



City of Mississauga Urban Forest Study

Technical Report

July 2011

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Executive Summary

The *City of Mississauga Urban Forest Study – Technical Report* has been prepared by the Toronto and Region Conservation Authority, in partnership with the Region of Peel, Credit Valley Conservation (CVC), the City of Mississauga, the City of Brampton, and the Town of Caledon. The purpose of the study was to assess the distribution, structure and function of the urban forest, and to provide management recommendations for enhancing the sustainability of both the urban forest resource and the community as a whole. The study serves as a baseline for future research and monitoring, and will equip managers with the knowledge necessary to direct forest structure to deliver desired ecosystem services, including climate change mitigation and adaption, air pollution removal, stormwater management, residential energy savings, wildlife habitat, and community aesthetics.

Summary of Results

A suite of tools of analysis created by the United States Department of Agriculture (USDA) Forest Service, Northern Research Station and the University of Vermont, Spatial Analysis Laboratory were used to quantify the distribution, structure and function of the urban forest in the City of Mississauga.

Tree Cover and Leaf Area:

The City of Mississauga's 2.1 million trees cover 15 percent of the total land area, providing 224 km^2 of total leaf area. By ownership type, homeowners and tenants (renters) control the largest percentage of the City's urban forest; more than half of the existing tree cover is located within the residential land use. The greatest opportunity to increase total leaf area and canopy cover is also found within the residential land use.

Tree Cover by Land Use:

- Agriculture: 13 %
- Commercial: 6 %
- Industrial: 5 %
- Institutional: 14 %
- Natural Cover: 44 %
- Open Space: 32 %
- Other: 24 %
- Residential Low Density: 20 %
- Residential Medium / High Density: 19 %
- Utilities and Transportation: 5 %

Tree Size:

As urban trees increase in size, their environmental, social and economic benefits increase as well. In Mississauga a tree that is 65 cm in diameter at breast height (dbh) stores 65 times more carbon and 11 times more pollution than a tree that is 11 cm dbh. Approximately 33 percent of all trees in Mississauga fall within the smallest diameter class and 63 percent of all trees are less than 15.3 cm dbh. The proportion of large trees is low; less than 7 percent of the tree population has a dbh of 38.2 cm or greater.

Most Common Tree Species by Land Use (expressed as a percent of the total leaf area):

Open Space + Natural Cover + Agriculture
- Sugar maple: 43 %
- Manitoba maple: 10 %
- Willow spp.: 10 %

Residential (Low, medium and high density)
- Norway maple: 12 %
- White ash: 9 %
- Green ash: 9 %

Commercial + Industrial
- Blue spruce: 29 %
- Red pine: 18 %
- Austrian pine: 16 %

Institutional + Utilities and Transportation
- Sugar maple: 28 %
- Norway maple: 16 %
- Red oak: 12 %

Other
- Sugar maple: 22 %
- Green ash: 16 %
- Elm spp.: 11 %

Structural Value of Trees in Mississauga:

The estimated structural value of all trees in Mississauga in 2008 is approximately **$1.4 billion**. This value does not include the ecological or societal value of the forest, but rather it represents an estimate of tree replacement costs and/or compensation due to tree owner's for tree loss.

Carbon Storage and Sequestration:

As a tree grows, it removes, or sequesters, carbon dioxide from the atmosphere. This carbon is stored in the woody biomass of the tree. When a tree dies, much of the stored carbon is released back to the atmosphere through decomposition. Annually, trees in Mississauga sequester approximately 7,400 tonnes of carbon, with an associated annual value of $220,000. Trees in Mississauga store 203,000 tonnes of carbon, with an associated value of $5.8 million.

Air Pollution Removal:

The urban forest can improve local air quality by absorbing and intercepting air born pollutants. Mississauga's urban forest removes 292 metric tonnes of air pollution annually; this ecosystem service is valued at $4.8 million annually.
- Ozone: 237 metric tonnes
- Particulate matter (10 microns) : 88 metric tonnes
- Nitrogen dioxide: 87 metric tonnes
- Sulfur dioxide: 12 metric tonnes
- Carbon monoxide: 4 metric tonnes

Residential Energy Savings:

Trees reduce local air temperature due to shading effects, wind speed reductions, and the release of water vapor through evapotranspiration. In Mississauga the urban forest reduces the annual energy consumption by approximately 79,000 MBTUS and 7,300 MWH, with an associated annual financial savings of approximately $1.2 million. As a result of this reduced demand for heating and cooling the production of over 2,100 tonnes of carbon emissions is avoided annually (associated annual savings of $61,800).

Hydrologic Effects of the Urban Forest:

The i-Tree Hydro model simulated the effects of tree and impervious cover on stream flow in the Spring Creek and Fletcher's Creek subwatersheds. Based on model estimates, the loss of existing tree cover (14 percent) in the Spring Creek subwatershed would increase total stream flow by approximately 1.2 percent. Increasing tree cover from 14 percent to 30 percent would reduce overall flow by 1.8 percent (149,000 m^3) during the 8 month period in 2008 and by 1.9 percent (128,000 m^3) in the 8 month period in 2006 (see Figure 26 for the 2008 simulation period). In the Fletcher's Creek subwatershed a loss of existing tree cover (10.6 percent) would increase total flow by approximately 0.9 percent during the 2007 simulation period and by 1.1 percent. Increasing canopy cover from 10.6 percent to 20 percent would reduce overall flow by 1.0 percent (15,300 m^3) during the 2007 simulation period, and by 1.2 percent (49,100 m^3) during the 2008 simulation period.

Summary of Recommendations

The recommendations provide here reflect the actions needed in order to progress towards many of the short and long term objectives associated with the criteria and performance indicators for sustainable urban forest management presented by Kenney *et al.* (2011). To evaluate the City's performance for each of the 25 criteria is beyond the scope of this report. Such an extensive exercise should be conducted through the development of the City of Mississauga's Urban Forest Management Plan. It follows that the development of a Management Plan that will more fully explore the operational actions and resources required to achieve success is of the highest priority. The Management Plan should draw directly on the results of this study and incorporate the recommendations offered here.

1. Neighbourhoods identified by the Priority Planting Index should be targeted for strategic action that will increase tree cover and leaf area in these areas.

2. Use the parcel-based TC metrics together with the City's GIS database to identify and prioritize contiguous parcels that maintain a high proportion of impervious cover and a low percent canopy cover.

3. Increase leaf area in canopied areas by planting suitable tree and shrub species under existing tree cover. Planting efforts should be focused in areas where mature and aging trees are over-represented, including the older residential neighbourhoods located south of the Queensway. Neighbourhoods in these areas that maintain a high proportion of ash species should be prioritized.

4. Utilize the Pest Vulnerability Matrix during species selection for municipal tree and shrub planting.

5. Establish a diverse tree population in which no single species represents more than 5 percent of the tree population, no genus represents more than 10 percent of the tree population, and no family represents more than 20 percent of the intensively managed tree population both city-wide and the neighbourhood level.

6. In collaboration with the Toronto Region Conservation Authority and Credit Valley Conservation, develop and implement an invasive species management strategy that will comprehensively address existing infestations as well as future threats posed by invasive insect pests, diseases and exotic plants.

7. Utilize native planting stock grown from locally adapted seed sources in both intensively and extensively managed areas.

8. Evaluate and develop the strategic steps necessary to increase the proportion of large, mature trees in the urban forest. Focus must be placed on long-term tree maintenance and by-law enforcement to ensure that healthy specimens can reach their genetic growth potential. The value of the services provided by mature trees must be effectively communicated to all residents.

9. Determine the relative dbh of the tree population in Mississauga; consider utilizing relative dbh as an indicator of urban forest health.

10. Conduct an assessment of municipal urban forest maintenance activities (e.g. pruning, tree planting) to determine areas where a reduction in fossil fuel use can be achieved.

11. Reduce energy consumption and associated carbon emissions by providing direction and assistance to residents and businesses for strategic tree planting and establishment around buildings.

12. Focus tree planting and establishment in “hot-spots” identified by thermal mapping analysis.

13. Review and enhance the Tree Permit By-law 474-05 to include the protection all trees that are 20 cm or greater in diameter at breast height.

14. Develop a comprehensive Public Tree By-law that provides protection to all trees on publically owned and managed lands.

15. Develop a Tree Protection Policy that outlines enforceable guidelines for tree protection zones and other protection measures to be undertaken for all publically and privately owned trees.

16. Allocate additional funding to the Urban Forestry Unit for the resources necessary to ensure full public compliance with Urban Forestry By-laws and policies.

17. Create a Community Animator Program that assists residents and groups acting at the neighbourhood scale in launching local conservation initiatives.

18. Conduct a detailed assessment of opportunities to enhance urban forest stewardship through public outreach programs that utilize community-based social marketing.

19. Develop and implement a comprehensive municipal staff training program as well as information sharing sessions that target all departments and employees that are stakeholders in sustainable urban forest management.

20. Increase genetic diversity in the urban forest by working with local growers to diversify stock and reduce reliance on clones.

21. Utilize the UTC analysis together with natural cover mapping to identify priority planting and restoration areas within the urban matrix.

22. Implement the target natural heritage system in the Etobicoke and Mimico Creeks Watersheds; work with CVC to identify and implement the target natural heritage system in the Credit Valley Watershed.

23. Develop and implement an urban forest monitoring program that tracks trends in the structure and distribution of the urban forest using the i-Tree Eco analysis and Urban Tree Canopy analysis. The structure and distribution of the urban forest should be comprehensively evaluated at regular 5-year intervals and reported on publically.

24. Develop a seed collection program for native ash species in partnership with TRCA, CVC and National Tree Seed Centre

25. Develop municipal guidelines and regulations for sustainable streetscape and subdivision design that 1) ensure adequate soil quality and quantity for tree establishment and 2) eliminate conflict between natural and grey infrastructure.

26. Apply and monitor the use of structural soils, subsurface cells and other enhanced rooting environment techniques for street trees. Utilizing these technologies at selected test-sites in the short-term may provide a cost-effective means of integrating these systems into the municipal budget.

27. Utilize the criteria and performance indicators developed by Kenney *et al.* (2011) to guide the creation of a strategic management plan and to assess the progress made towards sustainable urban forest management and planning.

Table of Contents

List of Figures:

List of Tables:

1.0 Introduction

The urban forest is vital "natural infrastructure" that provides multiple benefits and services to residents of the City of Mississauga. Extending from street trees to forest ravines, it is the ecological framework for environmental, social and economic health; it is the City's natural life support system. The vision of a sustainable and livable City of Mississauga can be realized, in part, through the maintenance, restoration, and enhancement of the City's urban forest.[1] A healthy and resilient urban forest can mitigate the impacts of climate change, improve local air quality, reduce the speed and volume of stormwater runoff, decrease residential energy use, provide habitat for local wildlife, and foster a sense of community pride. Thus, programs that restore and enhance tree cover represent a cost-effective and sustainable ''biotechnological'' means to meet multiple standards, as trees provide multiple benefits for a singular cost (Nowak, 2006).

The *City of Mississauga Urban Forest Study – Technical Report* seeks to evaluate this "biotechnology" by providing a detailed analysis of the existing urban forest. By modifying the urban forest structure managers can affect and shape a city's physical, biological, and socioeconomic environments (Nowak and Dwyer, 2007), and influence the movement of energy, materials and organisms into, through, and out of an urban ecosystem (Zipperer, 2008). Thus, full knowledge of the structure and function of the urban forest is the essential foundation on which future management plans can be built.

An evaluation of Mississauga's urban forest is timely in light of the challenges now facing municipal urban forest managers. Urban population growth is among such challenges. To accommodate projected growth the population density of the City will increase; subsequent urban intensification will have implications for both the existing and potential urban forest. In addition, the impacts of climate change are also cause for concern. Moisture stress, extreme weather events, shifting plant hardiness zones, and intensified insect pest infestations will directly impact urban forest health and potentially limit the provision of ecosystem services. Careful consideration of the implications of climate change will enable managers to increase ecosystem resilience and effectively integrate the urban forest into municipal climate change mitigation and adaption strategies. In order to successfully address such challenges, a comprehensive understanding of urban forest structure and function will be necessary.

1.1 Purpose

The *City of Mississauga Urban Forest Study – Technical Report* has been prepared by the Toronto and Region Conservation Authority, in partnership with the Region of Peel, Credit Valley Conservation, the City of Mississauga, the City of Brampton, and the Town of Caledon. The purpose of the Study was to assess the distribution, structure and function of the urban forest, and to provide management recommendations for enhancing the sustainability of both the forest resource and the community as a whole. The Study will serve as a baseline for future research and monitoring, and will equip managers with the knowledge necessary to direct forest structure to deliver desired functions. Ultimately, the Study will inform and guide the creation of an Urban Forest Management Plant will assist the City of

[1] The urban forest is a dynamic system that includes all trees and vegetation as well as related biotic, abiotic and cultural elements located on publicly and privately owned land, within a city and the surrounding rural areas.

Mississauga and in fulfilling multiple social, environmental and economic objectives through urban forest management.

1.2 Objectives

The objectives of the Technical Report are:

- To quantify the existing distribution, structure (e.g. composition and condition), and function (e.g. carbon sequestration and air pollution removal) of the City's urban forest;
- To model the effects of existing and potential forest cover on hydrological systems;
- To establish a baseline for future comparisons; and
- To outline the preliminary actions needed to enhance the capacity of the urban forest to provide essential ecosystem services.

2.0 Background

2.1 Demographic and Ecological Context

The City of Mississauga, formed in 1974, is a lower-tier municipality within the Regional Municipality of Peel. In 2006, Statistics Canada recorded Mississauga as Canada's 6th most populous city, with approximately 670,000 residents. The City continues to grow rapidly and now supports a very ethnically diverse population. Mississauga is bounded by The Towns of Oakville and Milton to west/southwest, the City of Brampton to the north, the City of Toronto to the east and Lake Ontario to the south. The City is divided between the Credit River Watershed to the east and the Etobicoke and Mimco Creeks Watersheds to the west.

Mississauga is situated in ecodistrict 7E-4, within the Lake Erie – Lake Ontario ecoregion, as part of the mixedwood plains ecozone. Ecoregion 7E corresponds to the Carolinian Forest Region, also referred to as the Deciduous Forest Region (NRCan). It covers the southern-most portion of the province in a broad band along Lake Erie that extends up along the edge of Lake Ontario to the City of Toronto. This ecoregion includes many species commonly found in other parts of Ontario, such as sugar maple and beech, but also nationally rare species such as the Kentucky coffee tree (*Gymnocladus dioicus*), cucumber-tree (*Magnolia acuminate*), tulip tree (*Liriodendron tulipifera*), and sycamore (*Platanus occidentialis*). Mississauga sits at the northern most limit of this ecodistrict. In this region, coniferous trees, such as eastern white pine (*Pinus strobus*), red pine (*Pinus resinosa*), eastern hemlock (*Tsuga canadensis*) and white cedar (*Thuja occidentalis*), commonly mix with deciduous broad-leaved species, such as yellow birch (*Betula alleghaniensis*), sugar and red maples (*Acer saccharum, A. rubrum*), basswood (*Tilia americana*) and red oak (*Quercus rubra*).

Prior to European settlement, the City of Mississauga and nearly all of southern Ontario was covered by forests. Agriculture, urbanization, and industrial activity have led to the loss of pre-European settlement natural cover in the region, as well as the degradation of the remaining natural systems as a result of changes to local hydrology and soil quality. Concurrent with the loss of natural cover has been the loss of valuable ecosystem services, including water management and climate regulation. Consequently, urban dwellers now increasingly rely on costly engineering, or *grey infrastructure*, to deliver the services historically provided by functioning forests and wetlands. However, the capacity of grey infrastructure to meet the growing demands of an urbanized landscape is limited. In the face of continued population growth and urban expansion, grey infrastructure alone cannot offer an affordable, long term solution for the provision of the aforementioned services. Recognizing this, the City of Mississauga is now looking to natural infrastructure to provide more natural and sustainable options.

2.2 Policy Context

This section provides a brief summary of municipal policies and programs that are currently applied in the governance or management of the urban forest. Please see the Region of Peel Urban Forest Strategy for a more comprehensive assessment of federal, provincial, regional, conservation authority, and community level urban forest policies and programs.

Mississauga's updated Strategic Plan, *Our Future Mississauga*, identifies "Living Green" as one of the five "Strategic Pillars for Change". Specifically, under the Living Green umbrella, the plan outlines the following strategic goals:

- To lead and encourage environmentally responsible approaches;
- To conserve, enhance and connect natural environments; and
- To promote green culture.

The Strategic Plans lists "expand the tree canopy" as one of the strategies needed to respond to the threats of climate change as well as and the environmental issues associated with urbanization. The Living Green Action Plan lists ten strategic actions needed to achieve the Living Green vision. Four of these actions have direct implications for the urban forest. These actions are:

- Plant one million trees in Mississauga.
- Implement a city boulevard beautification program to foster civic pride and raise environmental awareness (focusing on the use of native species).
- Pro-actively acquire and/or enhance land along the waterfront and in natural areas for recreational ecological value.
- Implement an educational program that promotes "living green".

Mississauga Official Plan (adopted by Council in September 2010) will bring the City into conformity with all provincial requirements, incorporate the results of various City initiatives and establish a policy framework that will guide the City's development in the coming decades. Section 6.4 of the Official Plan specifically addresses the urban forest, providing a strong foundation and direction for sustainable urban forest management in the municipality, stating that "[t]rees are a fundamental component of a healthy city and sustainable community. As such, trees are a valuable asset to the City and contribute to community pride and cultural heritage" (City of Mississauga, 2010). Section 6.4.4 further sets out the following actions that are intended to protect and enhance the urban forest:

a. developing and implementing a strategic planting program, specific to distinct geographic areas within the city;
b. developing and implementing a strategic pro-active maintenance program pertaining to trees on public land;
c. providing sustainable growing environments for trees by allocating adequate soil volumes and landscaped areas during the design of new development and infrastructure projects;
d. ensuring that development and site alteration will not have negative impacts on the Urban Forest;
e. increasing tree canopy coverage and diversity, by planting trees appropriate to the location;

f. regulating the injury and destruction of trees on public and private property;
g. promoting the management and enhancement of the Urban Forest on Public and Private lands;
h. providing public education and stewardship;
i. providing strategic partnerships with regulatory agencies to address invasive alien species and diseases; and
j. compliance with by-laws pertaining to tree preservation and protection.

