.9	34.9	13.3	7.9
Parks	8.9	19.0	11.3	5.0	2.6
Open Space	6.1	7.3	10.0	1.9	2.3
Other	6.6	5.3	10.0	1.4	2.3
Institutional	6.6	5.1	8.6	1.4	2.0
Multi-family Residential	5.9	5.1	4.1	1.4	0.9
Industrial	10.9	2.6	8.3	0.7	1.9
Commercial	6.8	2.3	3.1	0.6	0.7
Utilities & Transportation	4.1	2.3	7.2	0.6	1.6
Unknown	1.9	1.0	2.4	0.3	0.6
Total	100.0	100.0	100.0	26.6	22.7

[a] AGS = potentially available growing space (non-agricultural soil or herbaceous cover) for tree planting

but accounts for an even greater proportion of the city's tree cover (49.9 percent). Two other land uses also contribute proportionally more tree cover than land area: parks and open space.

Land uses with greatest potentially available space to plant trees (defined as non-agricultural grass and soil space) are single family residential (34.9 percent of total available growing space in city), parks (11.3 percent), open space (10.0 percent), and other (10.0 percent). The available growing space (AGS) in single family residential land is about 7.9 percent of the total city area.

Increasing tree cover in pervious areas with existing available growing space is often cheaper than increasing tree cover over impervious surfaces. While tree canopy gains can be easily achieved on city property or rights-of way, this analysis of potentially available growing space does not take into account the potential limitations to tree planting in some grass and soil areas (e.g., sports fields, other land-use activities). Furthermore, achieving optimal tree growth along city streets and roads is challenging due to often difficult growing conditions and increased management costs. By recognizing potential available growing space and understanding the challenges to planting trees, Toronto officials can prioritize sites for expanding Toronto's tree cover.

Contrasting Tree Cover Estimates

City officials in Toronto are interested in understanding tree canopy changes to help attain their goal of increasing tree cover to 30-40 percent.[1] A previously published report, "Every Tree Counts: A Portrait of Toronto's Urban Forest"[1] used leaf-off aerial imagery to track canopy change from 1999 to 2005; the method showed a slight loss of tree cover (0.7 percent) in that period. Our study updates this earlier analysis with new tree-cover change estimates for the period of 1999-2009 (using imagery from 1999, 2005, and 2009; see Tree Cover Change section) and shows a gain in tree cover of 1.3 percent between 1999 and 2009.

The difference between the two sets of estimates is likely due to two factors: 1) different sets of random samples, and 2) different tree conditions captured in the imagery.

The original sets of data (ortho-rectified; 1999 and 2005) used leaf-off imagery, making it more difficult to detect some deciduous trees, thus underestimating the presence of some trees (Fig. 13). The current study used leaf-on imagery (2009) that provided information that helped interpretation in all three years (1999, 2005, 2009), as all three images were interpreted side-by-side.

Differences among estimates lead to the question: which method is best for determining tree cover or tree cover change. Both methods (photo-interpretation and high-resolution cover maps) can produce estimates with known accuracies, but both estimates have an inherent degree of uncertainty. Photo-interpretation uncertainty derives from the random sample itself, but is calculated in the standard error of the estimate. Photo-interpretation also relies on an accurate interpretation (by a human being) of the cover classes. In the case of the leaf-off imagery, some deciduous

Figure 13.—Comparison of leaf off and leaf on imagery, Toronto. A) 1999 imagery with sample point; B) 2009 imagery with sample point.

trees were likely misidentified due to the difficulty in assessing tree cover with leaf-off imagery (e.g., some small deciduous trees could not be seen). Thus, leaf-off interpretation likely underestimates tree cover.

Estimates of tree and other land-cover types in the cover map also have errors due to cover being incorrectly classified. Visual corrections were done to the map to reduce errors. However, misclassification errors are inherent with most map products, but are considered to be low in the Toronto map due to the visual corrections. However, the accuracy of the Toronto map is unknown. Since 2007, when the Toronto canopy study was initiated, many cities within the greater Toronto area have done comparable studies. A review of the differences in results has provided useful information for Toronto's Urban Forestry staff. Other cities in the Toronto area have used satellite imagery for estimating tree cover.

Both photo-interpretation and high-resolution cover maps can be used, and both have advantages and limitations. Limitations to both approaches relate to the accuracy of the estimate. In comparing detailed cover maps, changes between cover classes could be due to actual change or map misclassification. The higher the accuracy of the cover maps, the less likely that misclassification will lead to a false change. Misclassification errors can be human-caused during the photo-interpretation process, but can be limited by using trained photo-interpreters and high-quality leaf-on imagery.

The advantages of the photo-interpretation method to detect tree cover change are: 1) relatively quick and low cost; 2) images are compared side-by-side and the human interpreter can visually inspect and record change and detect issues of temporal change (e.g., agricultural fields that have soil or herbaceous cover depending upon time of year) or image parallax (apparent displacement of tall objects on images) that may lead to false change estimates using automated procedures; and 3) statistical estimates of sampling error can be produced. The advantage of the high-resolution cover map approach is that a detailed map of cover or change can be produced. These cover maps can provide detailed spatial information that photo-interpretation cannot, but at a higher cost. If these cover maps are integrated into an urban forestry or city management program, then the maps are likely well worth the investment. However, if only general estimates of tree cover, or estimates of cover change are needed, then photo-interpretation of leaf-on imagery is likely the best and most cost-effective approach.

The comparison of the various cover estimation methods has been a useful process that has helped Toronto officials select an appropriate canopy cover methodology for future comparisons.

Sustaining Tree Cover

Based on an average mortality of 4 percent, 380,000 new trees need to be established annually to maintain the existing tree cover of 26.6 percent over 50 years.

Tree cover will continue to change through time based on numerous factors, including annual tree mortality, growth of existing trees, and new tree establishment. To estimate a number of new trees needed annually to maintain current tree cover, Toronto's tree population data were input into the i-Tree Forecast Prototype model.

i-Tree Forecast estimates annual tree canopy cover amounts and growth based on tree population data for an area of interest. For Toronto, the i-Tree Forecast model estimated the number of new trees to be established to maintain tree cover of 26.6 percent or increase tree cover to 40 percent over 50 years. Several possible scenarios were entered into the i-Tree model: 1) average mortality rate of 3, 4, 5, or 6 percent, and 2) average mortality rate of 3, 4, 5, or 6 percent with an assumption that the entire ash population would die off in 10 years.

Tree cover expansion is predicted by the following tree characteristics: species (growth rate, longevity, height at maturity), diameter, crown light exposure, and dieback. Tree growth/annual diameter growth is based on the following: number of frost free days, crown light exposure, dieback, growth rate classification, and median height at maturity. Individual tree mortality is predicted by dieback, diameter, and average height at maturity. Tree size classes based on average species height at maturity are used in calculations to determine species-specific mortality rates. Trees falling into a smaller size class have higher mortality rates at smaller diameters compared to trees in the larger size classes. See Appendix IV for more detailed information.

The estimated number of new trees needed annually to maintain tree cover, for each scenario, is given in Table 7.

Based on an average mortality of 4 percent, 380,000 trees need to be established annually to maintain the existing tree cover of 26.6 percent over 50 years. To increase the tree cover to 40 percent over 50 years, 780,000 trees need to be established. In the event that all ash trees die within 10 years, the number of new trees needed annually to maintain or increase tree cover becomes 470,000 and 900,000, respectively.

Table 7.—Estimated number of new trees needed annually to sustain or reach desired tree cover level, Toronto		
Maintain existing tree cover of 26.6%		
	No Additional Mortality	Ash Kill in 10 Years
Mortality (%)	Trees Planted	Trees Planted
3	200,000	270,000
4	380,000	470,000
5	620,000	720,000
6	870,000	980,000
Increase tree cover to 40%		
	No Additional Mortality	Ash Kill in 10 Years
Mortality (%)	Trees Planted	Trees Planted
3	500,000	570,000
4	780,000	900,000
5	1,100,000	1,300,000
6	1,500,000	1,750,000

The different scenarios illustrate the natural variation in annual mortality and the influence of reduced mortality on annual planting rates. City efforts to reduce tree mortality through tree maintenance and management has a positive effect on reducing the number of new trees needed to maintain or reach a desired tree cover.

In addition, natural regeneration and actions to promote it will reduce annual tree planting needs. About 46 percent of Toronto's existing tree population was planted, with planting most common on residential lands and least common on parks and utility/transportation lands (Tables 8-9). This difference reflects the role of human intervention in tree cover variations among land use type. Human activities in urban areas (development, mowing) often preclude the establishment of tree cover. Decreasing activities such as mowing and maintaining pervious surfaces can facilitate more natural regeneration.

An annual establishment rate of 380,000 trees per year to maintain existing tree cover equates to about six trees per hectare per year. Long-term monitoring data from Baltimore, MD, and Syracuse, NY,[13] indicate that natural tree regeneration rates are around 4 to 8 trees/ha/yr. Thus, much of Toronto's needs for sustaining tree cover could be accomplished via natural regeneration, but natural regeneration might not provide the desired species composition or mix to meet the desires of the city residents. Much of the regeneration in Syracuse is from the exotic invasive European buckthorn.[14]

Community planting of large new naturalization within Toronto parkland system.
Photo by Urban Forestry, City of Toronto, used with permission.

Table 8.—Estimated percent of tree population planted, by land-use category, Toronto, 2008

Land Use	Percent Planted	n[a]
MF Residential	94.4	54
SF Residential	73.5	1,322
Industrial	44.9	49
Institutional	36.5	74
Commercial	31.0	71
Other	15.2	191
Open Space	14.6	103
Parks	11.3	750
Utility & Transportation	3.6	55
Toronto	45.9	2,669

[a] n = sample size

Table 9.—Estimated percent of species population planted in Toronto (minimum sample size of 15 trees), 2008

Species	Percent Planted	n[a]
Port-Orford-cedar	100.0	41
Norway spruce	100.0	32
Blue spruce	100.0	16
Red pine	96.3	27
Honeylocust	95.0	40
Common pear	94.7	19
Austrian pine	94.4	36
Eastern white-cedar	94.4	429
Sweet cherry	94.1	17
White spruce	89.0	91
Eastern redcedar	83.3	18
Silver maple	72.0	25
Norway maple	53.1	177
Siberian elm	50.7	75
European crab apple	45.0	60
Paper birch	44.7	38
Littleleaf linden	42.9	21
Green ash	41.1	95
White oak	34.6	26
Common chokecherry	32.7	52
Eastern white pine	22.9	35
American elm	22.5	40
Black cherry	21.3	61
Northern red oak	20.0	15
American basswood	16.7	36
Scotch pine	12.5	16
Boxelder	6.0	134
Sugar maple	5.7	263
Tree of heaven	5.6	18
American beech	5.6	18
European buckthorn	4.8	42
White ash	0.7	142
Eastern hophornbeam	0.0	82
Quaking aspen	0.0	60
Cockspur hawthorn	0.0	25

[a] n = sample size

The use of different average annual mortality scenarios also reflects the variation in planting program results. Many different types of planting programs are currently underway on Toronto's city-owned lands, primarily in parks and road rights-of-way. These planting programs vary in funding, maintenance, and the conditions of the environments where they take place. Therefore, annual mortality will likely vary among the different planting programs. For example, the land parallel to the roads within Toronto's downtown core produce a relatively inhospitable growing environment with constrained space for soil, limited nutrient inputs, salt loading, drought conditions, and soil compaction. To improve planting success, designs and planting methods are being modified in these areas to use soil cell supports or continuous soil trenches to increase soil volume and quality.

Monitoring of Toronto's urban forest will provide better data related to mortality, planting, and establishment rates to help guide urban foresters as they work toward a canopy goal of 30-40 percent within 50 years.

Continous soil trench construction to provide Toronto street trees with increased soil volume.
Photo by Urban Forestry, City of Toronto, used with permission.

Based on a GIS analysis carried out by Toronto officials, the land ownership is 55 percent private and 45 percent public. The City of Toronto has been increasing planting programs since 2004 and over the last 5 years the average number of trees planted is approximately 100,000 per year.[1,15] At this rate, however, suitable planting areas on public land will likely be fully allocated with new planting in the next few decades. Implementing innovative private property planting through education campaigns or planting incentives would help disperse planting responsibility and make steps towards attaining canopy goals.

Though this study does not specifically analyze the costs versus benefits of trees, various studies have shown a positive net benefit. For example, the average annual net benefits (benefits minus costs) for trees in New York City increase with mature tree size and differ based on location: from US$5 (yard) to US$9 (public) for a small tree, from US$36 (yard) to US$52 (public) for a medium tree, and from US$85 (yard) to US$113 (public) for a large tree.[16]

AIR POLLUTION REMOVAL BY URBAN TREES

The trees and shrubs in Toronto remove approximately 1,905 metric tons of air pollution each year, with a societal value of CAD$16.9 million/year.

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

Poor air quality is a common problem in many urban areas. It can lead to human health problems, damage to landscape materials and ecosystem processes, and reduced visibility. The urban forest can help improve air quality by reducing air temperature, directly removing pollutants from the air, and reducing energy consumption in buildings, which consequently reduce air pollutant emissions from power plants. Trees also emit volatile organic compounds that can contribute to ozone formation. However, integrative studies have revealed that an increase in tree cover leads to reduced ozone formation.[17]

Pollution removal by trees and shrubs in Toronto was estimated using the i-Tree Eco model in conjunction with field data and hourly pollution and weather data for the year 2007.[18] Pollution removal was greatest for ozone (O_3), followed by particulate matter less than 10 microns (PM_{10}), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and carbon monoxide (CO). It is estimated that trees and shrubs remove 1,905 metric tons of air pollution (CO, NO_2, O_3, PM_{10}, SO_2) per year with an associated value of CAD$16.9 million CND (based on estimated 2007 national median externality costs associated with pollutants[19]) (Fig. 14). Trees remove more than four times more air pollution than shrubs in Toronto.

The average percentage of air pollution removed by trees during the daytime, leaf-on season was estimated to be:

- O_3 2.3%
- PM_{10} 2.2%
- SO_2 2.4%
- NO_2 1.5%
- CO 0.01%

Commercial streetscape (College Street) in Toronto.
Photo by Urban Forestry, City of Toronto, used with permission.

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

- O_3 16.4%
- PM_{10} 14.1%
- SO_2 16.2%
- NO_2 9.0%
- CO 0.05%

The pollution removed by trees and shrubs was compared to facility emissions from Toronto (2006). Total pollution removed by trees (excluding ozone which is not emitted by facilities) is 22.3 percent of the total facilities emissions based on emissions data from Environment Canada's National Pollution Release Inventory (Table 10).[20] The greatest reduction compared to facility emission was for PM_{10} (61.0 percent). General recommendations to improve air quality with trees are given in Appendix V.

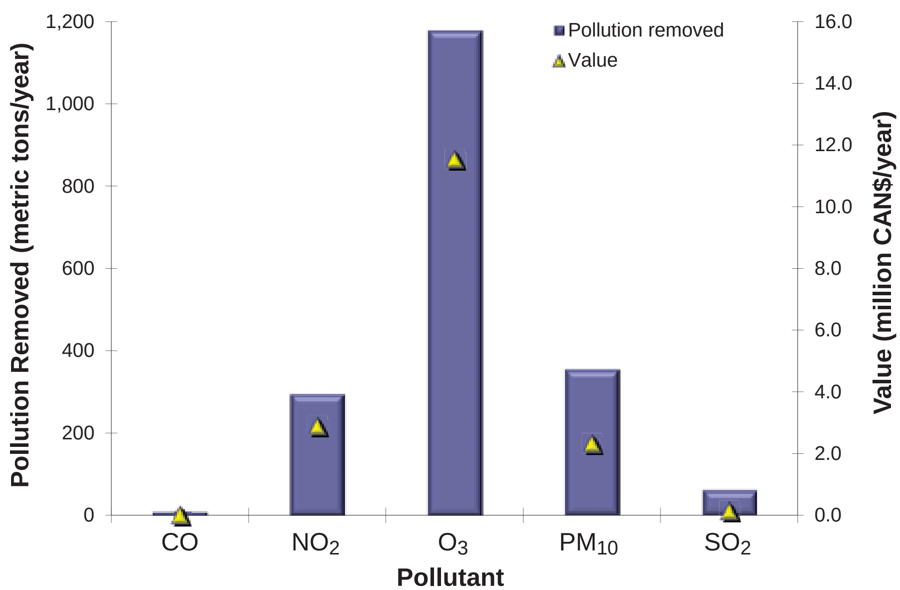


Figure 14.—Annual air pollution removed and value of removal by trees and shrubs, Toronto, 2008.

Table 10.—Comparison of pollutants removed by urban forest vs. emissions from facilities in Toronto

Pollutant	Urban forest removal (t/year)	Facility emissions (t/year)	Urban forest effect (%)
CO	10	894	1.1
NO_x	297	1,576	18.8
O_3	1180	n/a	n/a
PM_{10}	357	585	61.0
SO_2	62	195	31.8
Total (w/o O_3)	726	3,250	22.3

> **Urban forests may play important roles in capturing and storing carbon dioxide from the atmosphere. Net carbon sequestration is positive in healthy and actively growing trees, but can be negative if emission of carbon from decomposition is greater than sequestration by healthy trees.**

CARBON STORAGE AND SEQUESTRATION

Climate change is an issue of global concern to many. Urban trees can help mitigate climate change by sequestering atmospheric carbon (from carbon dioxide) in tissue and by reducing energy use in buildings, and consequently reducing carbon dioxide emissions from fossil-fuel based power plants.[21]

Trees reduce the amount of carbon in the atmosphere by sequestering carbon in new tissue growth every year. The amount of carbon annually sequestered is increased with healthier trees and larger diameter trees. Gross sequestration by trees in Toronto is about 46,700 metric tons of carbon per year with an associated value of CAD$1.1 million.[21] Net carbon sequestration in the urban forest is about 36,500 metric tons.

Carbon storage by trees is another way trees can influence global climate change. As trees grow, they store more carbon by holding it in their accumulated tissue. As trees die and decay, they release much of the stored carbon back to the atmosphere. Thus, carbon storage is an indication of the amount of carbon that can be lost if trees are allowed to die and decompose. Trees in Toronto are estimated to store 1.1 million metric tons of carbon (CAD$25.0 million) (Fig. 15). Of all the species sampled, the Norway maple population stores the most carbon (12.3% of the total carbon stored), while the sugar maple population annually sequesters the most carbon (11.8% of all sequestered carbon) (Fig. 16).

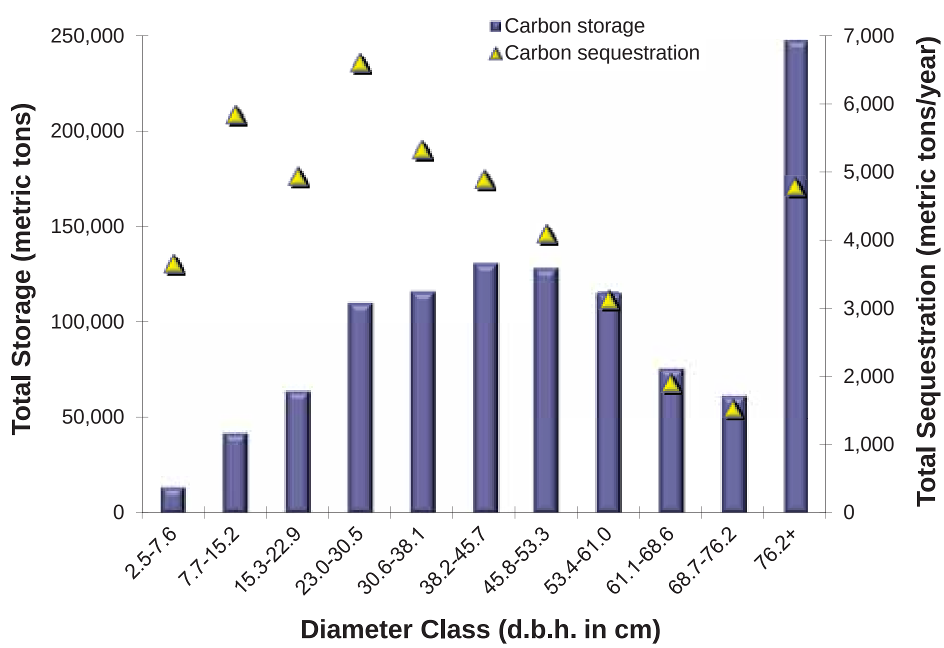


Figure 15.—Total carbon storage and sequestration by diameter class, Toronto, 2008.

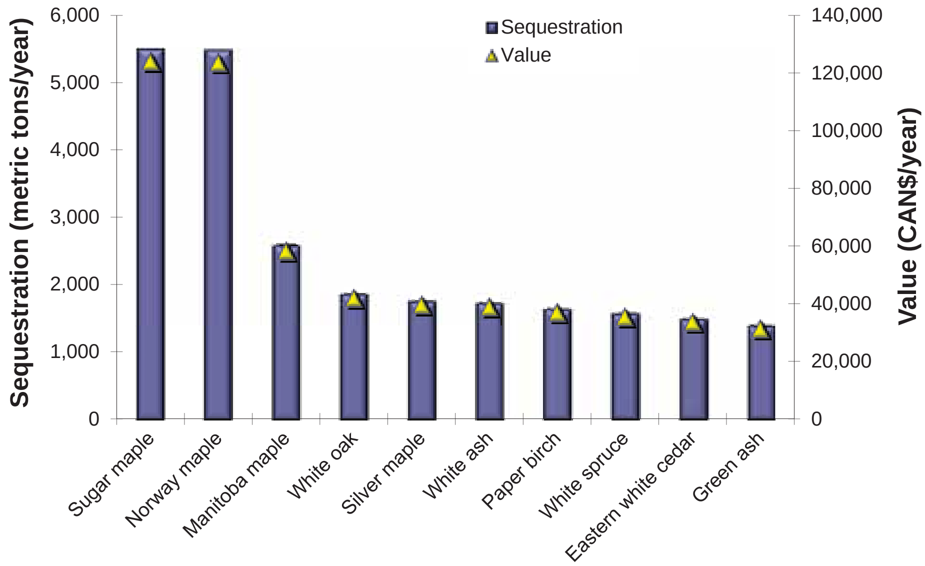


Figure 16.—Annual carbon sequestration and value for tree species with the greatest total sequestration, Toronto, 2008.

TREES AFFECT ENERGY USE IN BUILDINGS

Trees affect energy consumption by shading buildings, providing evaporative cooling, and blocking winter winds. Trees tend to reduce building energy consumption in the summer months and can either increase or decrease building energy use in the winter months, depending on the location of trees around the building. Estimates of tree effects on energy use are based on field measurements of tree distance and direction to space-conditioned residential buildings.[10]

Based on average energy costs in 2008,[22] trees in Toronto reduce energy costs from residential buildings by an estimated CAD$9.7 million annually (Tables 11-12). Trees also provide an additional CAD$382,200 in value per year by reducing the amount of carbon released by fossil-fuel based power plants (a reduction of 17,000 metric tons of carbon emissions).

Table 11.—Annual energy savings due to trees near residential buildings, Toronto, 2008

	Heating	Cooling	total
MBTU[a]	749,900	n/a	749,900
MWH[b]	6,400	34,800	41,200
Carbon avoided (t)	12,500	4,500	17,000

[a] MBTU = Million British Thermal Units
[b] MWH = Megawatt-hour

Table 12.—Annual savings[c] (CAD$) in residential energy expenditures during heating and cooling seasons, Toronto, 2008

	Heating	Cooling	Total
MBTU[a]	6,502,000	n/a	6,502,000
MWH[b]	499,000	2,709,000	3,208,000
Carbon avoided	281,700	100,500	382,200

[a] MBTU = Million British Thermal Units
[b] MWH = Megawatt-hour
[c] Based on 2008 energy costs[22]

STRUCTURAL AND FUNCTIONAL VALUES

Urban forests have a structural value based on the tree itself (e.g., the cost of replacing a similar tree). The compensatory value[11] of the urban forest in Toronto is about CAD$7.1 billion (Fig. 17). The structural value of an urban forest tends to increase with a rise in the number and size of healthy trees. The city has the following policy statement which supports the retention and planting of large stature trees: *the City recognizes that long-lived, large-growing tree species are an important component of a healthy, diverse urban forest.*

House in Rosedale, Toronto, Ontario.
Photo by WayneRay, Wikimedia Commons..

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

Structural values (CAD$):

- Compensatory value: $7.1 billion
- Carbon storage: $25.0 million

Annual functional values (CAD$):

- Carbon sequestration: $1.1 million
- Pollution removal: $16.9 million
- Lower energy costs and reduced carbon emissions: $10.1 million

Benefits such as these relate to a current initiative under way within Ontario for defining infrastructure to include trees and natural areas in an effort to protect and enhance these natural resources. The term "green infrastructure" is defined by the Ontario Coalition as the natural vegetation and vegetative technologies that are responsible for a variety of products and services to society. Green infrastructure promotes healthy living and can include things such as tree canopies, green roofs, and natural areas such as wetlands or meadows that are not dominated by trees. To learn more about the coalition's initiatives visit: http://greeninfrastructureontario.org/.

More detailed information on the urban forest in Toronto can be found at http://www.nrs.fs.fed.us/urban/data. Additionally, information on other urban forest values can be found in Appendix II and information comparing tree benefits to estimates of average carbon emissions in the city, average automobile emissions, and average household emissions can be found in Appendix VI.