There are three By-laws that apply to the governance of trees in the municipality: the Tree Permit By-law; the Street Tree By-law; and the Encroachment By-law. The City of Mississauga's Tree Permit By-law (By-law 474-05) regulates the removal of trees on private property. The By-law states that property owners require a permit to remove 5 or more trees that are 15 cm in diameter or larger from their private property in a calendar year. Thus, the removal of up to 4 trees of any size is allowed without a permit.

The City's Street Tree By-law (By-law 91-75) regarding the protection and preservation of City owned trees along road right-of-ways is currently being updated to better reflect the needs of the municipality.

The Encroachment By-law (0057-2004) is intended to allow the City to effectively address encroachments by adjacent landowners onto City property. Under the by-law, an *Encroachment* is defined as: "…any type of vegetation, man-made object or item of personal property of a person which exists wholly upon, or extends from a person's premises onto, public lands and shall include any aerial, surface or subsurface encroachments" (City of Mississauga, 2004). Through effective enforcement of the Encroachment By-law, a total of 3.5 acres of parkland has been reclaimed through the Encroachment Management Program.

The Natural Areas Survey identifies and inventories over 140 natural areas within the City including woodlands, wetlands, creeks and streams, and recommends strategies and guidelines for their future protection. Completed over a 3 year period, the study consists of 4 phases: review of existing reports and databases; survey of public opinion on environmental issues; site visits to 144 remnant natural areas; and development of databases for the natural areas. The City plans to utilize and expand on this work to create a Natural Heritage Strategy Plan in partnership with TRCA and CVC.

2.3 Collaborative Urban Forest Studies

A holistic ecosystem-based approach to management requires effective collaboration between upper and lower tier municipalities. A lack of collaboration can result in regional heterogeneity in the extent of urban tree cover; such heterogeneity could impact the flow of services between and across boundaries and compromise ecosystem health. According to Elmendorff and Luloff (1999), greenspace cannot be effectively conserved across jurisdictional lines without cooperation from multiple jurisdictions and planning agencies. Establishing a network of communication among stakeholders can reduce the negative impacts that fragmented responsibility and care engender, while clarifying and prioritizing local and regional goals (Carreiro and Zipperer, 2008).

In April 2007, TRCA coordinated the meeting of key stakeholders from across southern Ontario to explore the possibility of using compatible methodologies in the GTA and beyond. Consequently, the Regional Municipalities of Peel and York, Cities of Toronto, Mississauga, Brampton, Vaughan and

Pickering, and the Towns of Markham, Ajax, Richmond Hill, and Caledon all became part of an informal collaborative that ensued from the discussions. Following these preliminary discussions the members of the collaborative agreed to move forward with urban forest studies using the i-Tree Eco model and the additional suite of tools offered by the USDA Forest Service and partners. To date, TRCA has coordinated the studies for the municipalities of Mississauga, Brampton, Caledon, Vaughan, Markham, Richmond Hill, Pickering and Ajax. The City of Toronto led its own concurrent urban forest study using the same methodology and tools. Please see Figure 1 for an illustration of the municipalities engaged in collaborative urban forest studies.

The fundamental objective of the regional collaborative was to develop a standardized methodology that would allow for further comparative and complimentary research at the regional scale. Carreiro and Zipperer (2008) highlight the utility of such research, asserting that comparative ecological research will lay a foundation for distinguishing common urban effects and responses from those specific to a particular city or group of cities due to variation in factors such as geography, climate, soil, urban morphology, cultural values, and political and economic systems.

2.4 Literature Review

Please see Appendix A for a review of the relevant literature and research. This review explores the variables that affect and shape urban forest structure and function, and highlights the existing threats to urban forest health. Theories and concepts of sustainable urban forest management are also examined.

3.0 Methodology

Five complementary tools of analysis have been utilized in the study:

1) i-Tree Eco model
2) Urban Tree Canopy (UTC) spatial analysis
3) Priority Planting Index
4) Grow-Out simulations
5) i-Tree Hydro Model

Each tool is examined in more detail below. Taken together, these analyses provided a comprehensive understanding of Mississauga's urban forest. These tools have been developed by the USDA Forest Service, Northern Research Station in partnership with University of Vermont, Spatial Analysis Laboratory at the Rubenstein School of the Environment and Natural Resources.

While the i-Tree Eco analysis and the UTC analysis each represent stand-alone assessments capable of supporting an urban forest management plan, the technical working group felt it necessary to utilize both of these complementary tools. By incorporating the data collected in the field, the i-Tree Eco analysis quantified critical attributes such as tree species and tree height; such attributes cannot be obtained from aerial imagery. In contrast, using high resolution satellite imagery, the UTC analysis conducted by the University of Vermont's Spatial Analysis Laboratory digitally mapped the actual an

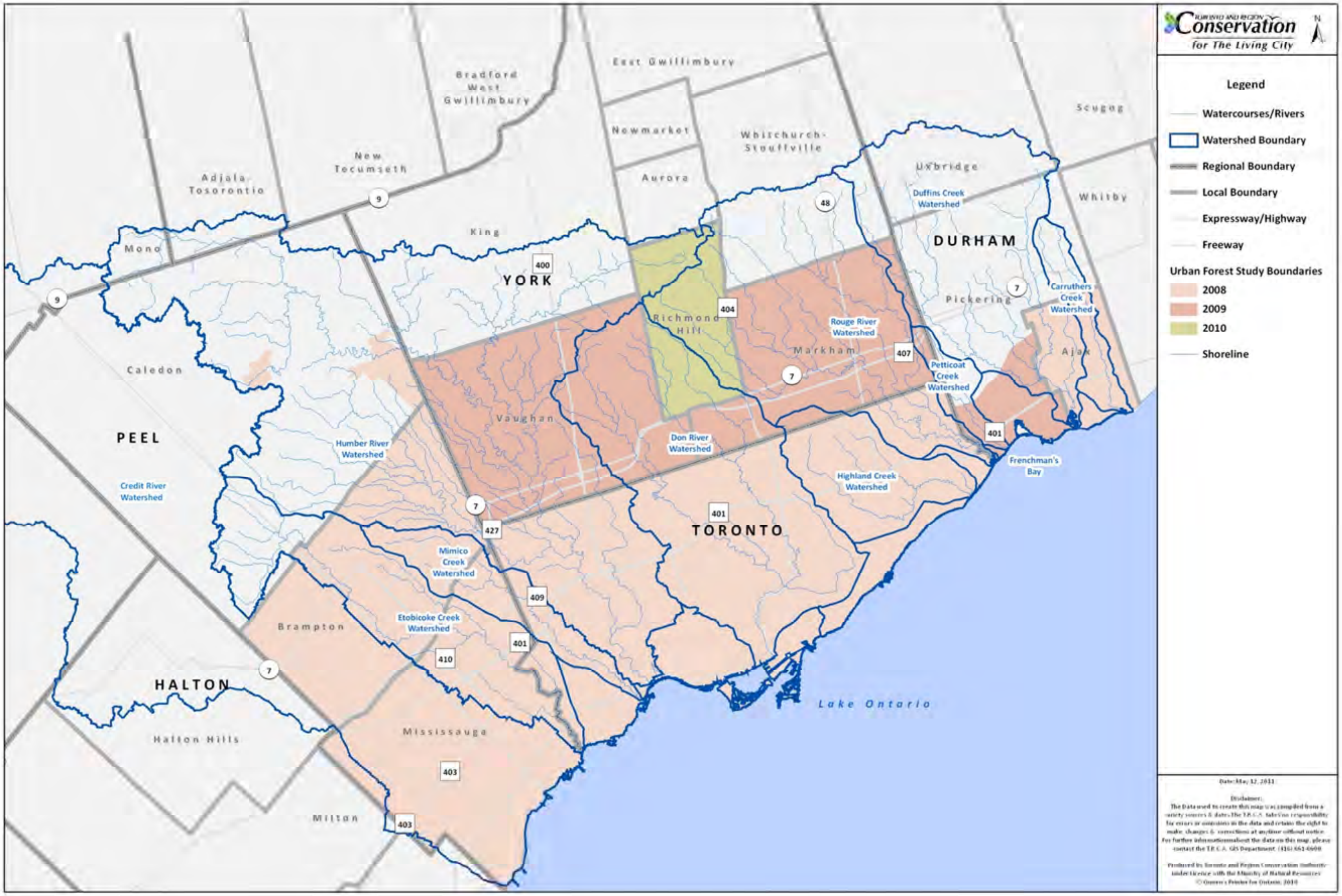

Figure 1: Greater Toronto Area municipalities engaged in collaborative urban forest studies

potential location of all individual trees in the study area (rather than only those trees measured within the i-Tree Eco sample plots), and projected future cover estimates based on a variety of different planting and mortality scenarios.

3.1 The i-Tree Eco Model

A number of models and software packages have been developed to assist urban forest managers in obtaining quantitative structural data. Following a review of the various applications, the technical working group, together with the regional collaborative, concluded that the i-Tree Eco model would provide the level of structural detail sought for urban forest studies across the Greater Toronto Area (GTA). Although the utility of the CityGreen model was also recognized, the need to tailor the analysis to values specific to the municipality was determined to be best met by the i-Tree Eco model. Finally, the extent to which the i-Tree Eco model has previously been utilized by other Canadian cities highlights the value of selecting a model that produces standardized and comparable results at both the provincial and national level.

3.1.1 Study Design

Study area boundaries were defined by the municipal boundaries of the City of Mississauga. In accordance with the randomized grid sampling method recommended by the USDA Forest Service, a grid was overlaid on a GIS-based map of the entire study area and a sample plot was placed randomly within each grid cell. A total of 207 plots were used in the analysis, with a density of approximately 1 plot for every 140 hectares. Each circular plot was 0.04 ha in size. Data from the plots were then statistically extrapolated upward to estimate totals and standard errors for the entire study area.

Although increasing the number of plots would have led to lower variances and increased certainty in the results, it would also have increased the cost of the data collection. Thus, the number of plots surveyed provided an acceptable level of standard error when weighed against the time and financial costs associated with additional field data collection. As a general rule, 200 (0.04 ha) plots in a stratified random sample in a city will yield a standard error of approximately 10 percent (USDA, 2007). In the past, large cities such as New York and Baltimore have used 200 sample plots and have obtained accurate results with acceptable levels of standard error.

A high resolution aerial orthophotograph that illustrated the location of plot centre and plot boundaries was generated for each plot (Figure 2). GPS coordinates were also generated to aid crews in navigation to plot centre.

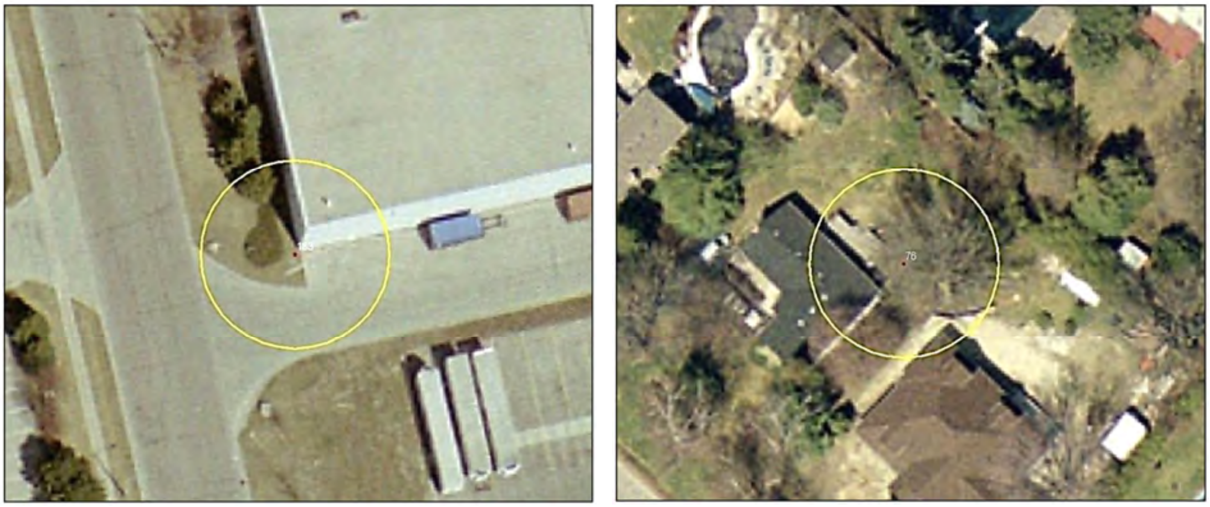

Figure 2: Aerial orthophotographs indicating plot center and plot boundaries.

3.1.2 Study Area Stratification

Stratifying the study area into smaller units can aid in understanding variations in the structure of the urban forest according to land use types (e.g. residential, commercial, etc.) or neighbourhoods. The study area was stratified by land use after the plots had been randomly distributed. If the distribution of land use categories changes in the future, this method of post-stratification will allow the City to revisit the sample plots and monitor change over time, while still reporting on trends within land use categories. In other words, the permanent sample plots are not dependent on a static land use distribution.

The study area was stratified into 10 land use categories. These categories were comprised of substrata represented by the Municipal Property Assessment Corporation (MPAC) codes assigned to each property in the municipality.[2] Each MPAC code, or substrata, was grouped into one of the 10 generalized categories based on similarities in ownership and management type. Please see Appendix B for a complete description of each land use category and the corresponding MPAC codes.

The *residential medium* and *residential high* categories, the *utilities and transportation* category, the *natural cover* category, and the *agricultural* category represented relatively small portions of the total study area. In order to produce statistically accurate results the USDA Forest Service recommends that a minimum of 15 to 20 plots fall within a distinct category. Consequently, the aforementioned categories were collapsed into a category of a similar land use type, to create a total of 5 land use categories (Table 1). Categories were grouped together based on similarities in vegetation cover and similarities in management needs.

[2] MPAC is an independent body established by the *Ontario Property Assessment Corporation Act, 1997.* MPAC administers a uniform, province-wide property assessment system based on current value assessment.

Table 1: Land use categories and corresponding number of plots and land area.

Land Use Category	Number of Plots	Area (ha)
Open Space + Natural Cover + Agriculture	16	2,116
Residential Low + Residential Medium + Residential High	81	11,368
Commercial and Industrial	60	8,626
Institutional + Utilities and Transportation	28	3,790
Other	20	2,900

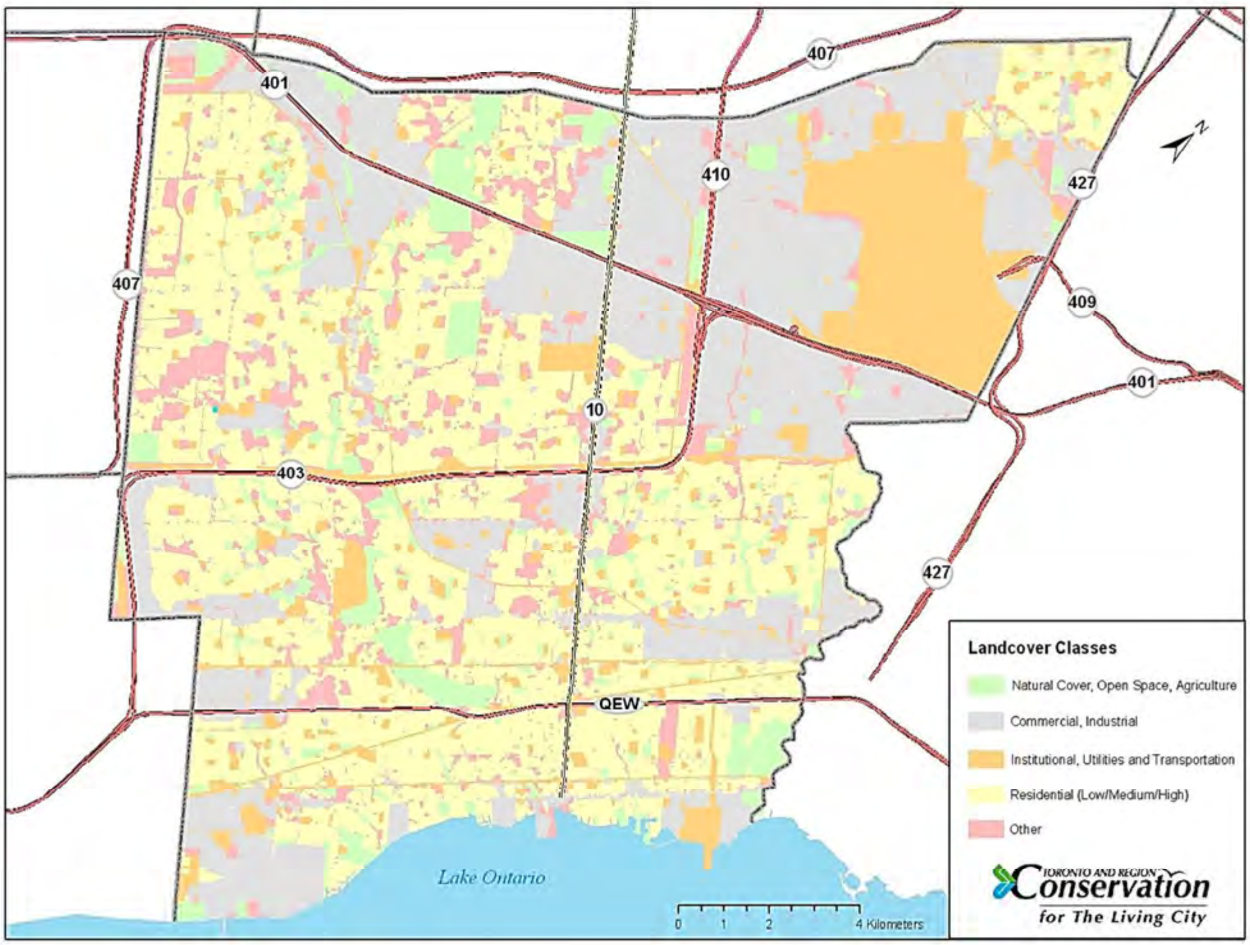

Figure 3: Generalized land use map for the City of Mississauga. Land use categories have been derived from groupings of Municipal Property Assessment Corporation (MPAC) codes assigned to each parcel in the municipality.