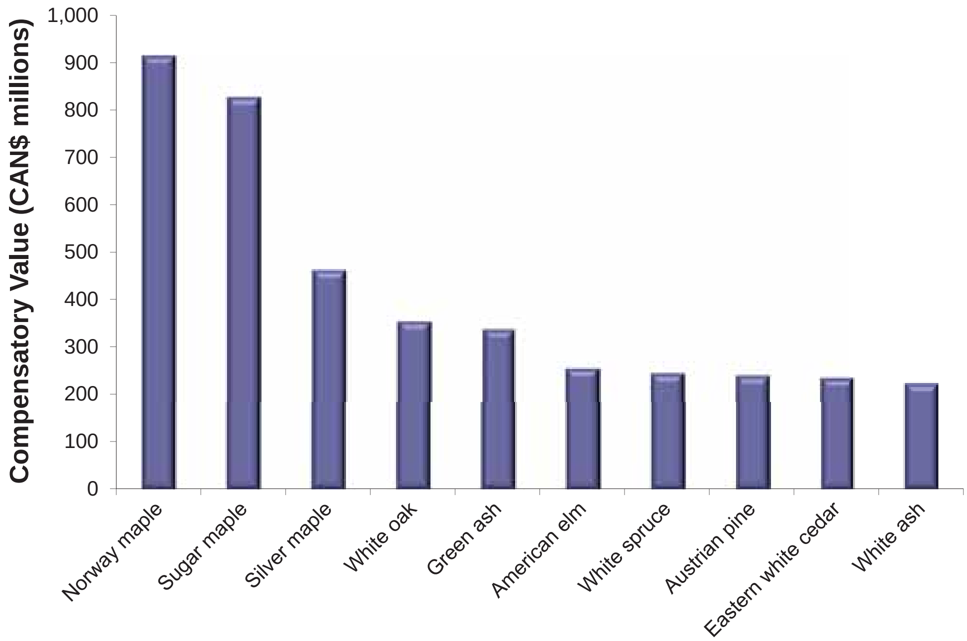


Figure 17.—Tree species with the greatest compensatory value, Toronto, 2008.

Urban forests have a structural value based on the characteristics of the trees themselves.

Urban forests also have functional values based on the ecosystem functions the trees perform.

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

SPECIES RECOMMENDATIONS

To help sustain urban forest benefits in the future, proper species selection and landscape design will be essential. To aid in selecting tree species to maximize environmental benefits, the i-Tree species selector program was used.[23] The program selected from the potential list of 1,585 tree species, eliminating trees not appropriate for Toronto's hardiness zone (USDA zone 5b). The program then weighted various species function or benefits based on the following weights supplied by the city of Toronto. Functions are weighted on a scale of 0 to10, with a weight of 0 indicating no importance and a weight of 10 indicating highest importance.

- Air pollution removal = 10
- Stream flow reduction = 10
- Air temperature reduction = 10
- Ultraviolet radiation reduction = 9
- Building energy conservation = 9
- Wind reduction = 8
- Low volatile organic compound (VOC) emissions = 3
- Carbon storage = 2
- Pollen allergenicity = 1

Recommended species based on the weights provided are given in 10 percent grouping for the available species (e.g., top 10 percent, 10-20 percent, etc.) (Table 13). The recommended species list is designed to be only a beginning guide for species selection based on desired tree functions. Numerous other species attributes need to be considered in selecting species: invasiveness, native vs. exotic, pest or other problems, maintenance requirements, life span, adapted to local site conditions, etc. In addition, some species that are hardy to the Toronto area are not in the species selection program[23] (i.e., there are likely other good species candidates for planting). Consult local tree experts to determine a final planting list.

City of Toronto Urban Forestry Staff have prepared two lists of recommended species. One list is relevant for street tree and urban applications and includes some of the most available urban tolerant species. It can be found at: http://www.toronto.ca/trees/pdfs/FreeTree_Final.pdf. The second list details native species for naturalized areas and ravines and can be found at: http://www.toronto.ca/trees/pdfs/Tree_List.pdf.

Table 13.—Top rated species for desired ecosystem services

Scientific name	Common name
Species – top 10%	
Abies concolor	White fir
Abies holophylla	Manchurian fir
Acer pseudoplatanus	Sycamore maple
Acer rubrum	Red maple
Acer saccharum	Sugar maple
Acer x freemanii	Freeman maple
Aesculus flava	Yellow buckeye
Aesculus glabra	Ohio buckeye
Aesculus hippocastanum	Horsechestnut
Betula alleghaniensis	Yellow birch
Betula papyrifera	Paper birch
Celtis laevigata	Sugarberry
Celtis occidentalis	Northern hackberry
Corylus colurna	Turkish hazelnut
Fagus grandifolia	American beech
Juglans nigra	Black walnut
Larix decidua	European larch
Larix kaempferi	Japanese larch
Larix laricina	Tamarack
*Larix leptolepis**	Japanese larch
Liriodendron tulipifera	Yellow-poplar or tuliptree
Magnolia acuminata	Cucumbertree
*Metasequoia glyptostroboides**	Dawn redwood
Picea abies	Norway spruce
Picea abies x asperata	Norway x chinese spruce
Pinus jeffreyi	Jeffery pine
Pinus monticola	Western white pine
Pinus ponderosa	Ponderosa pine

continued

Table 13.—continued

Scientific name	Common name
Pinus strobus	Eastern white pine
Pinus sylvestris	Scotch pine
*Platanus hybrida**	London planetree
Platanus occidentalis	American sycamore
Populus deltoides	Eastern cottonwood
Pseudotsuga macrocarpa	Bigcone douglas fir
Pseudotsuga menziesii	Douglas fir
Quercus petraea	Durmast oak
Tilia americana	American basswood
Tilia cordata	Littleleaf linden
Tilia platyphyllos	Bigleaf linden
Tilia tomentosa	Silver linden
Tsuga canadensis	Eastern hemlock
Tsuga caroliniana	Carolina hemlock
Tsuga mertensiana	Mountain hemlock
Ulmus americana	American elm
Ulmus glabra	Wych elm
Ulmus serotina	September elm
Zelkova serrata	Japanese zelkova
Species – top 11-20%	
*Aesculus parviflora**	Bottlebrush buckeye
*Aesculus x hybrida**	Hybrid chestnut
Betula lenta	Black birch
Carpinus betulus	European hornbeam
Chamaecyparis nootkatensis	Alaska cedar
Fagus sylvatica	European beech
Ginkgo biloba	Ginkgo
Juglans cinerea	Butternut
Juglans regia	English walnut
Larix occidentalis	Western larch
Magnolia macrophylla	Bigleaf magnolia
Magnolia tripetala	Umbrella magnolia
Morus rubra	Red mulberry
Picea glehnii	Sagholia spruce
Picea mariana	Black spruce
Picea omorika	Serbian spruce
Picea pungens	Blue spruce
Pinus contorta	Lodgepole pine

continued

Table 13.—continued

Scientific name	Common name
Pinus densiflora	Japanese red pine
Pinus parviflora	Japanese white pine
Pinus radiata	Monterey pine
Pinus resinosa	Red pine
Pinus rigida	Pitch pine
Pinus strobiformis	Southwestern white pine
Prunus serotina	Black cherry
Taxodium distichum	Baldcypress
Taxus cuspidata	Japanese yew
*Tilia euchlora**	Crimean linden
*Tilia x vulgaris**	Common linden

For methods – see i-Tree Species Selector (Beta) Utility at www.itreetools.org.

* Some uncertainty to hardiness zone. As hardiness estimates or maps did not always exactly match USDA Plant Hardiness Zones, some extrapolations were made to the closest hardiness zone. Hardiness is based on USDA Plant Hardiness Zones. For hardiness zones with decimal (e.g., 4.5), values were rounded down for maximum hardiness (e.g., 4) and up for minimum hardiness zone (e.g., 5)
Species with hardiness zone uncertainty from genera or family averages were removed from the list.

Norway maple (*Acer platanoides)* and Siberian elm (*Ulmus pumila*) have been removed from the species recommendation lists because they are invasive species in the Toronto area.

White ash (*Fraxinus americana*), European ash (*Fraxinus excelsior*), green ash (*Fraxinus pennsylvanica*), and blue ash (*Fraxinus quadrangulata*) have been removed from the species recommendation list because they are common hosts to the plant pest the emerald ash borer.

POTENTIAL INSECT AND DISEASE IMPACTS

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

Asian longhorned beetle

Photo by Kenneth R. Law
USDA APHIS PPQ, www.invasive.org

The Asian longhorned beetle (ALB)[24] is an insect that bores into and kills a wide range of hardwood species. This beetle was discovered in 1996 in Brooklyn, NY, and has subsequently spread to Long Island, Queens, and Manhattan. In 1998, the beetle was discovered in the suburbs of Chicago, IL. Beetles have also been found in Jersey City, NJ (2002), Toronto/Vaughan, Ontario (2003) and Middlesex/Union counties, NJ (2004). In 2007, the beetle was found on Staten and Prall's Island, NY. Most recently, beetles were detected in Worcester, MA (2008). This beetle represents a potential loss to the Toronto urban forest of CAD$4.0 billion in compensatory value (42.9 percent of the population).

Toronto and the Canadian Food Inspection Agency (CFIA) collaborated on an aggressive ALB eradication program when the beetle was first found in Toronto in 2003. Since then about 27,000 host trees have been removed in the Toronto and Vaughan areas as part of the eradication program. Tree replacement funded by the CFIA, Ministry of Natural Resources, and city of Toronto has mitigated this loss of tree canopy through replacement planting initiatives. Monitoring for ALB continues and no viable life stages of ALB have been detected since the summer of 2007.

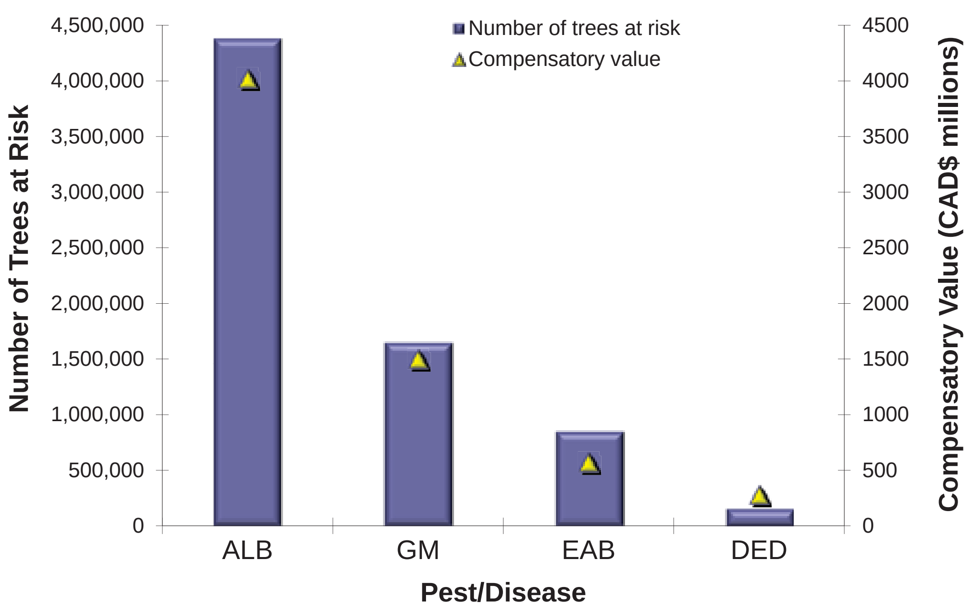


Figure 18.—Potential number of trees and value potentially affected by various insects and diseases, Toronto, 2008.

The gypsy moth (GM)[25] is a defoliator that feeds on many species causing widespread defoliation and tree death if outbreak conditions last several years. This pest could potentially result in damage to or a loss of CAD$1.5 billion in compensatory value (16.2 percent of the population). In 2007 and 2008 Toronto successfully implemented a control program for the European gypsy moth. As part of the program, 320 ha (790 acres) were sprayed with the biological control agent *Bacillus thuringiensis* subspecies *kurstaki* (Btk) using a low-flying helicopter and egg masses were removed from over 3,500 trees. Approximately 100 trees were treated with Btk from the ground. The result of this proactive integrated pest management approach was a drastic reduction of the European gypsy moth population to acceptable levels. Additional control measures have not been necessary since 2008.

Emerald ash borer

Photo by David Cappaert Michigan State University, www.invasive.org

Since being discovered in Detroit in 2002, emerald ash borer (EAB)[26] has killed millions of ash trees in Illinois, Indiana, Kentucky, Maryland, Michigan, Minnesota, Missouri, New York, Ohio, Ontario, Pennsylvania, Tennessee, Quebec, Virginia, West Virginia, and Wisconsin. EAB has the potential to affect 8.4 percent of Toronto's trees (CAD$570 million in compensatory value). Loss of ash trees in Toronto would reduce tree and shrub cover in the city from 26.6 % to about 24.4%. The city is monitoring emerald ash borer populations and aggressively removing trees from infested areas in an effort to manage the risk to the public (Figs. 19-20).

American elm, one of the most important street trees in the 20th century, has been devastated by the Dutch elm disease (DED). Since first reported in the 1930s, it has killed more than 50 percent of the native elm population in the United States.[27] Although some elm species have shown varying degrees of resistance, Toronto possibly could lose 1.6 percent of its trees to this disease (CAD$279 million in structural value).

An elm-lined street in St. Paul, MN, before most of the trees were killed by Dutch elm disease. Photo by Joseph O'Brien, U.S. Forest Service.

Symptoms of Dutch elm disease. Photo by Joseph O'Brien, U.S. Forest Service.

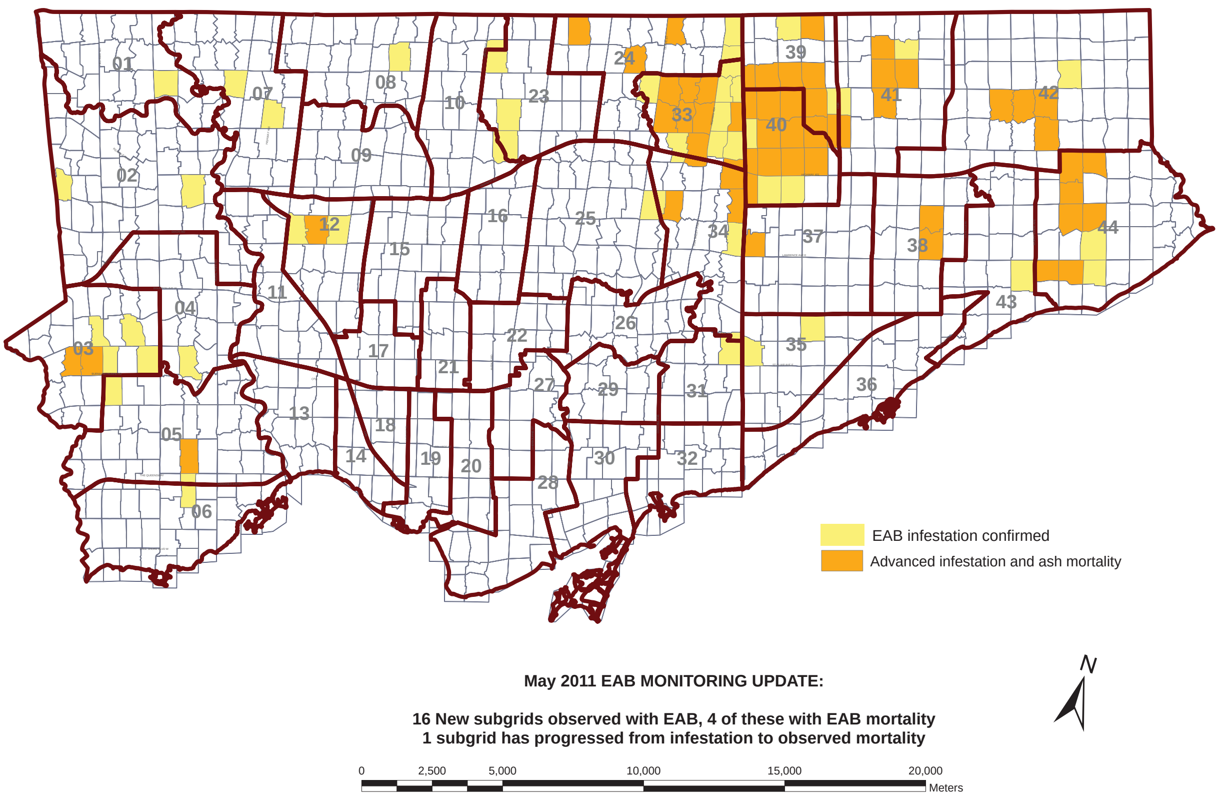


Figure 19.—Emerald ash borer infestation, Toronto, May 2011.
Image from Ruthanne Henry, Toronto Parks, Forestry and Recreation.

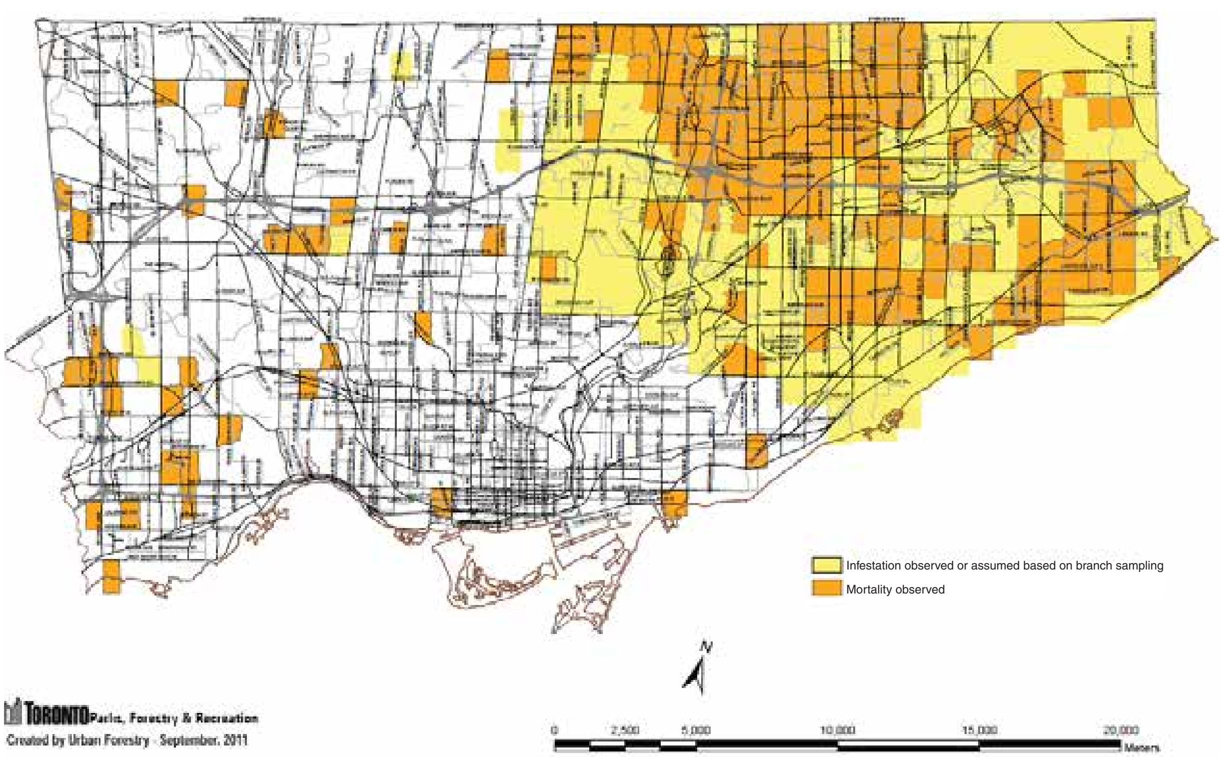


Figure 20.—Emerald ash borer infestation, Toronto, September 2011.
Image from Ruthanne Henry, Toronto Parks, Forestry and Recreation.

DON WATERSHED ANALYSIS

Toronto has designated approximately 11,000 ha (27,000 acres) or 17.5 percent of the city land area for the protection of natural features. This land buffers watercourses within six major watersheds running through the city.

The Don Watershed (Fig. 21; 46,000 ha) in the Toronto area contains areas of ravines, which are common features in Toronto and cover about 17.5 percent of the city. The Don Watershed was analyzed using the i-Tree-Hydro model.[28] i-Tree-Hydro is a semi-distributed, physical-based model created to simulate and study tree effects on urban hydrology. The model simulates the stream flow hydrograph using hourly precipitation data, digital elevation data, and cover parameters. The model flow is calibrated against actual stream flow values.

The precipitation data were collected from the Toronto City weather station (Ontario Climate Centre, climate ID: 6158355; WMO ID: 71508). The digital elevation model data were obtained from the Toronto Regional Conservation Authority. Tree, impervious, and other land cover parameters were derived from

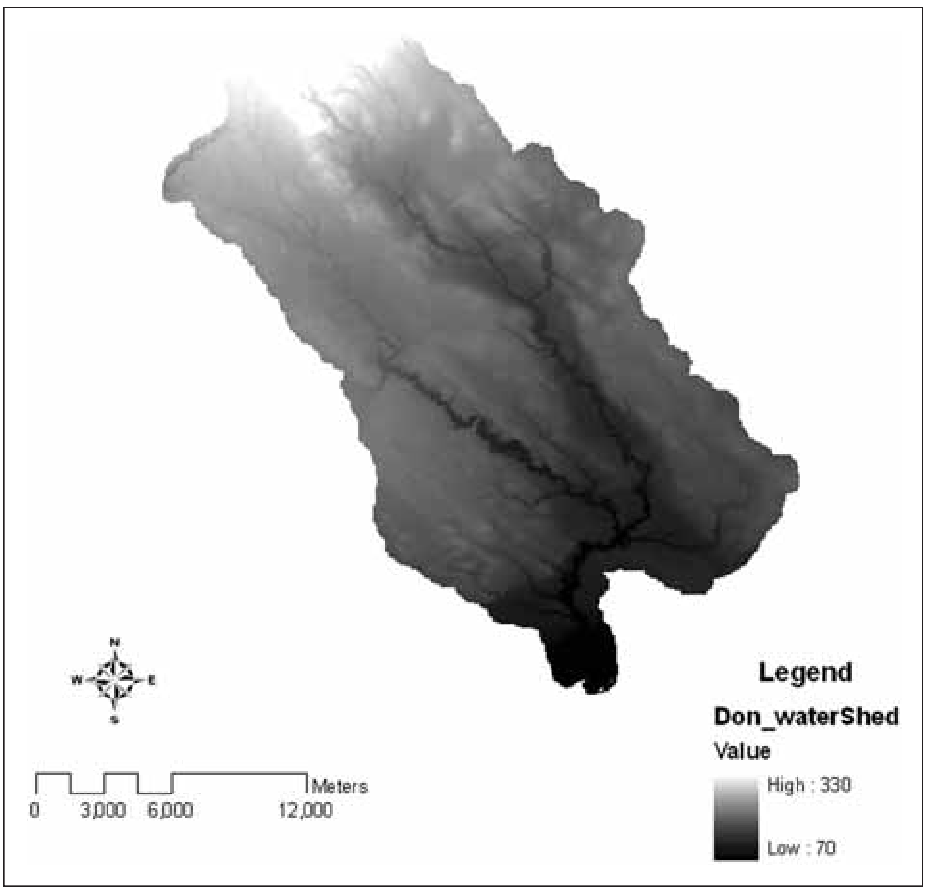


Figure 21.—Digital elevation map, Don Watershed.

photo-interpretation of Google Earth imagery (image dates circa 2005) using 500 randomly located points. Watershed land cover was estimated as follows:

- Impervious cover = 47.8%
- Tree cover = 15.7%
- Grass and shrub cover = 27%
- Bare soil = 9%

In addition, field data from Toronto were used to estimate the tree canopy leaf area index (5.1) and percent of impervious cover connected to the stream was estimated at 40 percent. The model was calibrated using hourly stream flow data collected at the gauge at Don River at Tormorden (monitor ID: 02HC024) from April 1, 2007 to October 31, 2007. Model calibration indicated a reasonably good fit to the measured flow data. The calibration coefficients of the model were (1.0 = perfect fit):

- Peak flow weighted = 0.39
- Base flow weighted = 0.31
- Balance flow (peak and base) = 0.52

After calibration, the model was run a number of times under various conditions to see how the stream flow would respond given varying tree and impervious cover in the watershed. For tree cover simulations, impervious cover was held constant (47.8 percent) with tree cover varying between 0 and 100 percent. Increasing tree cover was assumed to fill bare soil spaces first, then grass and shrub covered areas, and then finally impervious covered land. At 100 percent tree cover, all impervious land is covered by trees. This assumption is unreasonable as all buildings, roads, and parking lots would be covered by trees. However the results illustrate the potential impact. Reductions in tree cover were assumed to be filled with grass and shrub cover.

For impervious cover simulations, tree cover was held constant (15.7 percent) with impervious cover varying between 0 and 100 percent. Increasing impervious cover was assumed to fill bare soil spaces first, then grass and shrub covered areas, and then finally under tree canopies. The assumption of 100 percent impervious cover is unreasonable, but the results illustrate the potential impact. In addition, as impervious increased from the current conditions, so did the percent of the impervious cover connected to the stream such that at 100 percent impervious cover, all (100 percent) impervious cover is connected to the stream. Reductions in impervious cover were assumed to be filled with grass and shrub cover.