3.1.3 Landowner Contact

Permission to access plots located on private property was obtained through written communication. Prior to entry, all property owners received a request for access form in addition to a letter outlining the scope and duration of the study. If no response was given, field staff requested permission to access the property in person. In the event that permission was not granted, access was restricted due to physical barriers, or the site was deemed unsafe, field staff recorded measurements at the nearest representative location.

3.1.4 Field Data Collection

Field data collection was conducted by a two member field crew during the summer leaf-on season of 2008. At each sample plot field staff recorded the distance and direction from plot centre to permanent reference objects, where possible, so that plots could be relocated for future re-measurement. Once plot centre had been located, detailed vegetation information was recorded in accordance with the i-Tree manual specifications. The following general plot data were recorded:

- percent tree cover
- land use
- percent of plot within the land use
- percent ground cover
    - building
    - cement
    - tar-blacktop/asphalt
    - soil
    - rock
    - duff/mulch
    - herbaceous (exclusive of grass and shrubs)
    - maintained grass
    - wild/unmaintained grass
    - water

For each shrub mass, the following information was recorded:

- genus
- height
- percent of shrub mass volume occupied by leaves
- percent of total shrub area in the plot occupied by the shrub mass

For each tree with the centre of its stem in the plot and a minimum diameter at breast height (dbh) of 2.5 cm, the following information was recorded:

- species
- number of stems
- diameter at breast height
- tree height
- height to base of live crown
- crown width (average of two perpendicular measurements)
- percent canopy missing
- tree condition (based on percent of branch dieback in crown):
    - excellent (< 1 dieback)
    - good (1-10)
    - fair (11-25)
    - poor (26-50)
    - critical (51-75)

    - dying (76-99)
    - dead (100 - no leaves)
- distance and direction from the building (for trees ≥ 6.1m in height and located within 18.3m of a residential building)
- street tree indicator

3.1.5 Pollution Data Compilation

Hourly 2007 pollution concentrations of sulphur dioxide (SO_2), carbon monoxide (CO), ozone (O_3), and nitrogen dioxide (NO_2) were obtained from the Ontario Ministry of the Environment. Measurements of $PM_{2.5}$ and O_3 were recorded at the Mississauga Monitoring Station[3]; measurements of CO, NO_2 and SO_2 were recorded at the Toronto West Monitoring Station.[4] Daily PM10 measurements were provided by Environment Canada and were recorded at the Etobicoke and Scarborough Monitoring Stations. Measurements were not recorded on a daily basis at the Etobicoke station; in order to generate a complete data set, measurements from the Scarborough station were included to supplement missing entries. In the event that each station produced a record for the same day an average measurement was calculated.

3.1.6 Data Analysis

The i-Tree Eco model used standardized field, air pollution-concentration, and meteorological data for the City of Mississauga to quantify urban forest structure and function. Five model components were utilized in this analysis:

1) **Urban Forest Structure:** quantifies urban forest structure (e.g., species composition, tree density, tree health, leaf area, leaf and tree biomass) based on field data.

2) **Biogenic Emissions**: quantifies 1) hourly urban forest volatile organic compound (VOC) emissions (isoprene, monoterpenes, and other VOC emissions that contribute to O_3 formation) based on field and meteorological data, and 2) O_3 and CO formation based on VOC emissions.

3) **Carbon Storage and Annual Sequestration:** calculates total stored C, and gross and net C sequestered annually by the urban forest based on field data.

4) **Air Pollution Removal:** quantifies the hourly dry deposition of O_3, SO_2, NO_2, CO, PM_{10}, and $PM_{2.5}$ by the urban forest and associated percent improvement in air quality throughout a year. Pollution removal is calculated based on local pollution and meteorological data.

5) **Building Energy Effects:** estimates effects of trees on building energy use and consequent emissions of carbon from power plants.

For a detailed description of the i-Tree Eco model methodology please see Appendix C.

[3] Located at 310 Bristol Road East, Mississauga
[4] Located at 125 Resources Road, Toronto

3.2 Urban Tree Canopy Analysis

The Urban Tree Canopy (UTC) analysis was conducted by the Spatial Analysis Laboratory of the University of Vermont's Rubenstein School of the Environment and Natural Resources, in consultation with the USDA Forest Service's Northern Research Station. Advanced automated processing techniques using high-resolution QuickBird imagery acquired in the summer of 2007 and ancillary datasets were used to map land cover for the entire city with such detail that single trees were detected (Figure 4).[5] The following land cover categories were mapped: tree canopy; grass/shrub; bare soil; water; buildings; roads; and other paved.

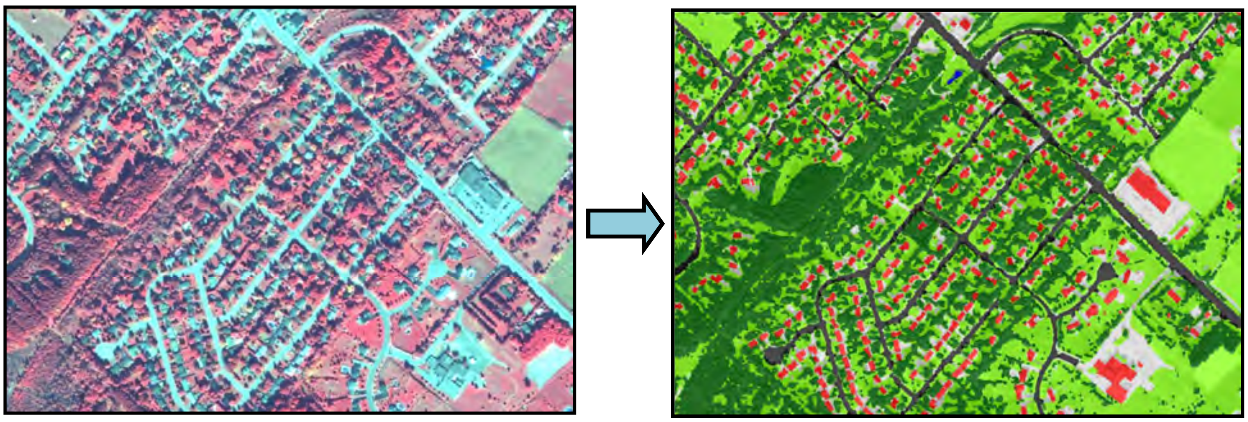

Figure 4: High resolution satellite imagery (left) used to produce digital surface cover map (right).

Using the land cover data the following tree cover statistics were calculated: existing tree canopy; impervious possible tree canopy; and vegetated possible tree canopy (see Table 2 for a description of each metric). Tree canopy metrics were summarized for each property in the City's parcel database. For each parcel both the absolute area and percent of existing and possible tree canopy were computed.

Table 2: Description of tree canopy metrics used in Urban Tree Canopy (UTC) analysis for the City of Mississauga.

Tree Canopy Metric	Description
Existing tree canopy	The amount of tree canopy present when viewed from above using aerial or satellite imagery.
Impervious possible tree canopy	Asphalt or concrete surfaces - excluding roads and buildings - that are theoretically available for the establishment of tree canopy.
Vegetated possible tree canopy	Grass or shrub area that is theoretically available for the establishment of tree canopy. This estimate does not consider land use preferences.

Existing and possible tree canopy metrics were summarized for the following geographic categories: land use category; municipal right-of-way (ROW); small geographic unit (SGU); service delivery area (SDA); municipal ward; and watershed.

[5] Resolution of imagery is 0.6m.

3.3 Priority Planting Index

The digital cover maps described in section 3.2 together with 2006 census data were used to produce an index that prioritizes tree planting areas within small geographic units in the City of Mississauga. The index combines three criteria:

1. Population density: The greater the population density, the greater the priority for tree planting.
2. Canopy green space: Canopy greenspace is the proportion of total greenspace area (non-impervious areas) filled with tree canopies. The lower the value, the greater the priority for tree planting.
3. Tree canopy cover per capita: The lower the amount of tree canopy cover per person, the greater the priority for tree planting.

Each criterion above was standardized on a scale of 0 to 1, with 1 representing the maximum population density and minimum canopy green space and tree cover per capita. The standardized values were weighted to produce a combined score:

$$I = (PD * 40) + (CG * 30) + (TPC * 30)$$

Where I is the combined index score, PD is the standardized population density value, CG is the standardized canopy green space value, and TPC is the standardized tree cover per capita value.

The combined score was standardized again and multiplied by 100 to produce the planting priority index. The tree planting priority index (PPI) ranks the small geographic units with values from 100 (highest priority) to 0 (lowest priority). Areas of higher human population density and lower canopy green space and tree cover per capita receive higher index values.

3.4 Grow Out Simulations

A computer model created by the USDA Forest Service, Northern Research Station, was used to estimate future canopy cover under the following three scenarios: 1) maintain existing canopy cover; 2) increase canopy to 25 percent; and 3) double existing canopy cover. Each scenario estimated future canopy cover using 5 different annual mortality rates, ranging from 1 percent annual mortality to 5 percent annual mortality. The actual mortality rate of trees in Mississauga is not known, but is assumed to fall within this range.

Tree measurements collected for the i-Tree Eco analysis were utilized to simulate future canopy cover. Projections for each tree were based on various tree characteristics including: species (growth rate, longevity, height at maturity); diameter at breast height (dbh); crown light exposure; and percent dieback in tree crown. Tree growth or annual increase in dbh was based on the number of frost free days (160), crown light exposure, dieback, growth rate classification and median height at maturity. Individual tree mortality was based on the percent dieback in the crown, dbh and average height at maturity for each tree. Average percent mortality was calculated for all trees measured.

3.5 i-Tree Hydro

The effects of tree and shrub cover on stream flow were modeled for two subwatersheds in the Region of Peel: the Spring Creek subwatershed (46.6 km^2); and the Fletcher's Creek subwatershed (42.5 km^2). The i-Tree Hydro model 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. Precipitation data for the Fletcher's Creek analysis were collected from the CVC Firehall and weather data were collected from Toronto Pearson International Airport (WBAN: 716240 99999). For the Spring Creek analysis the precipitation data were collected from weather stations at Heart Lake CA (PRCP0085) and Mississauga Works Yard (PRCP0115). Digital elevation model data were obtained from the Toronto Regional Conservation Authority. Tree and impervious cover parameters were derived for each watershed from photo-interpretation of Google Earth imagery using 1,000 randomly located points (Table 3).

Table 3: Cover estimates for the Fletcher's Creek and Spring Creek subwatersheds.

	Percent Cover			
Area	**Impervious**	**Tree**	**Grass/shrub**	**Bare Soil**
Fletcher Creek Watershed	42.6%	10.6%	43.3%	4.2%
Spring Creek Watershed	48.2%	14.3%	36.6%	3.2%

For a detailed description of the i-Tree Hydro model methodology please see Appendix D.

4.0 Results

4.1 Urban Forest Distribution

The Urban Tree Canopy (UTC) analysis found that approximately 4,350 ha of the City is covered by tree canopy (termed existing TC) representing 15 percent of all land cover in Mississauga (Figure 5). Impervious surfaces (roads, buildings, and other paved surfaces) represent approximately half of the municipal land cover. A total of 60 percent (17,470 ha) of the City could theoretically support tree canopy (possible TC) (Figure 6). Within the possible TC category, 25 percent (7,454 ha) of the City is impervious possible TC and another 35 percent is vegetated possible TC (10,016 ha). When classifying possible TC the analysis did not consider socio-economic and cultural expectations for land use. Accordingly, agricultural lands and sports fields have been classified as possible TC; however, land use practices in such areas may not be conducive to establishing tree cover.

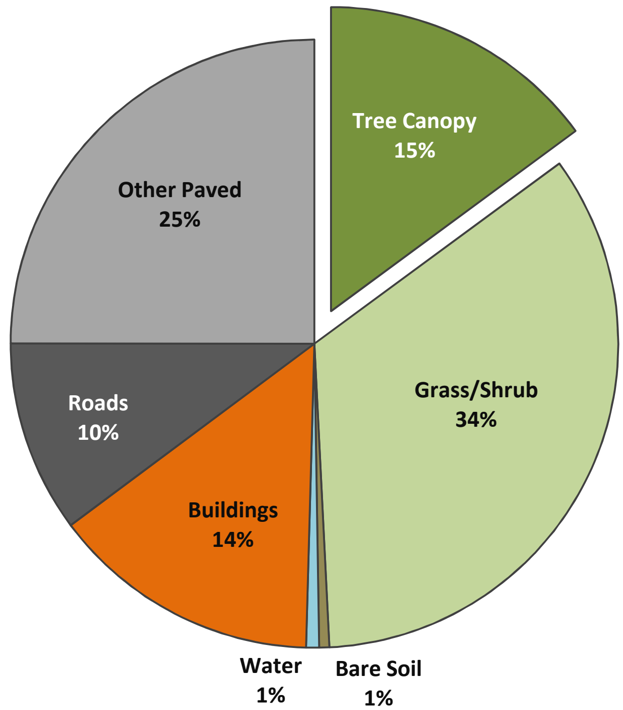

Figure 5: Land cover estimates for the City of Mississauga

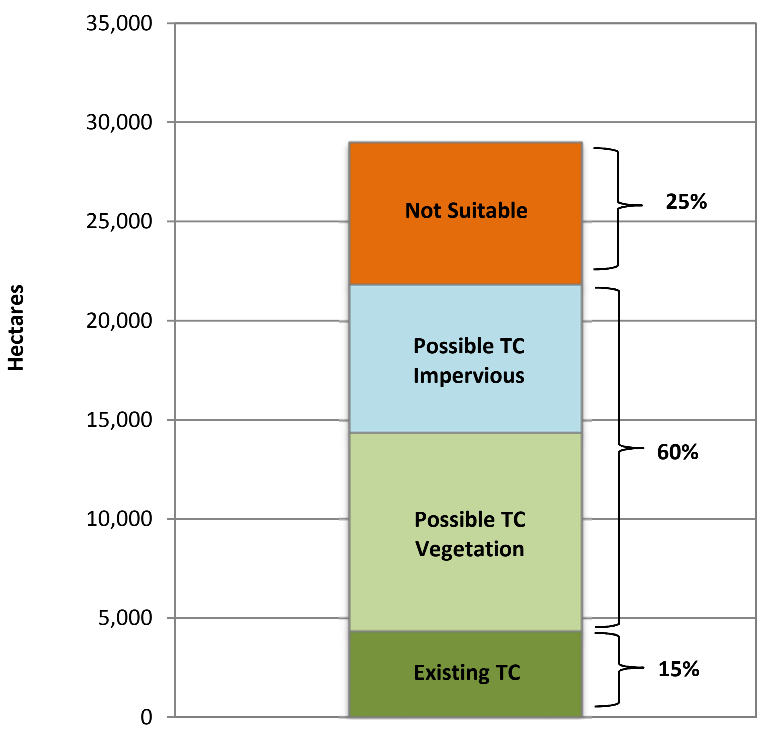

Figure 6: Tree canopy metrics for the City of Mississauga

Figure 7 illustrates the total area (ha) of existing and possible TC within each land use. Table 4 presents TC metrics for each land use calculated as a percentage of all land in the City (% City), and as a percentage of land area in the specified land use category (% Land Use). The *natural cover* land use category supports the highest existing TC by land use, with 44 percent tree cover; however, due to the relative size of this land use, tree cover within the *natural cover* category represents less than 1 percent of the City's total land area. Existing TC is lowest in the *industrial* and *utilities and transportation* land use categories. Approximately 2,242 ha of tree cover is found within the *residential low* category, which comprises more than half of all tree cover in the municipality and represents 8 percent of the City's total land area.

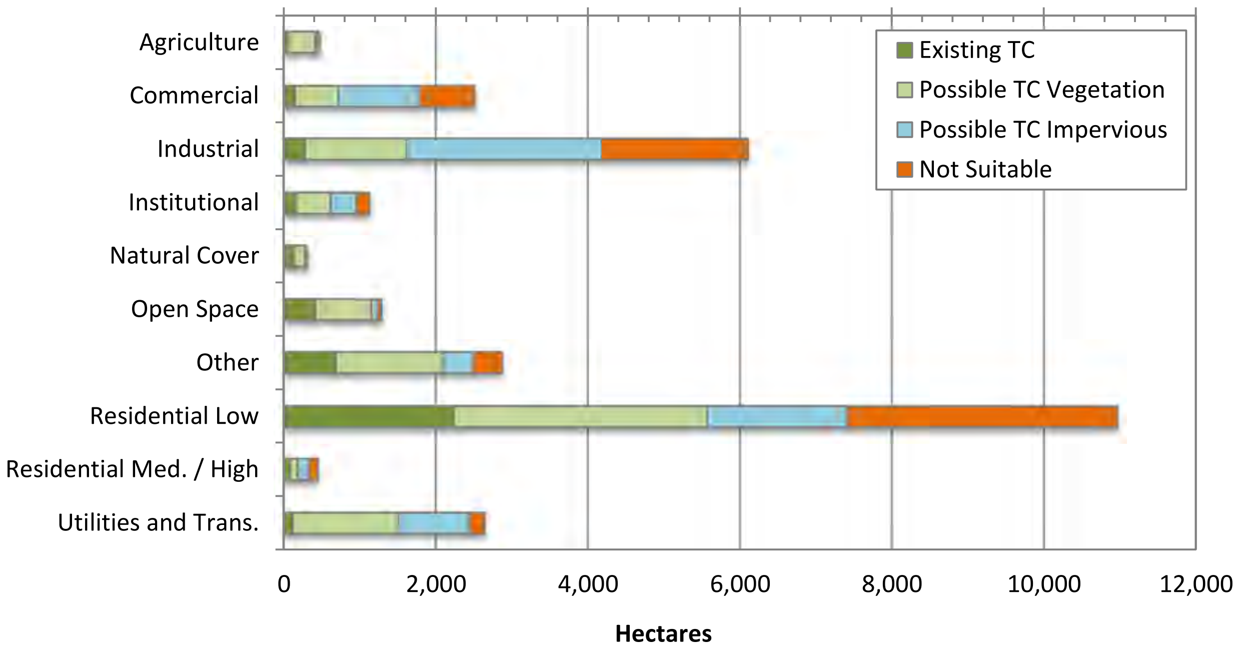

Figure 7: Tree canopy metrics summarized by land use category

The greatest opportunity to increase total municipal tree cover is found in the *residential low* land use category. Approximately 3,329 ha (30 percent) of the *residential low* category is classified as possible vegetated TC, which represents 12 percent of all land in Mississauga; another 1,837 ha (17 percent) of the *residential low* category is classified as possible impervious TC, which represents an additional 6 percent of the City (Table 4). The *industrial* land use category also maintains a large proportion of land available for tree establishment; 62 percent of the industrial category is classified as possible TC, which represents 14 percent (5 percent possible vegetated TC and 9 percent possible impervious TC) of all land area in the City of Mississauga.

Table 4: Tree canopy (TC) metrics summarized by land use. For each land use category TC metrics were calculated as a percentage of all land cover in the City (% City), and as a percentage of land cover within the specified land use category (% Land Use).

Land Use	Existing Tree Canopy		Possible Tree Canopy - Vegetation		Possible Tree Canopy - Impervious	
	% City	% Land Use	% City[6]	% Land Use	% City	% Land Use
Agriculture	< 1	13	1	76	0	7
Commercial	1	6	2	23	4	42
Industrial	1	5	5	22	9	42
Institutional	1	14	2	40	1	31
Natural Cover	< 1	44	1	48	< 1	5
Open Space	1	32	3	57	< 1	7
Other	2	24	5	49	1	14
Residential Low	8	20	12	30	6	17
Residential Medium / High	< 1	19	< 1	23	1	34
Utilities and Transportation	< 1	5	5	53	3	35

The average existing and possible TC metrics were generated for municipal rights-of-way (Figure 8). Approximately half of the right-of-way land area is considered "not suitable" for tree establishment. Only 12 percent is classified as existing tree canopy, with the remaining 40 percent classified as possible TC.

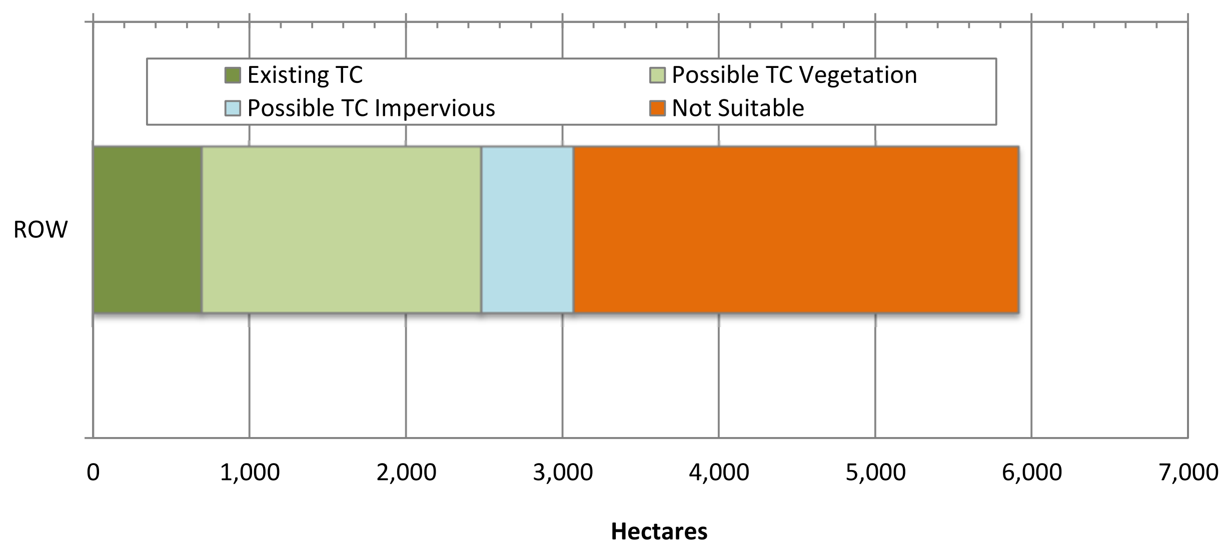

Figure 8: Tree canopy metrics summarized by right-of-way in the City of Mississauga.

[6] Columns shaded in green represent the percent of total land in the City that is available for tree planting and establishment.

Figure 9 presents the TC metrics by municipal ward. The highest existing percent TC was found in ward 2 followed by ward 1, respectively. The greatest opportunity to increase TC by ward was found in ward 5; 69 percent of this stratum was classified as possible TC, which represents approximately 22 percent of the land area in Mississauga.

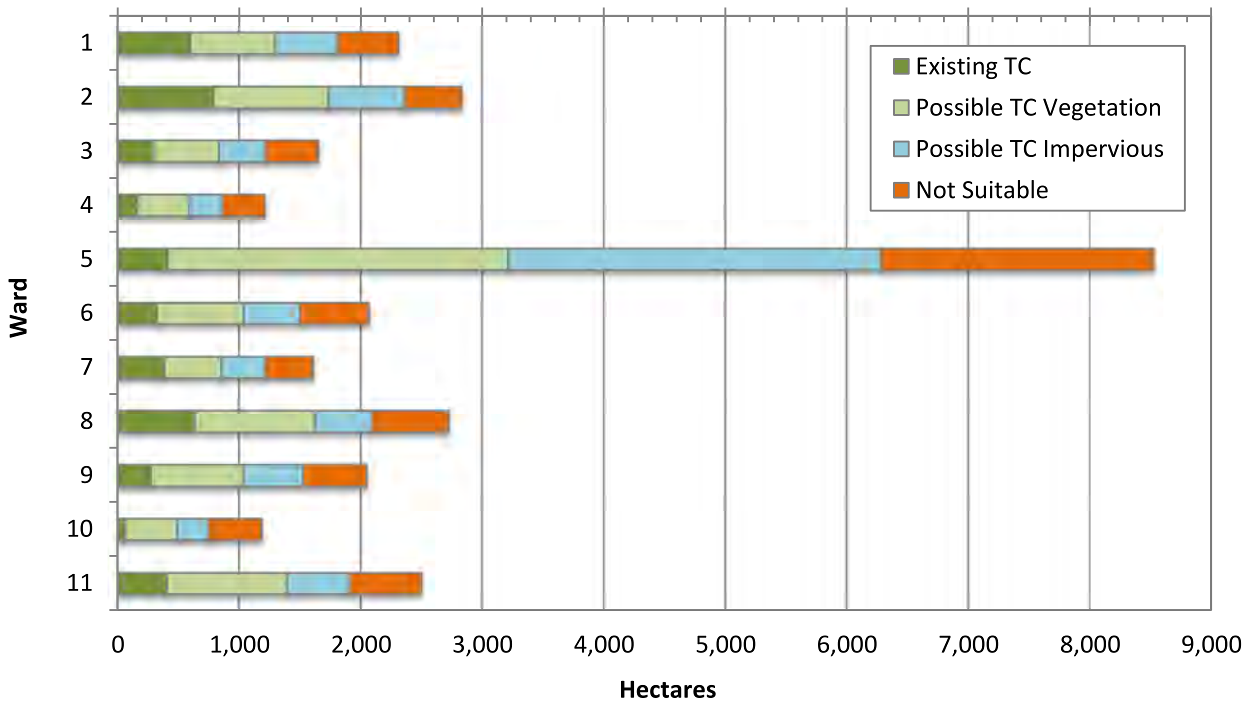

Figure 9: Existing and potential tree canopy metrics summarized by ward in the City of Mississauga.

Tree canopy metrics have been generated for small geographic units (SGU) and are presented in Figure 10. High existing TC is indicated by dark green shading; high possible TC (both vegetated and impervious) is indicated by dark orange shading. Highest existing TC is generally located in the southern most neighbourhoods of the City, along the Lake Ontario shoreline. Lowest existing is found in the industrial areas in the northeast corner of the City.

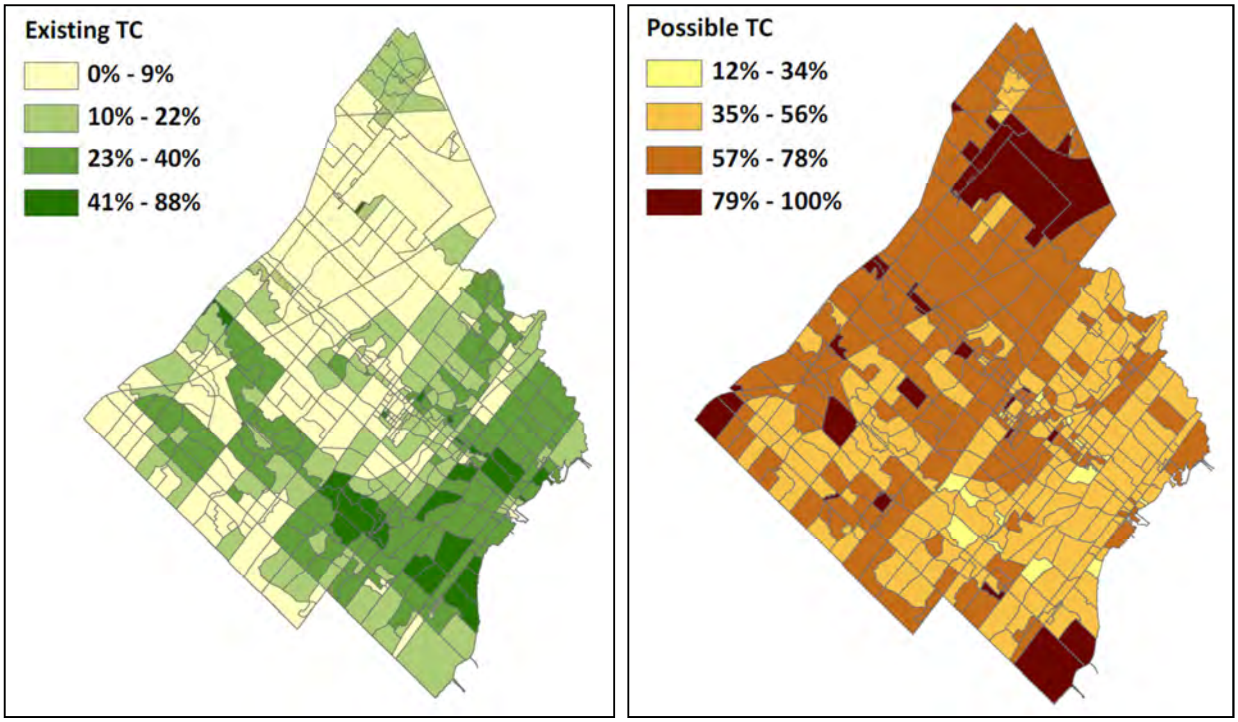

Figure 10: Existing and possible tree canopy metrics summarized by small geographic unit in Mississauga

Tree canopy metrics have also been summarized by subwatershed boundaries within Mississauga (Figure 11). Many of the subwatershed boundaries extend beyond the municipal boundaries. The highest percent existing TC is in the Moore Creek subwatershed within the (58 percent); however, this is also the smallest subwatershed in the municipality. The Norval to Port Credit subwatershed within the Credit River watershed covers the largest area of Mississauga (4,769 ha) and contributes the largest portion to total existing TC (7 percent). Figure 12 present the trees canopy metrics summarized by ward.

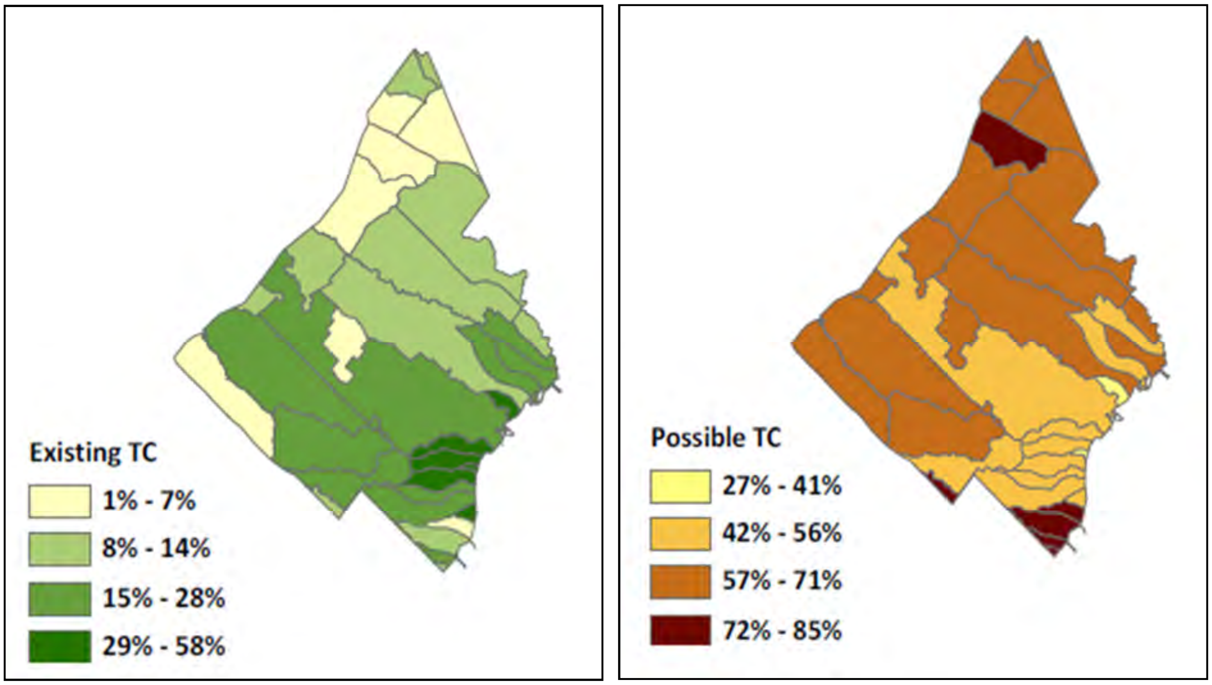

Figure 11: Existing and possible tree canopy summarized by watershed in Mississauga

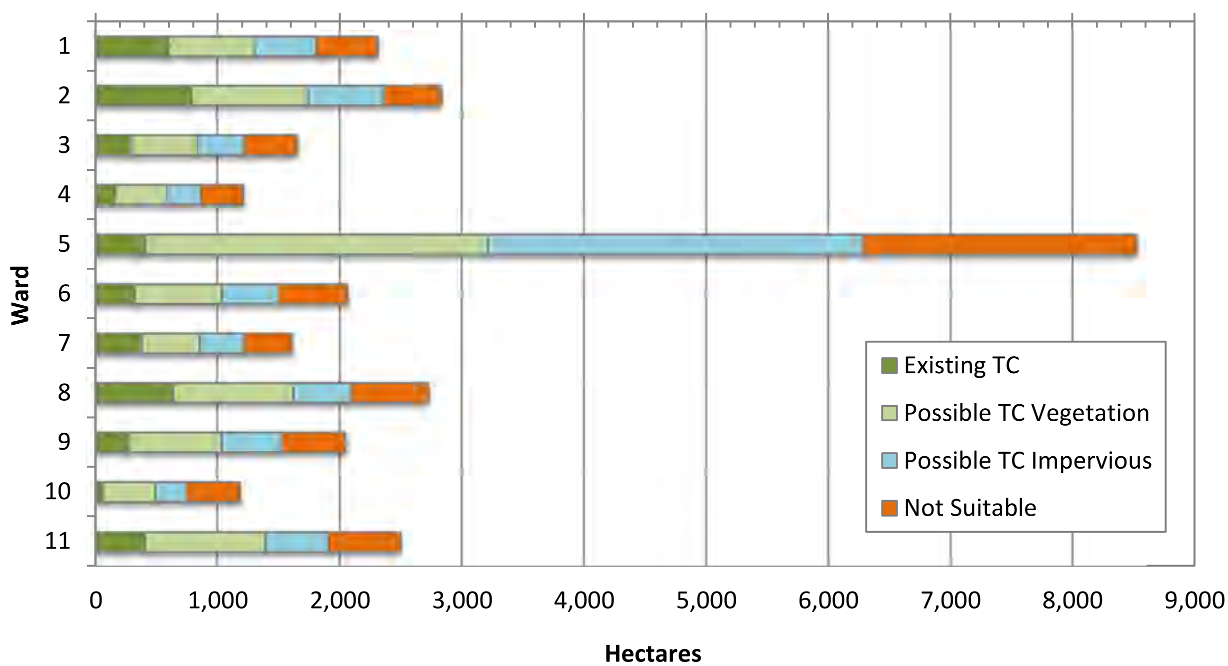

Figure 12: Existing and possible tree canopy summarized by ward in Mississauga

4.2 Priority Planting Index

The Priority Planting Index (PPI) provides direction for tree planting and establishment. The index has been summarized at the scale of small geographic unit (SGU). Each unit has been assigned a value between 0 (lowest priority) and 100 (highest priority). SGUs with a higher human population density and a lower canopy green space and tree cover per capita have received a higher index value. Figure 13 illustrates the results of the PPI.