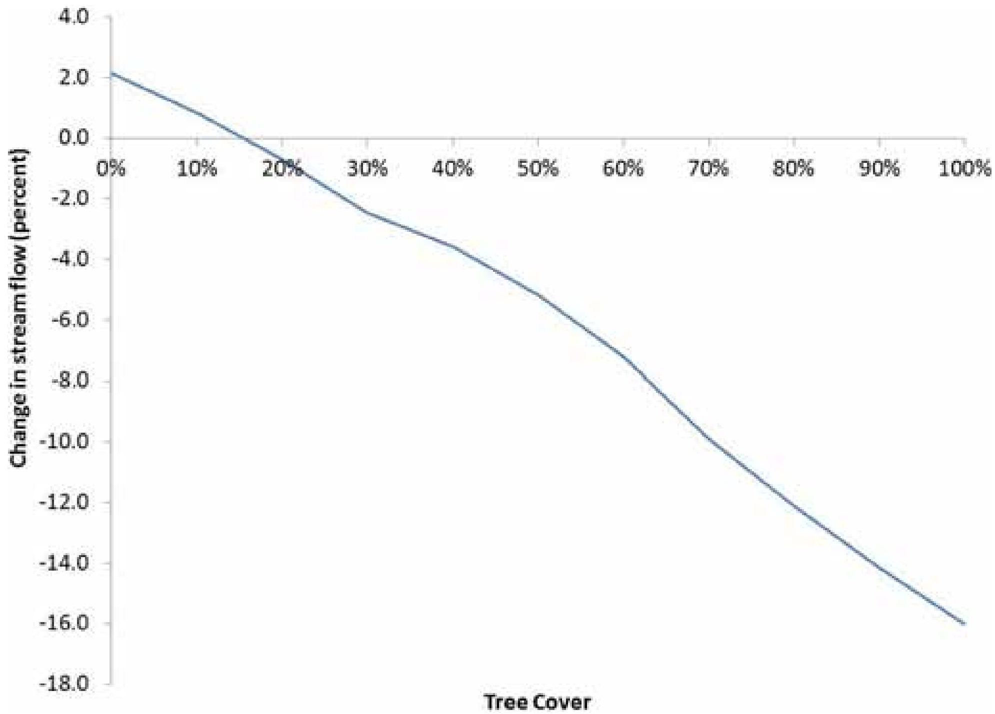


Figure 22.—Change in stream flow by tree cover in Don Watershed.

Tree Cover Effects

Loss of current tree cover would increase total flow during the simulation period by an average of 2.1 percent (943,000 m^3) (Fig. 22). Doubling of tree cover would reduce flow by 2.5 percent (1.1 million m^3) during this 7-month period. Increasing tree cover reduces base flow, as well as flow regenerated from both pervious and impervious areas.

Impervious Cover Effects

Removal of current impervious cover would reduce total flow during the simulation period by an average of 23.8 percent (10.5 million m^3) (Fig. 23). Increasing impervious cover from 47.8 to 60 percent of the watershed would increase total flow another 30 percent (13.3 million m^3) during this 7-month period. Increasing impervious cover reduces base flow while significantly increasing flow from impervious surfaces.

Increasing tree cover will reduce stream flow, but the dominant cover type influencing stream flow is impervious surfaces. Overall impervious cover had a 12-fold impact relative to tree cover. Increasing impervious cover by 1 percent averaged a 2.2 percent increase in stream flow, while increasing tree cover by 1 percent averaged only a 0.2 percent decrease in stream flow.

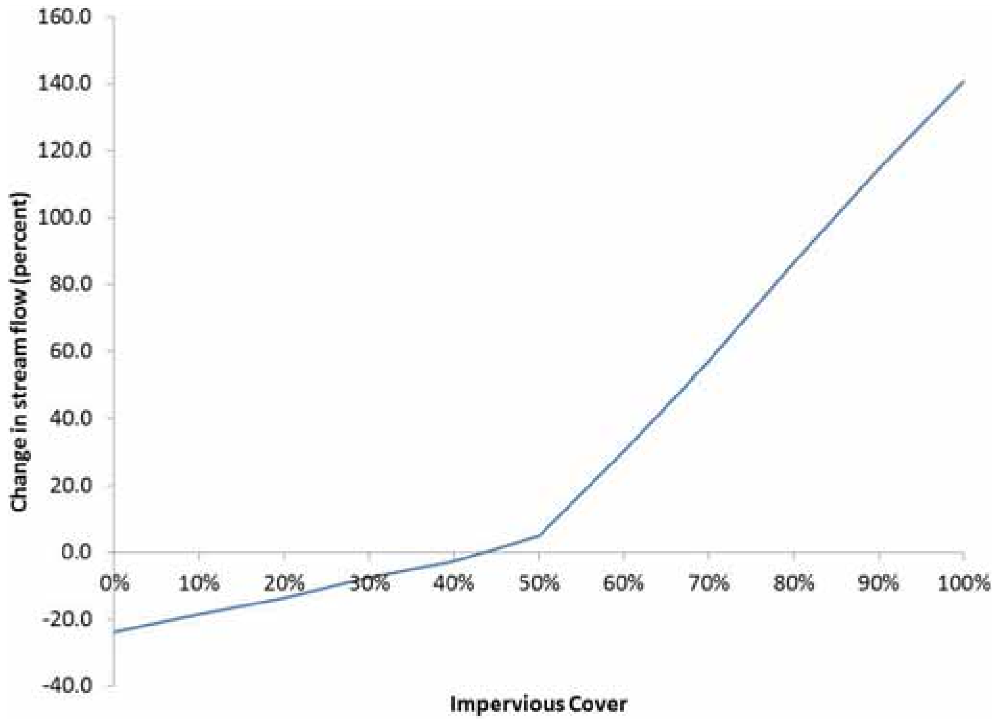


Figure 23.—Change in stream flow by impervious cover in Don Watershed

During the simulation period, the total rainfall recorded at the Toronto City weather station was 315.1 mm. Since that amount is assumed to have fallen over the entire 460 km^2 watershed, a total of 144.9 million m^3 of rain fell on the watershed during the simulation time. The total flow in Don Watershed throughout the simulation time was 43.9 million m^3. The total flow is made up of surface runoff and baseflow (water that travels underground to the stream). Baseflow and flow from impervious areas are the biggest contributors to stream flow with 47.5 percent and 47.3 percent of total flow generated from base and impervious surfaces, respectively. Flow from pervious areas was only estimated to generate 5.2 percent of total flow. Trees intercepted a little more than 17 percent of the precipitation that fell in their canopy areas, but since crowns only cover about 16 percent of the watershed, trees only intercepted about 2.7 percent of the total rainfall. Trees intercepted 24.9 million cubic meters of precipitation, and short vegetation, including shrubs, intercepted 8.4 million m^3. About 47 percent of total precipitation is estimated to re-enter the atmosphere through evaporation or evapotranspiration.

CONCLUSION

Data from this report provide the basis for a better understanding of the urban forest resource and the ecosystem services and values provided by Toronto's urban forest. Managers and citizens can use these data to help develop improved long-term management plans and policies to sustain a healthy urban tree population and ecosystem services for future generations. Improved planning and management to sustain healthy tree populations can lead to improved environmental quality and quality of life for Toronto residents.

A key product of this study was the development of a digital land and forest cover map for the entire city. For the first time, this map allows forest managers to assess the spatial distribution of the tree canopy and perform area-based analysis of forest and land cover for defined geographic areas. This map can assess both existing cover, but also potential space available for new tree cover. The map also provides a valuable communication tool for decision makers and residents who can use tree canopy maps to drive community interest in trees at a ward or neighbourhood level.

For additional information on estimating the costs of ecological benefits and ecosystem services, such as soil formation, nutrient cycling, pollination, natural regeneration, and habitat, there are a number of recent studies that are applicable to Ontario. One study in particular is the David Suzuki Foundation study, "Ontario's Wealth, Canada's Future: Appreciating the Value of the Greenbelt's Eco-Services".[29] This study references the 1.8 million acres of greenbelt that wraps the greater Toronto and Golden Horseshoe Areas, which contain the highest population density within Ontario. Another noteworthy study is the Ministry of Natural Resources' publication "Estimating Ecosystem Services in Southern Ontario".[30] In this study, the authors highlight the additional economic benefits of ecological services that are in proximity to higher populations often associated with urban areas that depend on these benefits. The Toronto and Region Conservation Authority (TRCA) has also published a "Peel Region Urban Forest Strategy".[31] The work by the TRCA along with information in this Toronto publication are providing a consistent urban forest data collection strategy for the region to help guide urban forests in the future.

Improved planning and management to sustain healthy tree populations can lead to improved environmental quality and quality of life for Toronto residents.

By ownership type, it is Toronto's residents and other private land owners (commercial/industrial) that control the majority (59.9 percent) of the city's tree canopy. In addition, single family residential land contributed the most new tree cover (26,300 ha) between 1999 and 2009 and have the most potentially available space to plant trees. Thus, incentives to encourage tree planting on private properties and programs to engage residents and property owners in tree stewardship are potential actions that can significantly support sustaining tree canopy in the long term. The city is interested in innovation and collaboration with private properties to continue to encourage growth, stewardship and conservation for the resource in private ownership.

This study highlights the need for consistent tree cover assessment methodology. Recommendations for future methods for canopy assessment within Toronto will be explored in more detail in the context of a strategic forest management plan. This report on Toronto's urban forest and tree cover provides valuable data that will help enrich the dialogue between decisionmakers, planners, forest managers, and residents regarding the future of Toronto's urban forest.

More information on trees in Toronto can be found at: http://nrs.fs.fed.us/data/urban.

City arborist in a Toronto parkland tree. Photo by Urban Forestry, City of Toronto, used with permission.

APPENDIX I. LIST OF SPECIES

Genus	Species	Common Name	% Pop	% Leaf Area	IV[a]
Abies	*balsamea*	Balsam fir	0.1	0.1	0.2
Abies	*concolor*	White fir	0.1	0.1	0.2
Acer	*campestre*	Hedge maple	0.1	0.1	0.2
Acer	*ginnala*	Amur maple	0.1	0.1	0.2
Acer	negundo	Manitoba maple	5.0	5.5	10.5
Acer	*nigrum*	Black maple	0.5	1.0	1.5
Acer	*palmatum*	Japanese maple	0.3	0.1	0.4
Acer	*platanoides*	Norway maple	6.5	14.9	21.4
Acer	*rubrum*	Red maple	0.2	0.8	1.0
Acer	*saccharinum*	Silver maple	0.9	4.5	5.4
Acer	*saccharum*	Sugar maple	10.2	11.6	21.8
Acer	*x freemanii*	Freeman maple	0.1	0.3	0.4
Aesculus	*hippocastanum*	Horsechestnut	0.1	0.2	0.3
Ailanthus	*altissima*	Tree-of-heaven	0.7	0.7	1.4
Alnus	glutinosa	European alder	0.2	0.1	0.3
Alnus	*incana*	Grey alder	0.4	0.1	0.5
Amelanchier	*alnifolia*	Western serviceberry	0.1	0.0	0.1
Amelanchier	*arborea*	Downy serviceberry	0.5	0.1	0.6
Amelanchier	*canadensis*	Eastern serviceberry	0.3	0.0	0.3
Amelanchier	*laevis*	Smooth serviceberry	0.0	0.0	0.0
Aralia	*spinosa*	Devils-walkingstick	0.1	0.0	0.1
Betula	*alleghaniensis*	Yellow birch	0.2	0.4	0.6
Betula	*nigra*	River birch	0.0	0.0	0.0
Betula	*papyrifera*	Paper birch	1.4	2.5	3.9
Carpinus	caroliniana	American hornbeam	0.2	0.1	0.3
Carya	*cordiformis*	Bitternut hickory	0.3	0.8	1.1
Catalpa	*speciosa*	Northern catalpa	0.3	0.3	0.6
Celtis	*occidentalis*	Common hackberry	0.0	0.1	0.1
Chamaecyparis	*lawsoniana*	Port-Orford-cedar	1.5	0.1	1.6
Cornus	*alternifolia*	Alternate-leaf dogwood	0.1	0.0	0.1
Cornus	*florida*	Flowering dogwood	0.0	0.0	0.0
Cornus	*mas*	Cornelian cherry	0.0	0.0	0.0
Crataegus	*calpodendron*	Pear hawthorn	0.3	0.0	0.3
Crataegus	*chrysocarpa*	Fireberry hawthorn	0.1	0.1	0.2
Crataegus	crus-galli	Cockspur hawthorn	1.0	0.4	1.4
Crataegus	*mollis*	Downy hawthorn	0.1	0.1	0.2
Cydonia	*oblonga*	Quince	0.0	0.0	0.0
Elaeagnus	*angustifolia*	Russian-olive	0.1	0.1	0.2
Euonymus	*atropurpureus*	Eastern wahoo	0.0	0.0	0.0
Euonymus	*europaea*	European spindle tree	0.0	0.0	0.0
Fagus	*grandifolia*	American beech	0.7	0.5	1.2
Fagus	*sylvatica*	European beech	0.2	0.2	0.4