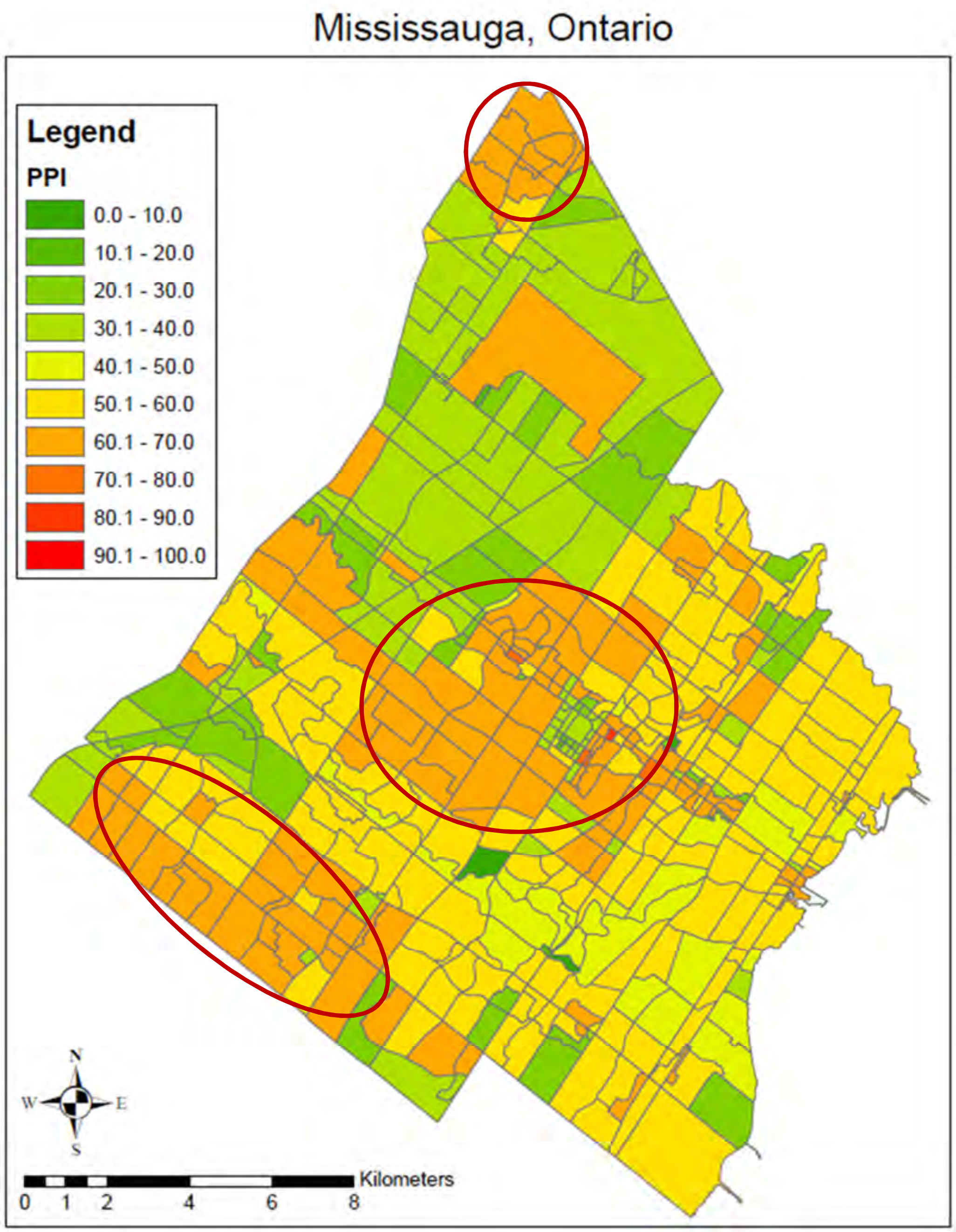

Figure 13: Priority Planting Index in the City if Mississauga summarized by small geographic unit. Areas recommended for priority tree planting and establishment are circled in red.

Although existing tree cover is very low in the industrial and commercial lands in the northeast corner of the municipality (north of Eglinton Avenue and east of Highway 10), as shown in Figure 10, population density is also low in these areas. Thus, these areas are not considered a priority. In contrast, the residential areas circled in red on the map are a greater priority as these areas support a higher population density and are not currently receiving an equitable distribution of the ecosystem services provided by the urban forest.

4.3 Urban Forest Structure

The i-Tree Eco model determined that there are approximately 2,104,000 trees in the City of Mississauga (with a standard error of 307,000). Nearly half of all trees in the City, approximately 1,000,000 trees, are located in the *residential* land use. Average tree density in Mississauga is 71.3 trees/ha, which is considered low in comparison to other cities in North America (Appendix E). Average leaf area density for Mississauga is approximately 7,770 m^2/ha. Tree density and leaf area density vary widely between land uses and are generally concentrated in the *open space + natural cover + agriculture* and *other* categories (Figure 14); these two land uses represent only 17 percent of the total land area in Mississauga. Both tree density and leaf area density are lowest in the *commercial + industrial* land use. This land use represents 30 percent of the total land area in Mississauga.

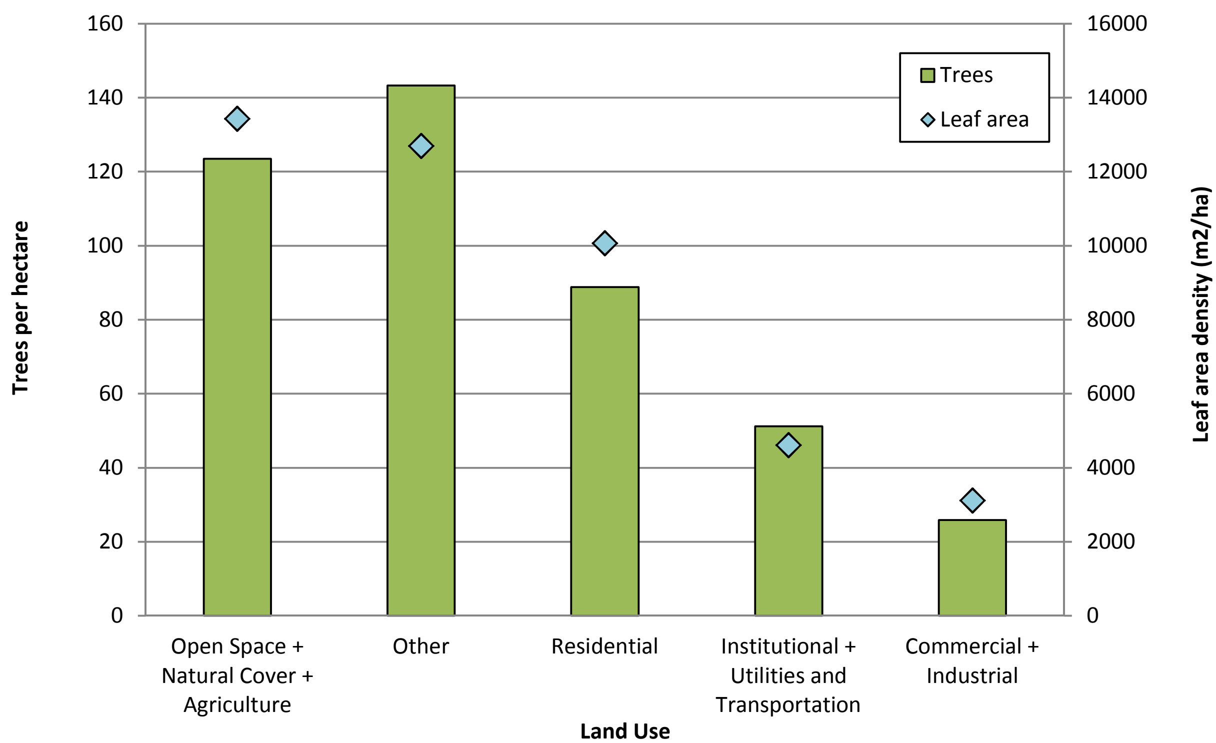

Figure 14: Tree density (trees/ha) and leaf area density (m^2/ha) by land use in the City of Mississauga.

Species composition can be expressed either as a percent of total leaf area or as a percent of the total number of stems (Figure 15). When the latter measure is used, species that maintain a smaller growth form and that grow in high densities, such as buckthorn (*Rhamnus spp.*) and hawthorn species

(*Crataegus spp.*), tend to dominate total species composition. In contrast, composition expressed as a percent of total leaf area captures the relative contribution made by each species to the canopy layer as well as to the provision of ecosystem services (as ecosystem services are generally a function of leaf area). With respect to total leaf area, the dominant tree species in Mississauga are sugar maple (*Acer saccharum*, 12 percent of total leaf area), Norway maple (*Acer platanoides*, 8 percent of total leaf area), and green ash (*Fraxinus pennsylvanica*, 8 percent of total leaf area). With respect to the total number of individual stems, the most common tree species are sugar maple (10 percent), white ash (*Fraxinus americana*, 10 percent), and eastern white cedar (*Thuja occidentalis*, 9 percent). Species dominance by land use is illustrated in Table 5.

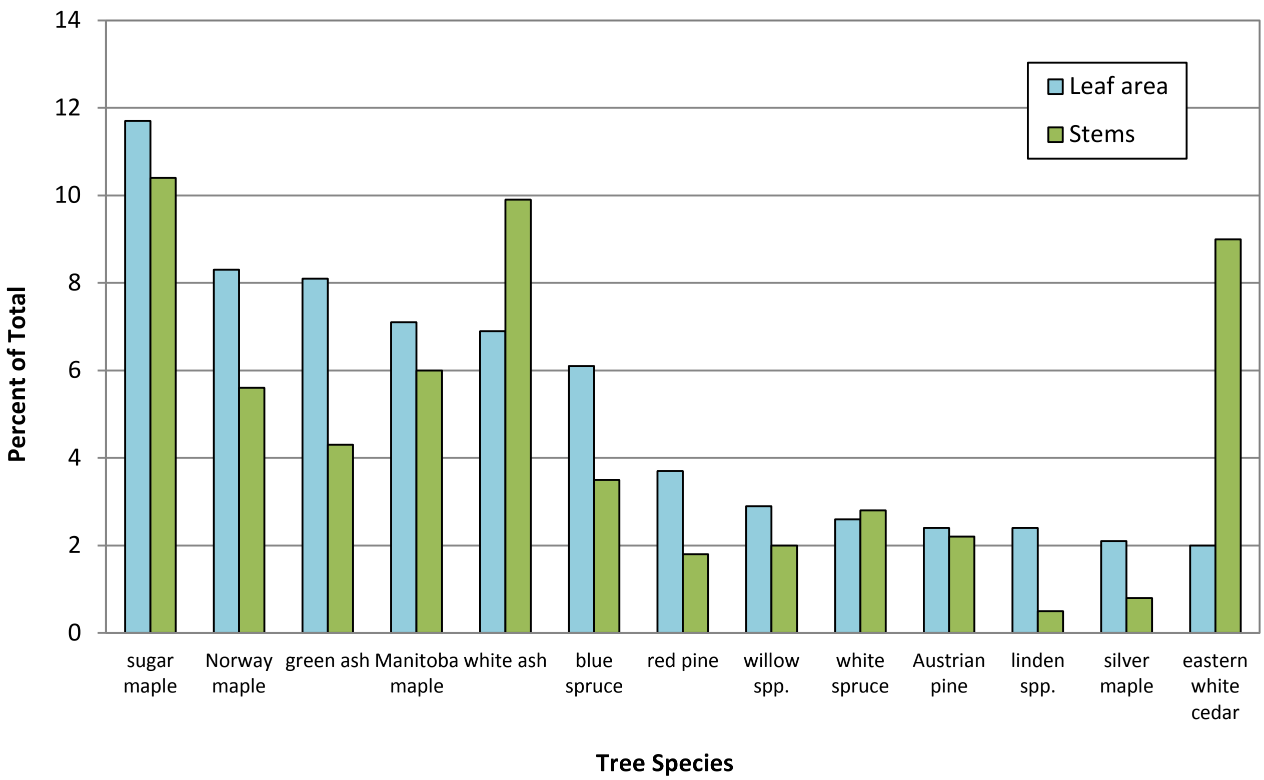

Figure 15: Tree species in Mississauga expressed as a percent of total leaf area and percent of total stems.

Among genera, maple (*Acer*) and ash (*Fraxinus*) are the most abundant in the urban forest, representing approximately 31 percent and 16 percent of the total leaf area, respectively. Within in the maple genus, Norway maple (*Acer platanoides*) and Manitoba maple (*Acer negundo*) represent approximately half of all maple species and 15 percent of the total leaf area in Mississauga. Both species are particularly abundant in the *residential* land use. These two species are known to be invasive and can spread into natural areas and threaten the survival of sensitive native vegetation.

Eastern white cedar was found to be the dominant shrub species, representing 20.7 percent of total shrub leaf area and 2.4 percent of total tree and shrub leaf area, followed by exotic bush honeysuckle species (*Lonicera spp.*), representing 12.3 percent of the total shrub leaf area and 1.5 percent of total tree and shrub leaf area. Dominant shrub species by land use are shown in Table 5.

Table 5: Dominant tree species by percent of total leaf area and percent of total stems within land uses in the City of Mississauga.

Land use	Percent of Total Leaf Area		Percent of Total Stems	
	Common Name	Percent	Common Name	Percent
Open Space + Natural Cover + Agriculture	sugar maple	43	sugar maple	56
	Manitoba maple	10	white ash	8
	willow spp.	10	black ash	6
Residential	Norway maple	12	eastern white cedar	16
	white ash	9	Norway maple	8
	green ash	9	Manitoba maple	5
Commercial + Industrial	blue spruce	35	blue spruce	18
	red pine	18	Austrian pine	18
	Austrian pine	16	red pine	10
Institutional + Utilities and Transportation	sugar maple	28	white ash	28
	Norway maple	16	sugar maple	16
	red oak	12	American beech	10
Other	sugar maple	22	white ash	19
	green ash	16	Manitoba maple	16
	elm spp.	11	green ash	11

Table 6: Dominant shrub species by percent of shrub leaf area within land uses in the City of Mississauga.

Land Use	Common Name	Percent of shrub leaf area
Open space + Natural cover + Agriculture	exotic bush honeysuckle spp.	25.8
	white ash	15.9
Residential	eastern white cedar	24.9
	viburnum spp.	11.2
Commercial + Industrial	exotic bush honeysuckle spp.	35.1
	eastern white cedar	24.0
Institutional + Utilities and Transportation	juniper spp.	25.9
	exotic bush honeysuckle spp.	23.7
Other	eastern white cedar	18.7
	viburnum spp.	18.4

A total of 69 tree species have been identified across all sample plots. Species richness and species diversity are highest in the *residential* land use (58 species); this comparatively high level of diversity can likely be attributed to the number of exotic horticultural species commonly found in residential gardens. It follows that in the context of urban forest studies, high species diversity should not necessarily be viewed as an indication of ecosystem health. Rather, high species diversity may simply indicate an abundance of exotic species. Thus, urban forests often have a tree diversity that is higher than surrounding native landscapes. In Mississauga, 56 percent of the trees species identified were native to Ontario (Figure 16).

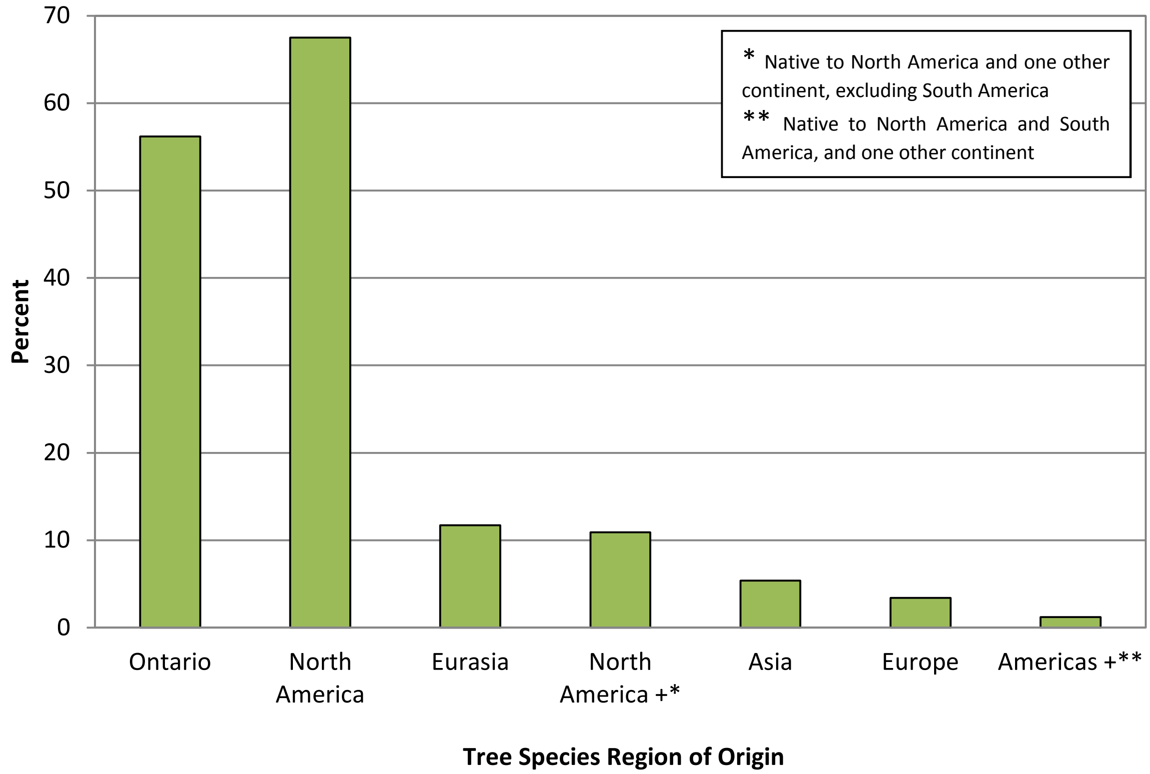

Figure 16: Region of origin of tree species recorded in Mississauga.

Approximately 42 percent of trees in Mississauga have been established through natural regeneration (Table 7). Among the species measured sugar maple (*Acer saccharum*), trembling aspen (*Populus tremuloides*), and white ash (*Fraxinus americana*) have the highest rates of natural regeneration (Table 8). In contrast, blue spruce (*Picea pungens*), Japanese tree lilac (*Syringa reticulata*), and eastern white cedar (*Thuja occidentalis*) have been established either completely or predominately through planting efforts. Also noteworthy is the incidence of natural regeneration observed in Norway maple stems; nearly 12 percent of the stems measured were established through natural regeneration suggesting that this species has the potential to become established outside of its intended planting zone

Table 7: Estimated percent of tree population planted versus establishment through natural regeneration in the City of Mississauga.

Land Use	Percent Planted	Percent Natural Regeneration	Sample Size
Commercial / Industrial	98	2	53
Residential	83	17	303
Transportation	43	57	21
Vacant	25	75	71
Parks	14	86	116
Institutional	9	91	44
City Total	58	42	608

Table 8: Estimated percent of species planted in the City of Mississauga (minimum sample size = 15 trees).