continued

APPENDIX I.—CONTINUED

Genus	Species	Common Name	% Pop	% Leaf Area	IV[a]
Fraxinus	*americana*	White ash	5.3	2.7	8.0
Fraxinus	*excelsior*	European ash	0.1	0.2	0.3
Fraxinus	*pennsylvanica*	Green ash	3.6	5.0	8.6
Ginkgo	*biloba*	Ginkgo	0.0	0.0	0.0
Gleditsia	*triacanthos*	Honeylocust	1.5	1.2	2.7
Hamamelis	*virginiana*	Witch hazel	0.1	0.0	0.1
Hibiscus	*syriacus*	Rose-of-sharon	0.0	0.0	0.0
Juglans	*cinerea*	Butternut	0.2	0.6	0.8
Juglans	*nigra*	Black walnut	0.2	0.7	0.9
Juniperus	*chinensis*	Chinese juniper	0.0	0.0	0.0
Juniperus	*communis*	Common juniper	0.1	0.0	0.1
Juniperus	*pinchotii*	Pinchot juniper	0.0	0.0	0.0
Juniperus	virginiana	Eastern redcedar	0.7	0.2	0.9
Larix	*laricina*	Tamarack	0.0	0.1	0.1
Ligustrum	*lucidum*	Chinese privet	0.1	0.0	0.1
Magnolia	*acuminata*	Cucumbertree	0.2	0.1	0.3
Magnolia	*x soulangeana*	Saucer magnolia	0.1	0.0	0.1
Malus	*angustifolia*	Southern crab apple	0.0	0.0	0.0
Malus	*baccata*	Siberian crab apple	0.1	0.3	0.4
Malus	*coronaria*	Sweet crab apple	0.2	0.1	0.3
Malus	*sylvestris*	European crab apple	2.3	1.5	3.8
Malus	*tschonoskii*	Crabapple	0.2	0.2	0.4
Morus	alba	White mulberry	0.5	0.3	0.8
Morus	*nigra*	Black mulberry	0.2	0.2	0.4
Morus	*rubra*	Red mulberry	0.0	0.0	0.0
Ostrya	*virginiana*	Eastern hophornbeam	3.2	2.4	5.6
Other	*species*	Other species	0.8	0.4	1.2
Picea	*abies*	Norway spruce	1.2	1.0	2.2
Picea	*glauca*	White spruce	3.3	4.6	7.9
Picea	*pungens*	Blue spruce	0.6	1.4	2.0
Pinus	*nigra*	Austrian pine	1.4	2.7	4.1
Pinus	*resinosa*	Red pine	1.1	0.3	1.4
Pinus	strobus	Eastern white pine	1.5	0.9	2.4
Pinus	*sylvestris*	Scotch pine	0.6	0.4	1.0
Populus	*balsamifera*	Balsam poplar	0.4	0.0	0.4
Populus	*deltoides*	Eastern cottonwood	0.3	0.4	0.7
Populus	*grandidentata*	Bigtooth aspen	0.5	0.6	1.1
Populus	*tremuloides*	Quaking aspen	2.0	1.0	3.0
Populus	*x canadensis*	Carolina poplar	0.1	0.3	0.4
Prunus	*americana*	American plum	0.2	0.1	0.3
Prunus	*armeniaca*	Apricot	0.1	0.1	0.2
Prunus	*avium*	Sweet cherry	0.6	0.6	1.2

continued

APPENDIX I.—CONTINUED

Genus	Species	Common Name	% Pop	% Leaf Area	IV[a]
Prunus	domestica	Common plum	0.3	0.1	0.4
Prunus	*pensylvanica*	Pin cherry	0.1	0.0	0.1
Prunus	*persica*	Peach	0.0	0.0	0.0
Prunus	*sargentii*	Sargent cherry	0.0	0.1	0.1
Prunus	*serotina*	Black cherry	2.3	1.8	4.1
Prunus	*virginiana*	Common chokecherry	1.9	0.9	2.8
Pyrus	*communis*	Common pear	0.7	0.4	1.1
Quercus	*alba*	White oak	1.0	2.0	3.0
Quercus	*macrocarpa*	Bur oak	0.2	0.1	0.3
Quercus	*robur*	English oak	0.0	0.1	0.1
Quercus	rubra	Northern red oak	0.6	1.3	1.9
Rhamnus	*cathartica*	European buckthorn	1.6	0.5	2.1
Robinia	*pseudoacacia*	Black locust	0.2	0.9	1.1
Salix	*alba*	White willow	0.3	1.5	1.8
Salix	*babylonica*	Weeping willow	0.1	0.5	0.6
Salix	*discolor*	Pussy willow	0.1	0.0	0.1
Salix	*nigra*	Black willow	0.1	0.6	0.7
Sorbus	*americana*	American mountain-ash	0.1	0.0	0.1
Sorbus	*aucuparia*	European mountain-ash	0.0	0.0	0.0
Sorbus	*decora*	Showy mountain-ash	0.0	0.0	0.0
Syringa	reticulata	Japanese tree lilac	0.0	0.0	0.0
Syringa	*vulgaris*	Common lilac	0.2	0.1	0.3
Taxus	*baccata*	English yew	0.3	0.1	0.4
Taxus	*canadensis*	Canada yew	0.4	0.1	0.5
Thuja	*occidentalis*	Eastern white-cedar	15.6	2.8	18.4
Thuja	*plicata*	Western redcedar	0.0	0.0	0.0
Tilia	*americana*	American basswood	1.4	1.5	2.9
Tilia	*cordata*	Littleleaf linden	0.8	1.1	1.9
Tsuga	*canadensis*	Eastern hemlock	0.2	0.5	0.7
Ulmus	*americana*	American elm	1.5	3.7	5.2
Ulmus	pumila	Siberian elm	2.7	2.3	5.0
Ulmus	*rubra*	Slippery elm	0.2	0.3	0.5

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

APPENDIX II. COMPARISON OF URBAN FORESTS

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

City totals, trees only

City	% Tree cover	Number of trees	Carbon storage (t)	Carbon sequestration (t/yr)	Pollution removal (t/yr)[†]	Pollution value C CAD$/yr[‡]
Calgary, Alberta[a]	7.2	11,889,000	404,000	19,400	296	2,329,000
Toronto, Ontario[a*]	26.6	10,220,000	1,108,000	46,700	1,905	16,940,000
Atlanta, GA[b]	36.7	9,415,000	1,220,000	42,100	1,509	12,066,000
New York, NY[b]	20.9	5,212,000	1,225,000	38,400	1,521	11,692,000
London, Ontario[c]	24.7	4,376,000	360,000	12,500	370	3,320,000
Brampton, Ontario[e*]	15.2	3,618,000	175,000	7,700	184	1,620,000
Baltimore, MD[d]	21.0	2,627,000	542,000	14,700	390	3,086,000
Philadelphia, PA[b]	15.7	2,113,000	481,000	14,600	522	4,100,000
Mississauga, Ontario[e*]	19.0	2,104,000	203,000	10,000	336	2,973,000
Washington, DC[f]	28.6	1,928,000	477,000	14,700	379	2,824,000
Oakville, Ontario[c]	29.1	1,908,000	133,000	6,000	172	1,404,000
Ajax, Ontario[e*]	18.4	1,366,000	106,000	3,500	39	350,000
Boston, MA[b]	22.3	1,183,000	290,000	9,500	257	2,067,000
Woodbridge, NJ[g]	29.5	986,000	145,000	5,000	191	1,507,000
Minneapolis, MN[h]	26.4	979,000	227,000	8,100	277	2,215,000
Syracuse, NY[d]	23.1	876,000	157,000	4,900	99	826,000
San Francisco, CA[a]	11.9	668,000	176,000	4,600	128	1,006,000
Moorestown, NJ[g]	28.0	583,000	106,000	3,400	107	831,000
Morgantown, WV[i]	39.6	577,000	77,000	2,700	52	387,000
Jersey City, NJ[g]	11.5	136,000	19,000	800	37	288,000
Casper, WY[a]	8.9	123,000	34,000	1,100	34	272,000
Freehold, NJ[g]	34.4	48,000	18,000	500	20	160,000

Per hectare values of tree effects

City	No. of trees (trees/ha)	Carbon Storage (t/ha)	Carbon sequestration (t/ha/yr)	Pollution removal (kg/ha/yr)[†]	Pollution value CAD$/ha/yr[‡]
Calgary, Alberta[a]	164.8	5.6	0.3	4.1	32.3
Toronto, Ontario[a]	160.4	17.4	0.7	24.3	265.8
Atlanta, GA[b]	275.8	35.7	1.2	44.2	353.4
New York, NY[b]	65.2	15.3	0.5	19.0	146.3
London, Ontario[c]	185.5	15.3	0.5	15.7	140.7
Brampton, Ontario[e]	134.3	6.5	0.3	6.8	60.1
Baltimore, MD[d]	125.6	25.9	0.7	18.6	147.5
Philadelphia, PA[b]	61.9	14.1	0.4	15.3	120.1
Mississauga, Ontario[e]	73.1	7.0	0.3	11.7	103.2
Washington, DC[f]	121.1	30.0	0.9	23.8	177.4

continued

APPENDIX II.—CONTINUED

Per hectare values of tree effects

City	No. of trees (trees/ha)	Carbon Storage (t/ha)	Carbon sequestration (t/ha/yr)	Pollution removal (kg/ha/yr)†	Pollution value CAD$/ha/yr‡
Oakville, Ontario[c]	192.9	13.4	0.6	17.4	101.0
Ajax, Ontario[e]	202.5	15.7	0.5	5.8	51.9
Boston, MA[b]	82.9	20.3	0.7	18.0	144.8
Woodbridge, NJ[g]	164.4	24.2	0.8	31.9	251.2
Minneapolis, MN[h]	64.8	15.0	0.5	18.3	146.6
Syracuse, NY[d]	134.7	24.2	0.8	15.2	127.0
San Francisco, CA[a]	55.7	14.7	0.4	10.7	83.9
Moorestown, NJ[g]	153.4	27.9	0.9	28.1	218.4
Morgantown, WV[i]	258.1	34.6	1.2	23.4	173.3
Jersey City, NJ[g]	35.5	5.0	0.2	9.6	75.3
Casper, WY[a]	22.5	6.2	0.2	6.2	49.8
Freehold, NJ[g]	94.6	35.9	1.0	39.6	317.7

† Pollution removal and values are for carbon monoxide, sulfur and nitrogen dioxide, ozone, and particulate matter less than 10 microns (PM10), except for London, Ontario, where estimate includes particulate matter less than 2.5 microns (PM2.5) instead of PM10.

‡ Pollution values updated to 2007 values. Values are given in Canadian dollars (CAD = 0.988 USD)

* includes shrub cover in tree cover estimate based on photo-interpretation

Data collection group

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

APPENDIX III. TREE COVER BY NEIGHBORHOOD

Tree cover (percent) by Toronto neighborhood for 1999, 2005, and 2009

	1999		2005		2009		
Neighborhood[a]	Tree Cover	SE[b]	Tree Cover	SE[b]	Tree Cover	SE[b]	n[c]
Agincourt North (129)	15.7	3.5	15.7	3.5	15.7	3.5	108
Agincourt South-Malvern West (128)	20.3	3.6	22.0	3.7	24.4	3.9	123
Alderwood (20)	22.4	4.5	21.2	4.4	24.7	4.7	85
Annex (95)	22.2	6.9	16.7	6.2	19.4	6.6	36
Banbury-Don Mills (42)	36.2	3.9	35.5	3.9	36.2	3.9	152
Bathurst Manor (34)	30.9	5.6	32.4	5.7	32.4	5.7	68
Bay Street Corridor (76)	6.7	4.6	6.7	4.6	6.7	4.6	30
Bayview Village (52)	35.6	5.6	39.7	5.7	43.8	5.8	73
Bayview Woods-Steeles (49)	39.1	6.1	39.1	6.1	37.5	6.1	64
Bedford Park-Nortown (39)	36.8	4.7	39.6	4.8	39.6	4.8	106
Beechborough-Greenbrook (112)	20.0	7.3	20.0	7.3	23.3	7.7	30
Bendale (127)	25.6	4.0	25.6	4.0	26.5	4.1	117
Birchcliffe-Cliffside (122)	29.9	4.9	32.2	5.0	31.0	5.0	87
Black Creek (24)	17.6	4.6	17.6	4.6	14.7	4.3	68
Blake-Jones (69)	20.0	7.3	23.3	7.7	26.7	8.1	30
Briar Hill-Belgravia (108)	8.3	4.6	8.3	4.6	11.1	5.2	36
Bridle Path-Sunnybrooke-York Mills (41)	56.3	4.1	55.6	4.1	55.6	4.1	144
Broadview North (57)	40.5	8.1	37.8	8.0	37.8	8.0	37
Brookhaven-Amesbury (30)	17.9	4.7	19.4	4.8	17.9	4.7	67
Cabbagetown-South St. Jamestown (71)	43.3	9.0	46.7	9.1	46.7	9.1	30
Caledonia-Fairbanks (109)	23.3	7.7	26.7	8.1	26.7	8.1	30
Casa Loma (96)	40.0	8.9	36.7	8.8	36.7	8.8	30
Centennial Scarborough (133)	19.5	4.3	21.8	4.4	23.0	4.5	87
Church-Yonge Corridor (75)	13.3	6.2	13.3	6.2	16.7	6.8	30
Clairlea-Birchmount (120)	15.0	3.6	16.0	3.7	15.0	3.6	100
Clanton Park (33)	11.1	3.7	9.7	3.5	11.1	3.7	72
Cliffcrest (123)	38.2	5.2	37.1	5.1	38.2	5.2	89
Corsa Italia-Davenport (92)	26.7	8.1	30.0	8.4	30.0	8.4	30
Crescent Town (61)	33.3	8.6	36.7	8.8	40.0	8.9	30
Danforth Village - East York (59)	17.6	6.5	20.6	6.9	23.5	7.3	34
Danforth Village - Toronto (66)	23.3	7.7	23.3	7.7	23.3	7.7	30
Don Valley Village (47)	25.6	4.7	25.6	4.7	30.2	5.0	86
Dorset Park (126)	11.1	3.3	10.0	3.2	12.2	3.5	90
Dovercourt-Wallace Emerson-Junction (93)	12.9	4.3	16.1	4.7	16.1	4.7	62
Downsview-Roding-CFB (26)	11.9	2.2	12.9	2.3	13.3	2.3	210
Dufferin Grove (83)	16.7	6.8	20.0	7.3	30.0	8.4	30
East End-Danforth (62)	34.3	8.0	37.1	8.2	37.1	8.2	35
Edenbridge-Humber Valley (9)	41.9	5.3	41.9	5.3	41.9	5.3	86
Eglinton East (138)	11.9	4.0	13.4	4.2	13.4	4.2	67
Elms-Old Rexdale (5)	27.8	7.5	27.8	7.5	30.6	7.7	36
Englemount-Lawrence (32)	26.5	6.3	30.6	6.6	32.7	6.7	49