Common Name	Scientific Name	Percent Planted	Sample Size
Blue spruce	*Picea pungens*	100	21
Japanese tree lilac	*Syringa reticulata*	100	16
Eastern white cedar	*Thuja occidentalis*	94.1	51
Littleleaf linden	*Tilia cordata*	93.3	15
Norway maple	*Acer platanoides*	88.2	34
White spruce	*Picea glauca*	88.2	17
Green ash	*Fraxinus pennsylvanica*	61.5	26
Manitoba maple	*Acer negundo*	19.4	36
White ash	*Fraxinus americana*	16.9	59
Trembling aspen	*Populus tremuloides*	6.7	15
Sugar maple	*Acer saccharum*	1.5	66

Pest-susceptibility was calculated for the following insects: Asian long-horned beetle (*Anoplophora glabripennis*); emerald ash borer (*Agrilus planipennis*); gypsy moth (*Lymantria dispar*); and Dutch elm disease (*Ophiostoma spp.*) (Figure 17). Estimates represent the maximum potential pest damage. Actual damage or loss incurred as a result of an outbreak would likely be less severe. Approximately 56 percent of Mississauga's live tree population (number of stems) is susceptible to Asian long-horned beetle; this equates to a loss in structural value of $ 702,000,000. Gypsy moth is a threat to 15 percent of the live tree population with a potential loss in structural value of $372,000,000. Emerald ash borer is a threat to 16 percent of the live tree population, representing a potential loss of $208,000,000 in structural value. Although some elm species have shown varying degrees of resistance, Dutch elm disease could destroy the remaining elm population, representing approximately 2 percent of the live tree population, valued at $3,500,000.

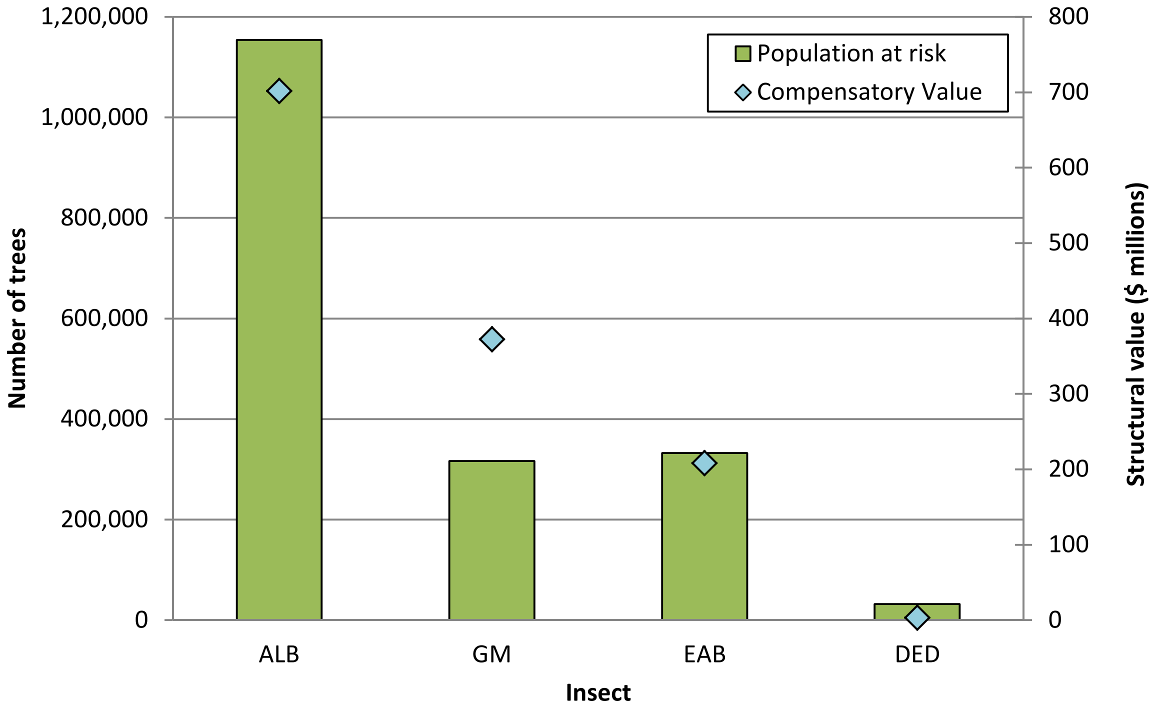

Figure 17: Number of trees susceptible to Asian longhorned beetle (ALB), gypsy moth (GM), emerald ash borer (EAB), and Dutch elm disease (DED), and potential loss in associated structural value of host trees.

All trees measured have been grouped into size classes based on diameter at breast height (dbh); diameter class increased at 7.6 cm increments. Approximately 33 percent of all trees in Mississauga fall within the smallest diameter class and 63 percent of all trees are less than 15.3 cm dbh (Figure 18). The proportion of large trees is low; less than 7 percent of the tree population has a dbh of 38.2 cm or greater. Figure 19 presents the diameter class distribution by land use. Across all land uses the trend is similar, with the smallest diameter classes containing the large majority or trees, while very few trees are found in the larger (> 38.1 cm) diameter classes.

Average tree diameter across the urban forest is 15.8 cm. Species with the highest average dbh are red oak (*Quercus rubra*, 25.5 cm), black cherry (*Prunus serotina*, 25.5 cm), white oak (*Quercus alba,* 22.8 cm) and American basswood (*Tilia americana,* 22.5 cm).

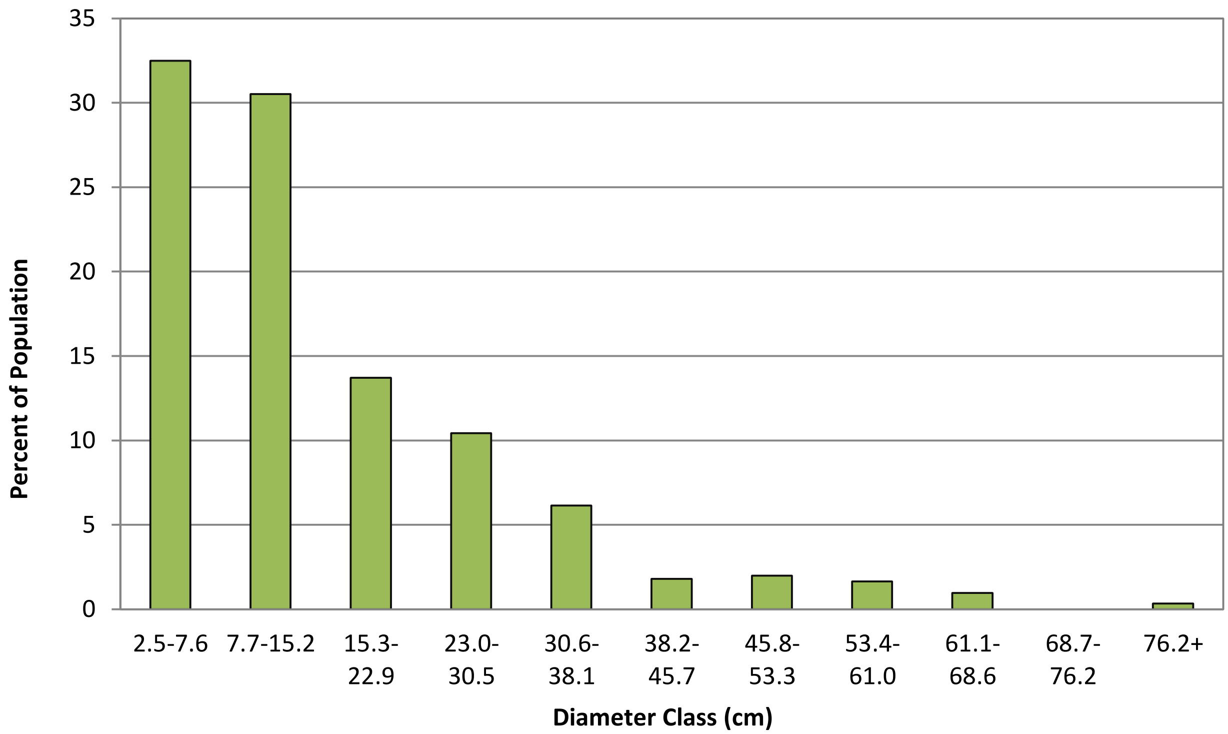

Figure 18: Diameter class distribution of trees in the City of Mississauga.

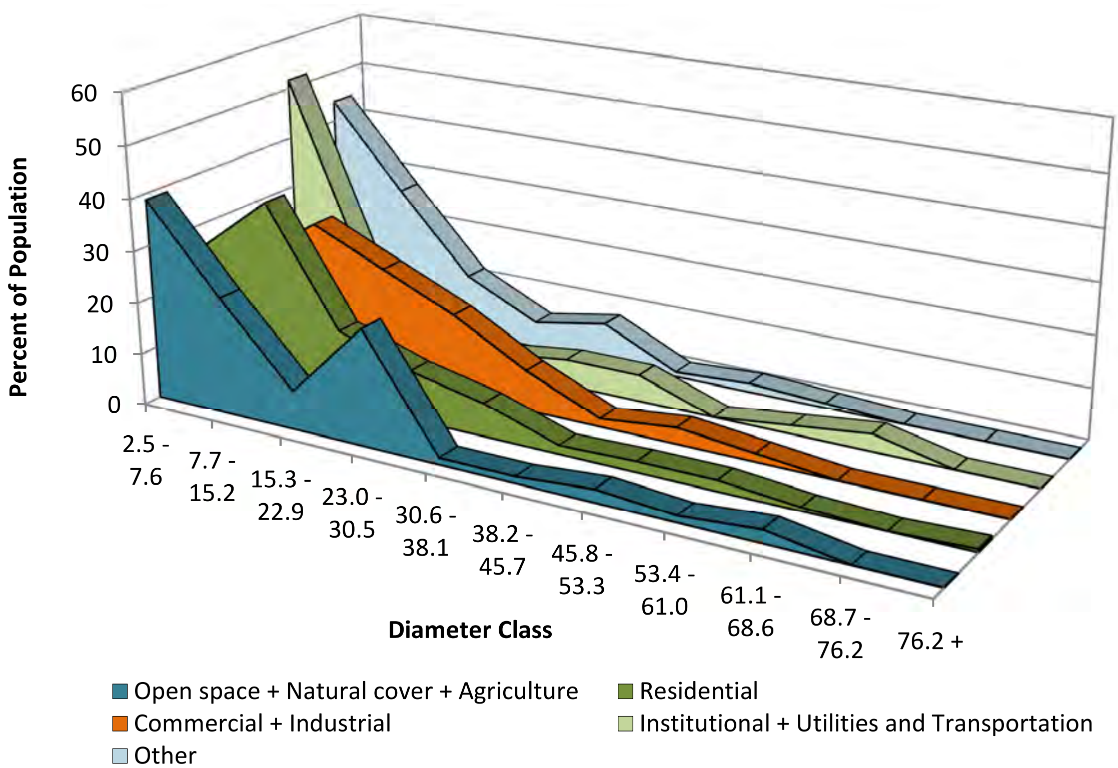

Figure 19: Diameter class distribution of trees by land use in the City of Mississauga.

All trees measured have been assigned a condition rating in the field based on the proportion of dieback in the crown. The crown condition ratings range from excellent (< 1 percent dieback) to dead (100 percent dieback). Approximately 80 percent of trees in Mississauga are estimated to be in either excellent or good condition (Figure 20). Condition ratings do not incorporate stem defects and root damage.

The estimated structural value of all trees in Mississauga in 2008 is approximately $1.4 billion. This value does not include the ecological or societal value of the forest, but rather it represents an estimate of tree replacement costs and/or compensation due to tree owner's for tree loss. There is a positive relationship between the structural value of an urban forest and the number and size of healthy trees.

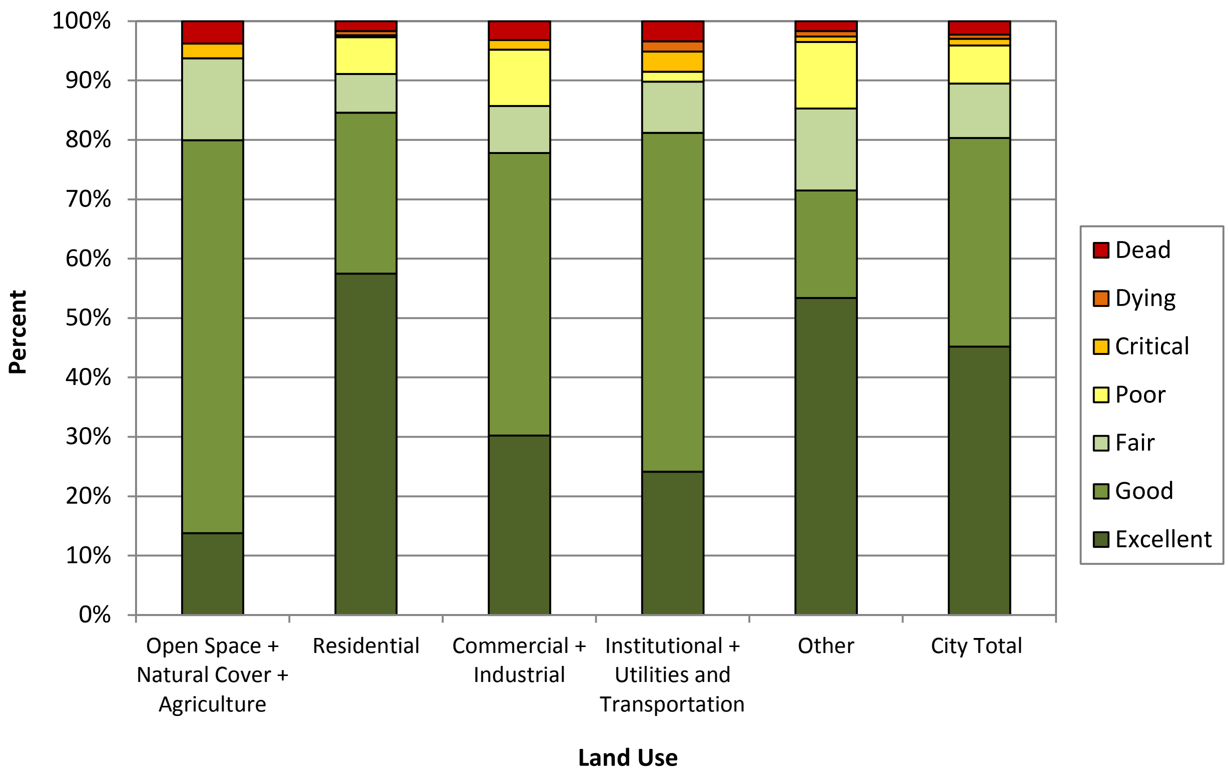

Figure 20: Average tree condition by land use and City total in the City of Mississauga

4.4 Grow Out Scenarios

The grow out simulations provide a general estimate of the level of annual tree planting required to meet multiple canopy cover targets within the next 50 years. The model simulates the growth of Mississauga's urban forest based on existing conditions as quantified by the Eco analysis. Simulations are based on existing urban forest characteristics, including species growth rates and current tree health. With an annual mortality rate of 4 percent, approximately 1,120 trees will need to be planted to simply maintain the existing canopy cover (Table 9). Approximately 2,950 trees must be planted annually across the municipality to reach a 25 percent canopy cover target (assuming a 4 percent annual mortality rate).

Table 9: Estimated amount of tree planting required in the City of Mississauga to: 1) maintain existing canopy cover of 15 percent; and 2) increase canopy cover to 25 percent over a 50 year period, given 5 possible annual mortality rates.

Annual Mortality Rate	Annual tree planting to maintain 15% canopy cover	Annual tree planting to increase to 25% canopy cover
1 %	0	0
2 %	0	750
3 %	400	1,800
4 %	1,120	2,950
5 %	2,000	4,000

As shown in Table 9, with an average mortality rate of 1 to 2 percent, no additional tree planting is required to maintain 15 percent canopy cover. However, given the almost certain loss of all ash trees due to emerald ash borer, an annual mortality rate of 5 percent may even be conservative. It follows that a greater amount of annual tree planting than is indicated in table 9 will be necessary to achieve a 25 percent canopy cover target as the mortality rates used in the grow out scenario do not reflect the threat posed by emerald ash borer. Thus, canopy cover targets can be aggressive but must still be realistic given the existing structure, current mortality rates and future threats.

4.5 Urban Forest Function

4.5.1 Carbon Storage and Sequestration

Gross carbon sequestration by trees in Mississauga is approximately 10,000 tonnes of carbon annually with an associated value of $285,000 per year; net carbon sequestration is approximately 7,400 tonnes per year.[7] Of all tree species measured, sugar maple (*Acer saccharum*) is estimated to sequester the largest volume of carbon (approximately 11.4 percent of total sequestered carbon). Average gross and net sequestration per tree is positively correlated with diameter class (Figure 22).

Trees in Mississauga are estimated to store 203,000 tonnes of carbon, with an associated value of $5.8 million. White ash (*Fraxinus americana*) store the largest total volume of carbon (approximately 11.5 percent of total carbon stored). Figure 23 illustrates the relationship between diameter class and total carbon storage. However, this graph must be viewed in the context of the diameter class distribution of the entire tree population (Figure 18). For example, trees between 53.4 and 68.6 cm dbh represent less than 3 percent of the total tree population in Mississauga yet these trees store approximately 26 percent of the total volume of carbon. In contrast the City's smallest trees (2.5 to 15.2 cm dbh) represent approximately 63 percent of the tree population but store less than 7 percent of the total volume of carbon. Thus, when the results are standardized to illustrate average *per tree storage capacity* individual large trees are shown to store significantly larger volumes of carbon than individual small trees (Figure 22). For example, the average tree in diameter class 7.7 – 15.2 cm stores 17.5 kg of carbon and sequesters 5 kg of carbon annually, while the average tree in diameter class 38.2 – 45.7 cm stores 403.8 kg of carbon and sequesters 14.5 kg of carbon annually.

[7] Net annual sequestration = gross sequestration minus estimated carbon emissions due to mortality or decomposition.