continued

APPENDIX III.—CONTINUED

Tree cover (percent) by Toronto neighborhood for 1999, 2005, and 2009

	1999		2005		2009		
Neighborhood[a]	Tree Cover	SE[b]	Tree Cover	SE[b]	Tree Cover	SE[b]	n[c]
Eringate-Centennial-West Deane (11)	20.5	3.5	19.7	3.5	20.5	3.5	132
Etobicoke West Mall (13)	16.7	6.8	16.7	6.8	20.0	7.3	30
Flemington Park (44)	25.0	6.8	25.0	6.8	30.0	7.2	40
Forest Hill North (102)	50.0	9.1	50.0	9.1	50.0	9.1	30
Forest Hill South (101)	48.8	7.8	48.8	7.8	51.2	7.8	41
Glenfield-Jane Heights (25)	25.0	4.7	22.6	4.6	21.4	4.5	84
Greenwood-Coxwell (65)	23.3	7.7	26.7	8.1	30.0	8.4	30
Guildwood (140)	39.2	6.8	41.2	6.9	39.2	6.8	51
Henry Farm (53)	37.8	7.2	33.3	7.0	33.3	7.0	45
High Park North (88)	36.7	8.8	36.7	8.8	36.7	8.8	30
High Park-Swansea (87)	44.8	5.1	45.8	5.1	46.9	5.1	96
Highland Creek (134)	28.8	5.1	30.0	5.1	30.0	5.1	80
Hillcrest Village (48)	17.9	4.3	17.9	4.3	17.9	4.3	78
Humber Heights-Westmount (8)	25.6	7.0	25.6	7.0	28.2	7.2	39
Humber Summit (21)	7.7	2.8	7.7	2.8	8.8	3.0	91
Humbermede (22)	10.3	4.0	13.8	4.5	15.5	4.8	58
Humewood-Cedarvale (106)	34.4	8.4	37.5	8.6	34.4	8.4	32
Ionview (125)	25.0	7.7	21.9	7.3	21.9	7.3	32
Islington-City Centre West (14)	15.4	2.3	15.4	2.3	15.4	2.3	246
Junction Area (90)	6.7	4.6	6.7	4.6	6.7	4.6	30
Keelesdale-Eglinton West (110)	17.6	6.5	14.7	6.1	17.6	6.5	34
Kennedy Park (124)	37.8	8.0	37.8	8.0	35.1	7.8	37
Kensington-Chinatown (78)	20.0	7.3	20.0	7.3	20.0	7.3	30
Kingsview Village-The Westway (6)	24.3	5.0	25.7	5.1	25.7	5.1	74
Kingsway South (15)	40.8	7.0	44.9	7.1	46.9	7.1	49
Lambton Baby Point (114)	36.7	8.8	33.3	8.6	33.3	8.6	30
L'Amoureaux (117)	29.8	4.3	28.9	4.2	28.9	4.2	114
Lansing-Westgate (38)	44.4	5.5	44.4	5.5	48.1	5.6	81
Lawrence Park North (105)	37.5	7.7	37.5	7.7	37.5	7.7	40
Lawrence Park South (103)	37.5	7.0	39.6	7.1	39.6	7.1	48
Leaside-Bennington (56)	43.8	5.8	45.2	5.8	47.9	5.8	73
Little Portugal (84)	10.0	5.5	10.0	5.5	10.0	5.5	30
Long Branch (19)	26.5	7.6	26.5	7.6	26.5	7.6	34
Malvern (132)	23.1	3.5	23.1	3.5	25.9	3.7	143
Maple Leaf (29)	20.0	5.7	20.0	5.7	22.0	5.9	50
Markland Woods (12)	30.8	6.4	28.8	6.3	28.8	6.3	52
Milliken (130)	9.2	2.2	8.7	2.1	8.1	2.1	173
Mimico (17)	11.3	3.2	12.4	3.3	13.4	3.5	97
Morningside (135)	48.8	5.6	52.5	5.6	53.8	5.6	80
Moss Park (73)	13.3	6.2	13.3	6.2	13.3	6.2	30
Mount Dennis (115)	25.6	7.0	25.6	7.0	25.6	7.0	39

continued

APPENDIX III.—CONTINUED

Tree cover (percent) by Toronto neighborhood for 1999, 2005, and 2009

	1999		2005		2009		
Neighborhood[a]	Tree Cover	SE[b]	Tree Cover	SE[b]	Tree Cover	SE[b]	n[c]
Mount Olive-Silverstone-Jamestown (2)	29.3	5.3	31.6	5.3	31.6	5.3	75
Mount Pleasant East (99)	54.8	7.7	52.4	7.7	54.8	7.7	42
Mount Pleasant West (104)	26.7	8.1	26.7	8.1	30.0	8.4	30
New Toronto (18)	15.2	5.3	8.7	4.2	8.7	4.2	46
Newtonbrook East (50)	23.8	5.4	23.8	5.4	28.6	5.7	63
Newtonbrook West (36)	24.7	4.6	24.7	4.6	24.7	4.6	89
Niagara (82)	14.8	4.8	14.8	4.8	16.7	5.1	54
North Riverdale (68)	20.6	6.9	20.6	6.9	26.5	7.6	34
North StJamestown (74)	20.0	7.3	16.7	6.8	13.3	6.2	30
Oakridge (121)	20.0	7.3	20.0	7.3	23.3	7.7	30
Oakwood-Vaughan (107)	10.0	5.5	16.7	6.8	16.7	6.8	30
O'Connor-Parkview (54)	33.8	5.3	35.0	5.3	35.0	5.3	80
Old East York (58)	23.3	6.4	23.3	6.4	23.3	6.4	43
Palmerston-Little Italy (80)	20.0	7.3	20.0	7.3	20.0	7.3	30
Parkwoods-Donalda (45)	34.0	4.7	34.0	4.7	35.9	4.7	103
Pelmo Park-Humberlea (23)	21.3	5.2	21.3	5.2	18.0	4.9	61
Playter Estates-Danforth (67)	36.7	8.8	36.7	8.8	36.7	8.8	30
Pleasant View (46)	26.3	7.1	26.3	7.1	26.3	7.1	38
Princess-Rosethorn (10)	37.1	6.1	35.5	6.1	38.7	6.2	62
Regent Park (72)	20.0	7.3	20.0	7.3	20.0	7.3	30
Rexdale-Kipling (4)	22.2	6.9	22.2	6.9	19.4	6.6	36
Rockcliffe-Smythe (111)	30.3	4.9	32.6	5.0	30.3	4.9	89
Roncesvalles (86)	10.0	5.5	10.0	5.5	13.3	6.2	30
Rosedale-Moore Park (98)	63.2	5.8	63.2	5.8	61.8	5.9	68
Rouge (131)	32.1	1.8	31.4	1.8	33.1	1.8	658
Runnymede-Bloor West Village (89)	23.3	7.7	23.3	7.7	26.7	8.1	30
Rustic (28)	30.0	8.4	30.0	8.4	30.0	8.4	30
Scarborough Village (139)	42.6	7.2	42.6	7.2	44.7	7.3	47
South Parkdale (85)	23.1	6.7	20.5	6.5	20.5	6.5	39
South Riverdale (70)	13.9	2.8	15.2	2.9	21.2	3.3	151
StAndrew-Windfields (40)	37.5	4.3	37.5	4.3	38.3	4.3	128
Steeles (116)	11.8	3.7	13.2	3.9	13.2	3.9	76
Stonegate-Queensway (16)	28.7	4.2	30.4	4.3	32.2	4.4	115
Tam O'Shanter-Sullivan (118)	26.1	4.7	23.9	4.5	28.4	4.8	88
The Beaches (63)	41.9	6.3	40.3	6.2	40.3	6.2	62
Thistletown-Beaumond Heights (3)	38.0	6.9	34.0	6.7	36.0	6.8	50
Thorncliffe Park (55)	16.3	5.3	16.3	5.3	18.4	5.5	49
Trinity-Bellwoods (81)	26.7	8.1	30.0	8.4	33.3	8.6	30
University (79)	30.0	8.4	30.0	8.4	30.0	8.4	30
Victoria Village (43)	17.7	4.3	20.3	4.5	21.5	4.6	79
Waterfront Communities-The Islands (77)	13.9	2.4	13.9	2.4	13.9	2.4	201

continued

APPENDIX III.—CONTINUED

Tree cover (percent) by Toronto neighborhood for 1999, 2005, and 2009

	1999		2005		2009		
Neighborhood[a]	Tree Cover	SE[b]	Tree Cover	SE[b]	Tree Cover	SE[b]	n[c]
West Hill (136)	39.1	3.9	39.7	3.9	42.3	4.0	156
West Humber-Clairville (1)	10.1	1.4	10.3	1.4	10.3	1.4	475
Westminster-Branson (35)	15.4	5.0	15.4	5.0	21.2	5.7	52
Weston (113)	32.6	6.9	28.3	6.6	34.8	7.0	46
Weston-Pellam Park (91)	23.3	7.7	23.3	7.7	23.3	7.7	30
Wexford/Maryvale (119)	12.7	2.5	10.5	2.3	12.2	2.4	181
Willowdale East (51)	28.4	5.2	28.4	5.2	28.4	5.2	74
Willowdale West (37)	30.2	6.3	26.4	6.1	30.2	6.3	53
Willowridge-Martingrove-Richview (7)	33.7	5.1	36.0	5.2	37.2	5.2	86
Woburn (137)	26.3	3.2	25.8	3.2	25.8	3.2	186
Woodbine Corridor (64)	36.7	8.8	43.3	9.0	43.3	9.0	30
Woodbine-Lumsden (60)	23.3	7.7	23.3	7.7	23.3	7.7	30
Wychwood (94)	30.0	8.4	26.7	8.1	26.7	8.1	30
Yonge-Eglinton (100)	46.7	9.1	46.7	9.1	43.3	9.0	30
Yonge-StClair (97)	46.7	9.1	43.3	9.0	50.0	9.1	30
York University Heights (27)	11.2	2.1	12.1	2.2	13.5	2.3	223
Yorkdale-Glen Park (31)	7.3	2.9	8.5	3.1	11.0	3.5	82

[a] Number in parenthesis refers to number on Toronto neighborhood map

[b] SE = standard error

[c] n = sample size

APPENDIX IV. I-TREE FORECAST PROTOTYPE MODEL METHODS

The i-Tree Forecast Prototype Model simulates future forest structure (e.g., number of trees and sizes) and various ecosystem services based on annual projections of the current forest structure data. There are three main components of the model:

1) Tree growth—simulates tree growth to project annual increases in tree diameter, crown size, and leaf area for each tree
2) Tree mortality—removes trees from the projections based on user-defined tree mortality rates
3) Tree establishment—annually adds new trees to each projection. These inputs can be used to illustrate the effect of the new trees or determine how many new trees need to be added annually to sustain a certain level of tree cover or benefits.