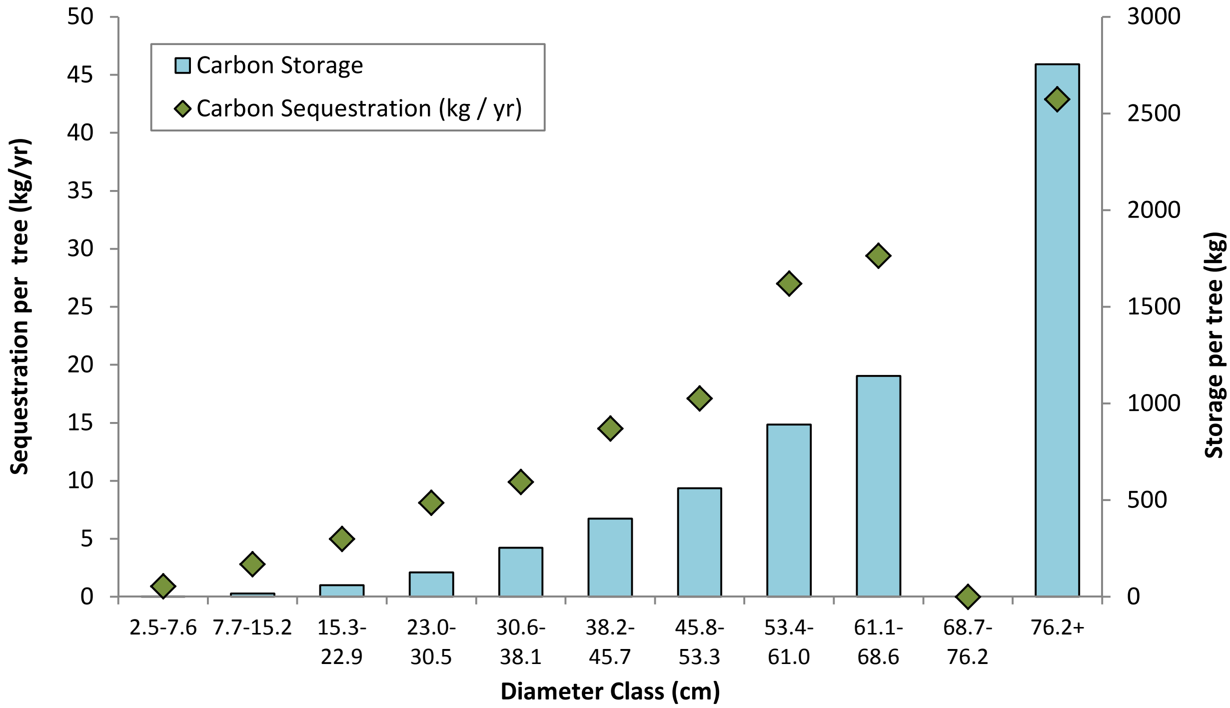

Figure 22: Average per tree carbon sequestration and storage by diameter class.

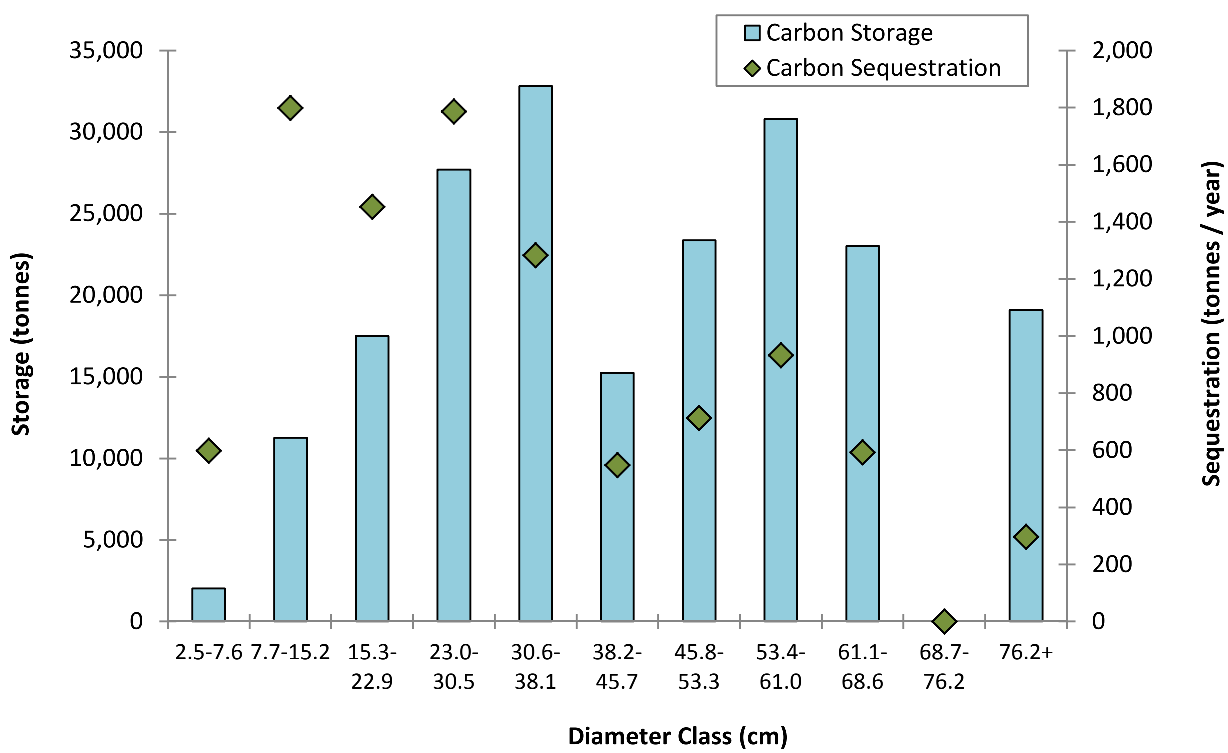

Figure 23: Total carbon storage and sequestration by diameter class.

4.5.2 Annual Pollution Removal

The i-Tree Eco model quantified pollution removal by trees and shrubs in Mississauga. Pollution removal is greatest for ozone (O_3), followed by nitrogen dioxide (NO_2), particulate matter less than ten microns (PM_{10}), sulfur dioxide (SO_2), and carbon monoxide (CO) (Figure 24). Trees and shrubs remove 429 tonnes of air pollution (CO, NO_2, O_3, PM_{10}, SO_2) annually with an associated removal value of $4.8 million (based on estimated 2007 national median externality costs associated with pollutants).[8] Average annual volume removed per tree increases with tree size (Figure 25).

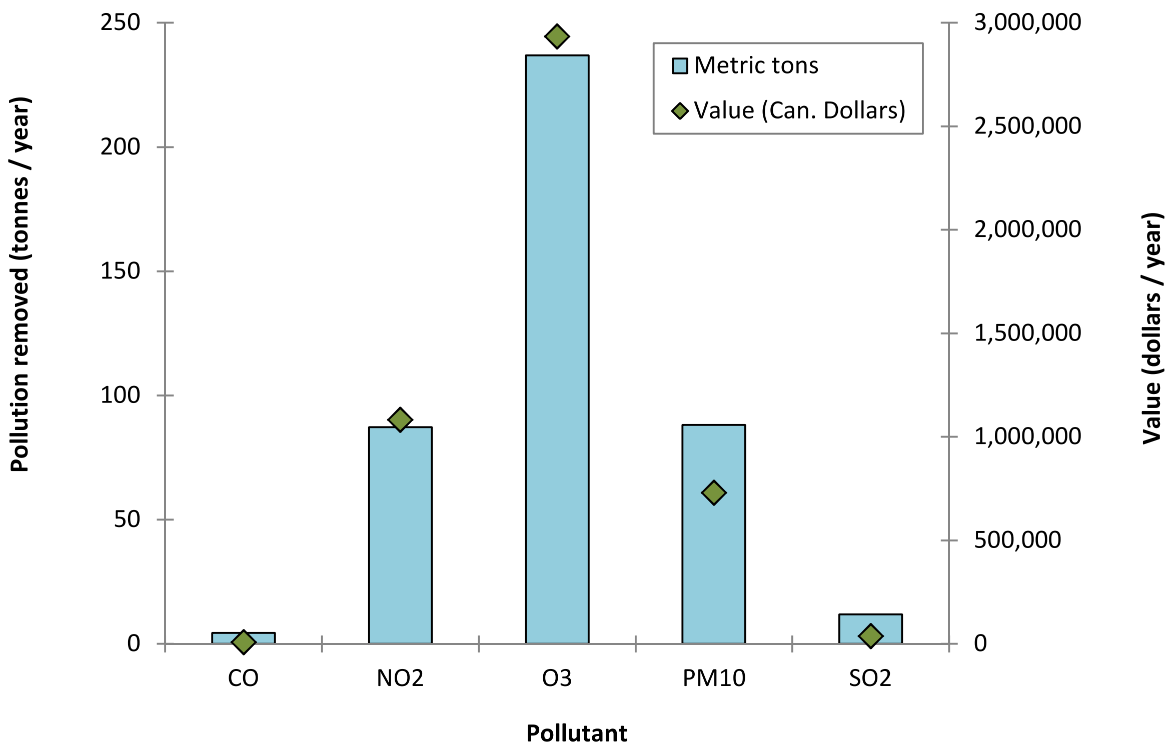

Figure 21: Annual pollution removal by trees and shrubs and associated removal value.

[8] Murray, F.J.; Marsh L.; Bradford, P.A. 1994. New York state energy plan, vol. II: issue reports. Albany, NY: New York State Energy Office. An externality is a side effect of an economic transaction whose damages or benefits are not taken into account in the price of the transaction. Water pollution from industries is an example of a negative externality. These values were updated to 2007 dollars based on the producer price index from U.S. Department of Labor, Bureau of Labor Statistics n.d. www.bls.gov/ppi. Values were adjusted to Canadian dollars with a conversion rate of 0.8 US dollars per Canadian dollar.

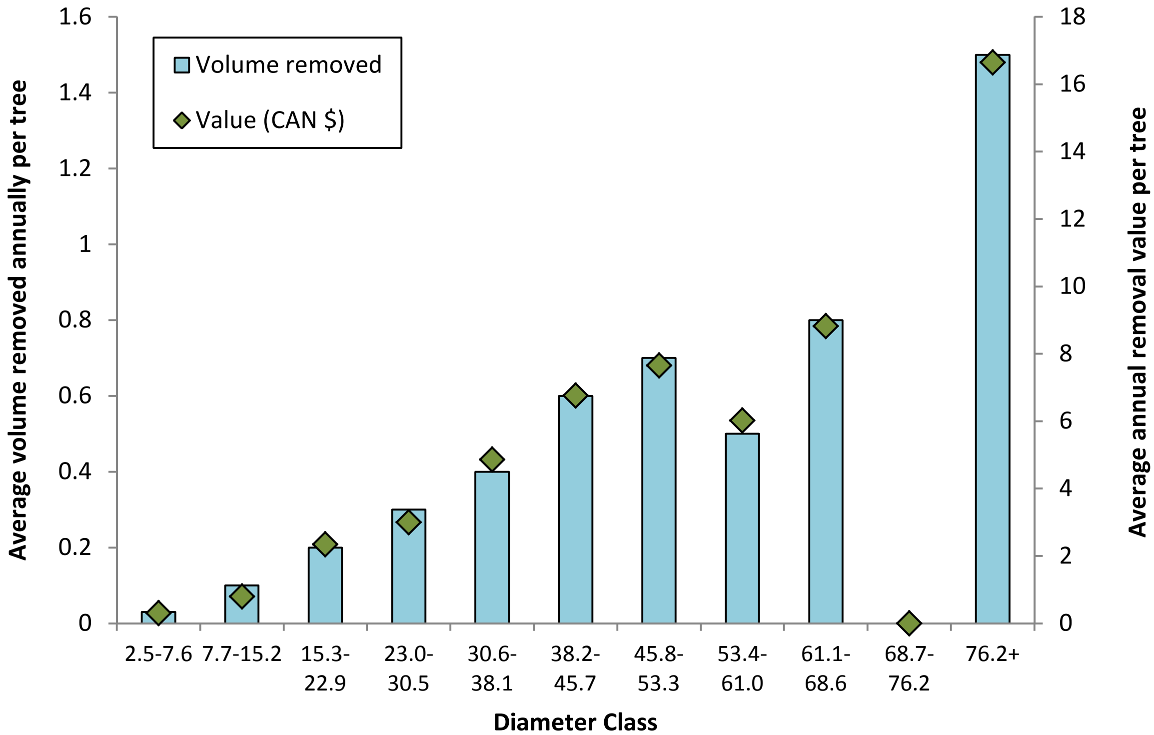

Figure 22: Average annual volume of pollution removed per tree and associated annual removal value summarized by diameter class.

4.5.3 Residential Energy Effects

The i-Tree Eco model estimated the effects of trees (≥ 6.1m in height and within 18.3m of a residential building) on building energy use as a result of shading, windbreak effects, and local micro-climate amelioration. Estimates of tree effects on energy use are based on field measurements of tree distance and direction to space-conditioned residential buildings. Annual energy savings are presented in Table 10. Annually, trees adjacent to residential buildings are estimated to reduce energy consumption by 79,200 million British thermal units (MBTU) for natural gas use (natural gas) and 7,300 megawatt-hours (MWH) for electricity use. Based on average energy costs in 2008-2009, trees in Mississauga are estimated to reduce energy costs from residential buildings by $1.2 million annually (Table 11).[9] Trees also provide an additional $61,800 per year by reducing the amount of carbon released by fossil-fuel based power plants (a reduction of 2,100 tonnes of carbon emissions or 7,700 tonnes of carbon dioxide).

[9] Based on 2009 electricity costs (6.7 cents/kWh) for Mississauga http://www.enersource.com/HM/ResidentialRateInfo.aspx, and 2008 MBTU costs from natural gas ($8.67 per MBTU) www.oeb.gov.on.ca/OEB. Most of Canada's non-electrical heating comes from natural gas www.nrcan.gc.ca/eneene/sources/pripri/reprap/2008-10-24/supsup-eng.php.

Table 10: nnual energy savings and carbon avoided due to trees near residential buildings.

Energy Units	Heating	Cooling	Total
MBTU†	79,200	n/a	79,200
MWH††	700	6,600	7,300
Carbon avoided (tonnes)	1,300	800	2,100

†Million British Thermal Units
††Megawatt-hour

Table 11: Annual savings in residential energy expenditures during heating and cooling seasons (based on 2008-2009 energy costs).

Energy Units	Heating	Cooling	Total
MBTU†	$ 687,000	n/a	$ 687,000
MWH††	$ 45,000	$ 443,000	$ 488,000
Carbon avoided (tonnes)	$ 37,600	$ 24,200	$ 61,800

†Million British Thermal Units
††Megawatt-hour

4.6 Effects on Urban Hydrology

The i-Tree Hydro model was used to simulate the effects of tree and impervious cover on stream flow in the Spring Creek subwatershed during April through November 2006 and 2008, and in the Fletcher's Creek subwatershed during May through November 2007 and 2008.

4.6.1 Spring Creek

Based on model estimates, the loss of existing tree cover (14 percent) in Spring Creek would increase total stream flow by approximately 1.2 percent. Increasing tree cover from 14 percent to 30 percent would reduce overall flow by 1.8 percent (149,000 m^3) during the 8 month period in 2008 and by 1.9 percent (128,000 m^3) in the 8 month period in 2006 (see Figure 26 for the 2008 simulation period).

In the Spring Creek subwatershed, interception of rainfall by tree canopies averaged between the two simulation periods was 12.2 percent of the total rainfall, but as only 14 percent of watershed in under tree cover, interception of total precipitation in the watershed by trees was only 1.7 percent. Areas of short vegetation, including shrubs, intercepted about 4.8 percent of the total rainfall, but as only 37 percent of watershed is under short vegetation, interception of total precipitation in the watershed by short vegetation was only 1.8 percent.

Increasing tree cover will reduce stream flow, but the dominant cover type influencing stream flow is impervious surface. In the Spring Creek subwatershed, the removal of existing impervious cover (48 percent) would reduce stream flow by approximately 50 percent across the two simulation periods. Increasing impervious cover from 48 percent to 60 percent of the watershed would increase total flow by 58 percent (see Figure 27 for the 2008 simulation period). Increasing impervious cover reduces base flow and pervious runoff while significantly increasing flow from impervious surfaces.

Overall, impervious cover had about a 20 fold impact on flow in the Spring Creek subwatershed, relative to tree cover. Increasing impervious cover by 1 percent averaged about a 2.5 percent increase in stream flow, while increasing tree cover by 1 percent averaged about a 0.13 percent decrease in stream flow.

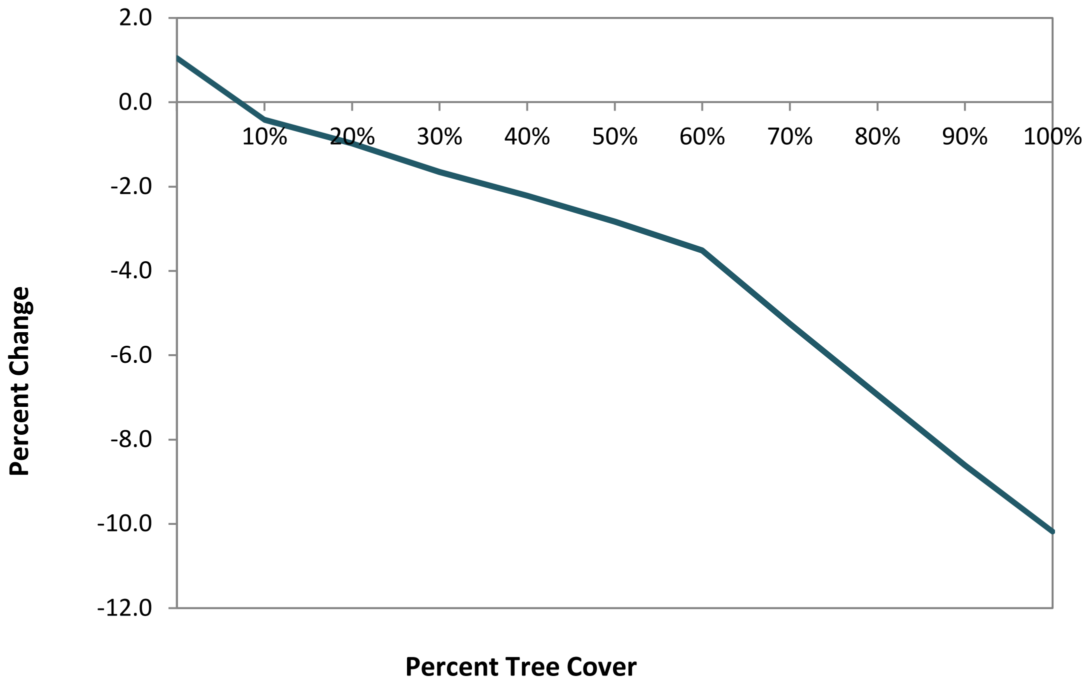

Figure 23: Projected percent change in total flow with changes in percent tree cover in the Spring Creek subwatershed (based on 2008 precipitation period).