Tree Growth

Annual tree diameter growth is estimated for the region based on: 1) the length of growing season; 2) species average growth rates; 3) tree competition; 4) tree condition; and 5) current tree height relative to maximum tree height.

To determine a base growth rate based on length of growing season, urban street tree, park tree, and forest growth measurements were standardized to growth rates for 153 frost-free days based on: Standardized growth = measured growth x (153/number of frost-free days of measurement).[2] Standardized growth rates of trees of the same species or genera were also compared to determine the average difference between standardized street tree growth and standardized park tree and forest tree growth rates. Park growth averaged 1.78 times less than street trees, and forest growth averaged 2.26 times less than street tree growth.

Standardized growth rates are multiplied by Toronto's number of frost-free days/153 to estimate a base growth rate. For this study, the average base growth rates for open-grown trees was assumed to be 6.1 mm/yr for slow growing species, 10.2 mm/yr for moderate growing species, and 14.2 mm/yr for fast growing species. There are limited measured data on urban tree growth for slow, moderate or fast-growing tree species, so the growth rates used here are estimates. These growth rates by species growth-rate class were estimated such that the entire population average growth rate was comparable to the estimated base growth rate for Toronto.

Crown light exposure (CLE) measurements of 0-1 were used to represent forest growth conditions; 2-3 for park conditions; and 4-5 for open-grown conditions. Thus, for: CLE 0-1: growth = base growth (BG)/2.26; CLE 2-3: growth = BG/1.78; and CLE 4-5: growth = BG. However, as the percent canopy cover increased or decreased, the CLE correction factors were adjusted proportionally to the amount of available greenspace (i.e., as tree cover decreased and available greenspace increased—the

CLE adjustment factor decreased; as tree cover increased and available greenspace decreased—the CLE adjustment factor increased).

Growth rates are also adjusted based on tree condition. These adjustments factors are based on percent crown dieback and the assumption that less than 25 percent crown dieback had a limited effect on diameter growth rates. For trees in fair to excellent condition (less than 25 percent dieback), growth rates are multiplied by 1 (no adjustment), trees in poor condition (crown dieback of 26-50 percent) by 0.76, critical trees (crown dieback of 51-75 percent) by 0.42, dying trees (crown dieback of 76-99 percent) by 0.15, and dead trees (crown dieback of 100 percent) by 0.

As trees approach their estimated maximum height, growth rates are reduced. Thus the species growth rates as described above were adjusted based on the ratio between the current height of the tree and the average height at maturity for the species. When a tree's height is over 80 percent of its average height at maturity, the annual diameter growth is proportionally reduced from full growth at 80 percent of height to one-half growth rate at height at maturity. The growth rate is maintained at one-half growth until the tree is 125 percent past maximum height, when the growth rate is then reduced to 0.

Tree height, crown width, crown height, and leaf area were then estimated based on tree diameter each year. Height, crown height, and crown width are calculated using species, genus, order and family specific equations that were derived from measurements from urban tree data (unpublished equations).

If there is no equation for a particular species, then the genus equation is used, followed by the family and order equations, if necessary. If no order equation is available, one average equation for all trees is used to estimate these parameters. Leaf area was calculated from the crown height, tree height, and crown width estimates based on i-Tree methods.[2]

Total tree cover was calculated by summing the two-dimensional crown area of each tree in the population. This calculated estimate of crown cover was adjusted to attain the actual tree cover of the study area based on photo-interpretation. Trees often have overlapping crowns, so the sum of the crown areas will often over-estimate total tree cover as determined by aerial estimates. Thus the crown overlap can be determined by comparing the two estimates:

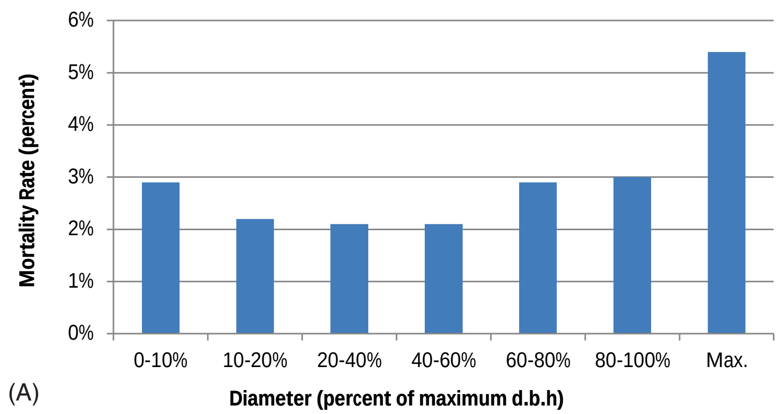
% crown overlap = (sum of crown area - actual tree cover area)/sum of crown area

When future projections predicted an increase in percent tree cover, the percent crown overlap was held constant However, when 100% tree cover was attained all new canopy added was considered as overlapping canopy. When there was a projected decrease in percent tree cover, the percent crown overlap decreased in proportion to the increase in the amount of available greenspace (i.e., as tree cover dropped and available greenspace increased—the crown overlap decreased).

Tree Mortality Rate

Canopy dieback is the primary determinant of tree mortality. Trees with 50-75 percent crown dieback have an annual mortality rate of 13.1 percent; trees with 76-99 percent dieback have a 50 percent annual mortality rate; trees with 100 percent dieback have a 100 percent annual mortality rate.[32] Trees with less than 50 percent dieback have a user-defined mortality rate that is adjusted to the tree size class and diameter.

Trees are assigned to species size classes: small trees have an average height at maturity of less than or equal to 40 ft (maximum diameter class = 20+ inches); medium trees have mature tree height of 41- 60 ft (maximum diameter = 30+ inches); large trees have a mature height of greater than 60 ft (maximum diameter = 40+ inches). Each size class has a unique set of seven diameter ranges to which base mortality rates are assigned based on measured tree mortality by diameter class (Fig. 24).29 The same distribution of mortality by diameter class was used for all tree size classes, but the range of the diameter classes differed by size class. The actual mortality rate for each diameter class was adjusted so that the overall average mortality rate for the base population equaled the mortality rates assigned by user. That is, the relative curve of mortality stayed the same among diameter classes, but the actual values changed based on the user-defined overall average rate.



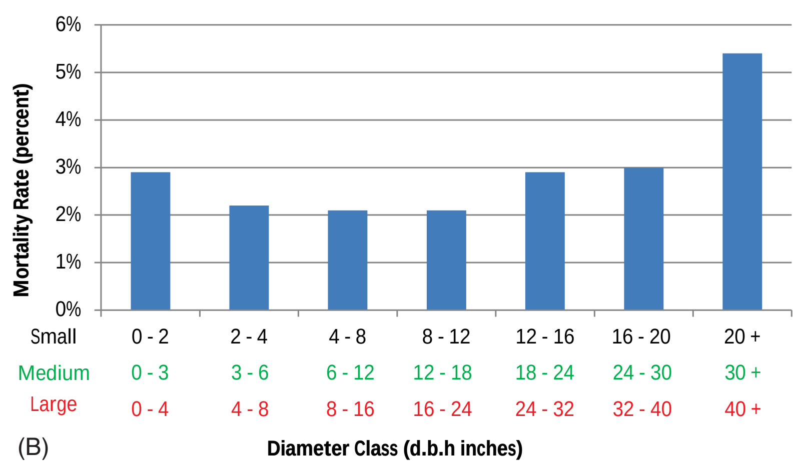


Figure 24.—Mortality rate distribution by diameter class with range classified by maximum d.b.h. for the species (A) and for actual d.b.h. classes for small, medium, and large tree species (B)

Tree Establishment

Based on the desired tree cover and the number of years desired to reach that canopy goal, the model calculates the number of trees needing to be established annually to reach that canopy goal given the model growth and mortality rates. In adding new trees to the model each year, the species composition of new trees was assumed to be proportional to the current species composition. Crown light exposure of newly established trees was also assumed to be proportional to the current growth structure of the canopy. Newly established trees were input with a starting diameter (d.b.h.) of 2.54 cm (1 inch).

For ash mortality scenarios, the entire ash population was killed off in 10 years, with 10 percent of the initial ash population killed off in each of the first 10 years.

The following inputs were used for Toronto:

- Area: 64,158.37 ha/641.58 km^2
- Number of Frost Free Days – 160
- Current tree cover: 26.6%
- Tree size classes
  - Small trees – 10.9%
  - Medium trees – 32.0%
  - Large trees – 57.1%

APPENDIX V. GENERAL RECOMMENDATIONS FOR AIR QUALITY IMPROVEMENT

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

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

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

Urban forest management strategies to help improve air quality include:

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

APPENDIX VI. RELATIVE TREE EFFECTS

The urban forest in Toronto provides benefits that include carbon storage and sequestration, and air pollutant removal. To estimate a relative value of these benefits, tree benefits were compared to estimates of average carbon emissions in the city[33], average passenger automobile emissions[34], and average household emissions.[35]

General tree information:

Average tree diameter (d.b.h.) = 16.3 cm
Median tree diameter (d.b.h.) = 10.2 cm
Average number of trees per person = 4.1
Number of trees sampled = 2,674
Number of species sampled = 115

Average tree effects by tree diameter

D.b.h.	Carbon storage			Carbon sequestration			Pollution removal	
Class (cm)	(kg)	(CAD$)	(km)[a]	(kg/yr)	(CAD$/yr)	(km)[a]	(kg)	(CAD$)
2.5-7.6	2.7	0.08	32	0.7	0.02	10	0.0	0.29
7.7-15.2	15.9	0.45	210	2.2	0.06	29	0.1	0.77
15.3-22.9	58.7	1.67	758	4.5	0.13	60	0.2	1.88
23.0-30.5	118.7	3.38	1,548	7.1	0.20	92	0.3	3.08
30.6-38.1	218.0	6.21	2,839	10.0	0.28	131	0.4	4.67
38.2-45.7	348.6	9.93	4,532	13.0	0.37	169	0.5	5.77
45.8-53.3	523.5	14.92	6,823	16.7	0.47	216	0.6	6.76
53.4-61.0	786.5	22.42	10,242	21.3	0.61	277	0.8	9.04
61.1-68.6	985.0	28.07	12,823	24.8	0.71	323	0.9	10.55
68.7-76.2	1,366.7	38.95	17,790	34.0	0.97	444	1.0	11.72
76.2+	2,708.6	77.20	35,258	52.4	1.49	682	1.8	19.91

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

The Toronto urban forest provides:

Carbon storage equivalent to:
Amount of carbon (C) emitted in city in 29 days or
Annual carbon emissions from 733,000 automobiles or
Annual C emissions from 367,900 single family houses

Carbon monoxide removal equivalent to:
Annual carbon monoxide emissions from 44 automobiles or
Annual carbon monoxide emissions from 180 single family houses

Nitrogen dioxide removal equivalent to:
Annual nitrogen dioxide emissions from 20,700 automobiles or
Annual nitrogen dioxide emissions from 13,800 single family houses

Sulfur dioxide removal equivalent to:
Annual sulfur dioxide emissions from 99,900 automobiles or
Annual sulfur dioxide emissions from 1,700 single family houses

Particulate matter less than 10 micron (PM_{10}) removal equivalent to:
Annual PM_{10} emissions from 1,047,000 automobiles or
Annual PM_{10} emissions from 101,100 single family houses

Annual C sequestration equivalent to:
Amount of C emitted in city in 1.2 days or
Annual C emissions from 30,900 automobiles or
Annual C emissions from 15,500 single family houses

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Explanation of Calculations of Appendix VI

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

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CO_2, NO_x, SO_2, PM_{10}, and CO emission per Btu for natural gas, propane and butane (average used to represent LPG), Fuel #4 and #6 (average used to represent fuel oil and kerosene) from:

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Autumn view of Queen's Park in Toronto, Ontario. Photo by MarcusObal, Wikimedia Commons.

Nowak, David J.; Hoehn, Robert E. III; Bodine, Allison R.; Greenfield, Eric J.; Ellis, Alexis; Endreny, Theodore A.; Yang, Yang; Zhou, Tian; Henry, Ruthanne. 2013. **Assessing urban forest effects and values: Toronto's urban forest.** Resour. Bull. NRS-79. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 59 p.

An analysis of trees in Toronto, Ontario, reveals that this city has about 10.2 million trees with a tree and shrub canopy that covers approximately 26.6 percent of the city. The most common tree species are eastern white-cedar, sugar maple, and Norway maple. The urban forest currently stores an estimated 1.1 million metric tons of carbon valued at CAD$25.0 million. In addition, these trees remove about 46,700 metric tons of carbon per year (CAD$1.1 million per year) and about 1,905 metric tons of air pollution per year (CAD$16.9 million per year). Trees in Toronto are estimated to reduce annual residential energy costs by CAD$9.7 million per year. The compensatory value is estimated at CAD$7.1 billion. Information on the structure and functions of the urban forest can be used to improve and augment support for urban forest management programs and to integrate urban forests within plans to improve environmental quality in the Toronto area.

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

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