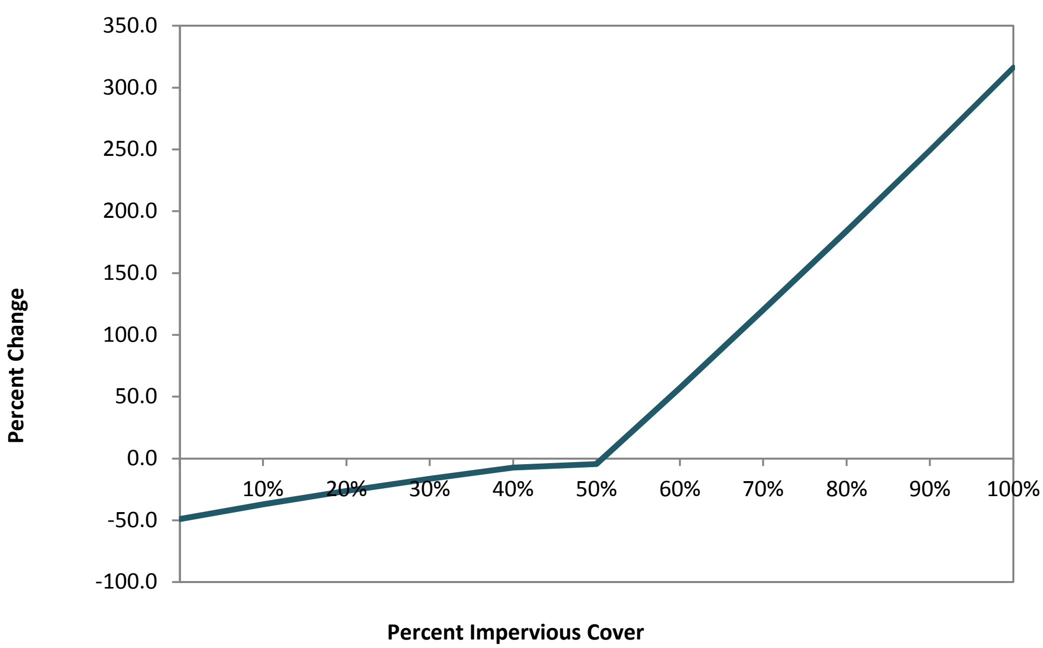

Figure 24: Projected percent change in total flow with changes in percent impervious cover in the Spring Creek subwatershed (based on the 2008 precipitation period).

4.6.2 Fletcher's Creek

In the Fletcher's Creek subwatershed a loss of existing tree cover (10.6 percent) would increase total flow by approximately 0.9 percent during the 2007 simulation period and by 1.1 percent. Increasing canopy cover from 10.6 percent to 20 percent would reduce overall flow by 1.0 percent (15,300 m^3) during the 2007 simulation period, and by 1.2 percent (49,100 m^3) during the 2008 simulation period.

Interception of rainfall by tree canopies averaged between the 2007 and 2008 simulation periods was 16.9 percent of the total rainfall. Interception of total precipitation in the subwatershed by trees was 1.8 percent. Areas of short vegetation, including shrubs, intercepted 5.9 percent of the total rainfall, which represents approximately 2.6 percent of the total precipitation in the subwatershed averaged between the two simulation periods.

During the 2007 simulation period, increasing impervious cover by 1% averaged a 3.4% increase in stream flow, while increasing tree cover by 1% averaged only a 0.19% decrease in stream flow. Increasing impervious cover by 1% averaged a 2.6% increase in stream flow during the 2008 simulation period, while increasing tree cover by 1% averaged only a 0.18% decrease in stream flow.

Increasing tree cover reduces base flow, as well as flow regenerated from both pervious and impervious areas. The relative effect of trees on flow (percent change in flow per percent change in tree cover) increases as percent impervious cover increases, while the relative effect of impervious surface on flows decreases as percent tree cover increases.

5.0 Discussion

5.1 State of the Urban Forest

5.1.1 Existing and Possible Urban Forest Distribution

The City of Mississauga's 2.1 million trees cover 15 percent of the total land area, providing 224 km^2 of total leaf area. By ownership type, homeowners and tenants (renters) control the largest percentage of the City's urban forest; more than half of the existing tree cover is located within the residential land use. The greatest opportunity to increase total leaf area and canopy cover is also found within the residential land use. The UTC analysis determined that 47 percent of the *residential low* category is currently available for the establishment of tree cover. This represents 18 percent of the land area in the City of Mississauga. The Priority Planting Index has identified areas within the City that currently support a high population density and a relatively low canopy cover (Figure 13). These *small geographic units* (SGUs) should be prioritized for targeted action in order to ensure that the residents of these neighborhoods can fully benefit from the services provided by the urban forest. The proportion of municipally owned land within these SGUs is low relative to the area of privately owned land, so the greatest potential for increasing the quantity of urban forest cover is found in residential yards. Therefore, available resources should be directed towards providing programs that educate residents on tree stewardship and offer incentives for tree planting and protection (please see Section 5.2.2). However, tree planting by the City is encouraged in the boulevards and municipal rights-of-way in these neighbourhoods.

Recommendation 1: Neighbourhoods identified by the Priority Planting Index should be targeted for strategic action that will increase tree cover and leaf area in these areas.

Tree planting and establishment should be prioritized for parcels within the City that maintain large contiguous impervious surfaces. The establishment of tree canopy on these parcels will reduce runoff during periods of peak overland flow and mitigate the heat island effect; please see Section 5.1.7 for a more complete discussion of urban heat island mitigation. Such parcels are common in the *commercial* and *industrial* land use categories, where tree cover and leaf area density are currently low. The UTC analysis indicates that opportunities to increase tree cover in the *industrial* land use are abundant; 64 percent of this land use has been classified as possible TC. Given that the volume of vehicle emissions is likely greater in these high traffic areas, increasing the leaf area in the *commercial* and *industrial* land uses will also be beneficial to meeting air quality objectives (specifically particulate matter). Parcel-based TC metrics have been generated as part of the UTC digital cover mapping exercise. Decision makers can use this GIS layer to identify specific TC metrics for a parcel or set of parcels that have a large relative area of impervious cover.

Recommendation 2: Use the parcel-based TC metrics together with the City's GIS database to identify and prioritize contiguous parcels that maintain a high proportion of impervious cover and a low percent canopy cover.

Planting and establishment activities need not be focused only in areas lacking tree cover. Rather, a successful strategy for increasing the ecosystem services provided by the urban forest should include an under-planting program, which will not only increase leaf area density in the short-term, but will also ensure that aging trees are gradually replaced by a younger generation. The City is proactively managing the threat of EAB by planting understory replacement trees for many of the ash trees located along roadways. Succession planning will be important in the older neighbourhoods south of the Queensway, where mature trees are abundant. In addition, increasing native shrub cover under canopied areas also represents an opportunity to increase total leaf area. Furthermore, shrub cover that is established around significant mature trees can discourage the trampling and compaction of root zones. Many of the benefits provided by the urban forest, such as microclimate amelioration and sequestration of gaseous pollutants, are directly related to leaf-atmospheric processes (e.g., interception, transpiration) (McPherson, 2003). It follows that an increase in the provision of these benefits can be best achieved by increasing total leaf area density. Management goals that incorporate a variety of targets, including tree size and species composition, will cultivate a more sustainable urban forest. A set of criteria and indicators that incorporate a variety of measures is therefore appropriate, and will be discussed in section 5.3.

Recommendation 3: Increase leaf area in canopied areas by planting suitable tree and shrub species under existing tree cover. Planting efforts should be focused in areas where mature and aging trees are over-represented, including the older residential neighbourhoods located south of the Queensway. Neighbourhoods in these areas that maintain a high proportion of ash species should be prioritized.

5.1.2 Tree Species Effects

Species composition in Mississauga was strongly influenced by the pattern of vegetation distribution between land uses. The dominant tree species in Mississauga was sugar maple (*Acer saccharum*), representing approximately 12 percent of the total leaf area. However, this species was not equally distributed between land uses. Rather, it was highly concentrated in the *open space + natural cover + agriculture* category (43 percent of the total leaf area). This land use supported the highest leaf area density but represented the smallest portion of municipal land area. Thus, the *open space + natural cover + agriculture* land use category exerted an influence on municipal species composition that was disproportionate to its size.

Sugar maple (*Acer saccharum*) is a very common native species in this ecoregion and is characteristically abundant under presettlement conditions. However, this species was found to be rare in the streetscapes and boulevards of the *residential* and *commercial + industrial* land uses as it requires high quality soil conditions and is intolerant to air pollution. In contrast Norway maple (*Acer platanoides,* 8 percent of the total leaf area) was abundant in such land uses as this species is tolerant of air pollution and harsh growing conditions. Among all species and genera, the genus ash (including *Fraxinus pennsylvanica, F. americana, F. nigra*) was the most evenly distributed across land use categories. This common native genus is known to thrive in a variety of natural areas in addition to performing well in high traffic zones where soil quality is low.

Another notable trend was the high proportion of conifer species in the *commercial + industrial* land use. Conifer species can be an effective component of air quality improvement strategies that focus on particulate matter reduction, which is assumed to be relatively high in this land use due to vehicle traffic and industrial emissions.

The genus maple and the genus ash represented nearly half of the total leaf area in Mississauga (31 percent and 16 percent, respectively). As previously noted a high relative abundance of maple and ash species is typical in the forests of this ecoregion; however, the lack of diversity among genera is a threat to the sustainability of the urban forest. Species diversity is a prerequisite of ecosystem resiliency. Dominance by a single tree species or genus will increase the possibility of large-scale tree mortality in the event of pest outbreaks that are species-specific (Sanders, 1978). Thus, an urban forest that is not sufficiently diverse is at risk of widespread canopy loss. In order to avoid such canopy loss, Santamour (1990) recommends that an urban forest contain no more than 10 percent of any single species, no more than 20 percent of any single genus, and no more than 30 percent of any single family. However, the “10-20-30” approach has been criticized for its inability to account for potential damage by multi-host pests, such as the Asian long-horned beetle (Raupp *et al.*, 2006), which was identified as a threat to 56 percent of the tree population in Mississauga. To address this concern, Lacan and McBride (2008) created the Pest Vulnerability Matrix (PVM), which provides a rapid analysis and graphic display of the interaction between urban tree species diversity and the susceptibility of the urban forest to insects and diseases. The model predicts how the introduction of certain tree species, or a new pest species, will affect the overall vulnerability of the urban forest. Consideration must be given to multi-host pests; thus, vulnerable species assemblages should also be accounted for when designing diversification programs.

Recommendation 4: Utilize the Pest Vulnerability Matrix during species selection for municipal tree and shrub planting.

The City of Mississauga is located in an ecoregion capable of supporting a high level of diversity (utilizing both Carolinian and Great Lakes St. Lawrence flora species), relative to other ecoregions in Canada. Furthermore, the frequency and severity of pest outbreaks is increasing, creating an ever greater need for diversity and resilience. Therefore, more aggressive diversity targets are feasible. In addition, by utilizing a diverse mix of species from both the Carolinian and Great Lakes St. Lawrence forest zones Mississauga’s urban forest will be more adaptable to both the predicted and unknown environmental changes caused by climate change. The City is advised to establish a species composition in which no species represents more than 5 percent of the tree population, no genus represents more than 10 percent of the tree population, and no family represents more than 20 percent of the total tree population. Diversity targets must also include a spatial scale in order to ensure that a sufficient amount of diversity is observed at the neighbourhood and land use level. Recognizing that site conditions and stock availability can constrain diversity target, this target is not likely feasible within the street tree population; few species can survive the harsh growing conditions found along high traffic boulevards and streetscapes.

Recommendation 5: Establish a diverse tree population in which no single species represents more than 5 percent of the tree population, no genus represents more than 10 percent of the tree population, and no family represents more than 20 percent of the intensively managed tree population both city-wide and the neighbourhood level.

A number of exotic invasive tree and shrub species were identified at the sample plots. Most notable were Norway maple (*Acer platanoides*), Manitoba maple (*Acer negundo*) and white mulberry (*Morus alba*) among the tree species, and buckthorn (*Rhamnus cathartica* and *R. frangula*) and exotic bush honeysuckle (*Lonicera japonica, L. maackii, L. morrowi, L. tartarica*) among the shrub species.

Norway maple (*Acer platanoides)*, the second most common species in Mississauga (8.3 percent of total leaf area), has been favored in the GTA for landscaping and streetscaping projects because it is tolerant of urban conditions and it produces a desirable form. However, the Ontario Invasive Plant Council (OIPC) has listed this prolific seed producer as invasive because it is known to spread into natural areas and threaten sensitive native vegetation. In Mississauga, 62 percent of all Norway maple stems were between 2.5 and 15.2 cm in dbh, indicating that this species is being sustained through both natural regeneration (12 percent of stems measured regenerated naturally) and active planting efforts.

In both tree and shrub form Manitoba maple (*Acer negundo)* represented approximately 6 percent of the total leaf area in Mississauga and was the fourth most common tree species. Manitoba maple is locally native to southwestern Ontario. However, this species has spread east and north by rapidly colonizing disturbed sites and floodplains well beyond its natural range. White mulberry (*Morus alba)* was common in the *residential* land use (2.2 of total leaf area in land use; 1.2 percent of total leaf area in Mississauga). This popular ornamental tree is known to hybridize with red mulberry (*Morus rubra*), an endangered species protected under the provincial and federal species at risk legislation. In southern Ontario, white mulberry frequently invades fields, forest edges and roadsides.

Exotic bush honeysuckles (*Lonicera japonica, L. maackii, L. morrowi, L. tartarica*) were the second most common shrub in Mississauga, representing 12 percent of the total shrub leaf area and 1.5 percent of the total leaf area (trees and shrubs). These species readily invade open woodlands, abandoned agricultural fields and other disturbed sites. Honeysuckle species spread rapidly via seed dispersal by birds and mammals and can form a dense, understory thicket that restricts native plant growth and tree seedling establishment. Exotic bush honeysuckles were introduced from eastern Asia and have been planted as ornamental shrubs across North America. In addition, buckthorn species (*Rhamnus cathartica* and *R. frangula*) were identified as a common shrub in Mississauga (2.3 percent of total leaf area). Buckthorn species invade forests, thickets, meadows and savannas. Once established, buckthorn species are very difficult to control.

Future planting of all of the aforementioned species must be avoided, particularly at sites adjacent to natural areas. Control measures vary between species but generally require a long-term commitment to rigorous site management and the application of bio-controls where appropriate. TRCA and CVC are actively involved in invasive species control measures at multiple sites across the GTA. Municipal strategies for the management and restoration of infested areas need to be developed and should be done so in partnership with the appropriate conservation authority.

Recommendation 6: In collaboration with the Toronto Region Conservation Authority and Credit Valley Conservation, develop and implement an invasive species management strategy that will comprehensively address existing infestations as well as future threats posed by invasive insect pests, diseases and exotic plants.

Private property owners in Mississauga, particularly residential homeowners and tenants, can play an important role in preventing the spread of invasive species. Horticultural species that escape from residential gardens are a common cause of infestations in natural areas. By purchasing and planting only native or non-invasive exotic plant species in yards and gardens the incidence of future infestations may be greatly reduced. In addition the horticultural industry can play a significant role by phasing out the sale of highly invasive species, such as Norway maple and winged euonymus (*Euonymus alatus*), and offering as replacements similar native plants, such as red maple (*Acer rubrum*) and burning-bush euonymus (*Euonymus atropurpureus*).[10] The *Neighbours of Mississauga's Natural Areas* Information Booklet provides useful information to municipal residents. However, additional targeted outreach for residents surrounding the natural system must be provided by the municipality via stewardship and education programs.

The use of high quality native planting stock grown from locally adapted seed sources is strongly encouraged in all municipal planting projects, particularly in locations adjacent to natural areas. Planting stock availability will be directly dependent on the supply levels of local nurseries. In anticipation of an increasing demand for suitable native stock the City should work with local growers to ensure that this demand can be met.

Recommendation 7: Utilize native planting stock grown from locally adapted seed sources in both intensively and extensively managed areas.

TRCA's Terrestrial Natural Heritage System Strategy (TNHSS) provides a ranking system for all flora and fauna species in TRCA's jurisdiction. This ranking system assigns a conservation priority to each species based on a number of criteria, including: local occurrence; population trend; habitat dependence; and sensitivity to development. This approach represents a departure from traditional species ranking systems in that it identifies and protects species and communities long before they become rare. This proactive approach has proven to be more effective in securing stable populations at both the site and landscape scale. Recognizing that individual flora and fauna species can be viewed as indicators of ecosystem function, this approach enables TRCA and partner municipalities to set regional targets for species populations and natural cover that will sustain the required level of ecological function across

[10] The Ontario Invasive Plant Council (OIPC), TRCA, CVC are coordinating a Horticultural Outreach Program with the following objectives: to work with the nursery and landscape industry to phase-out the sale of highly invasive horticultural plants and phase-in the provision of non-invasive alternatives, including native species; and to promote the sale, use and production of native plant species within the horticultural and landscape industry.

the jurisdiction in the long-term. Table 12 presents the species of regional concern as ranked by the TNHSS, with highest priority given to L1 species, followed by L2 and L3. The regeneration rates of such species found in the urban forest should be monitored closely and active restoration of associated habitats is strongly encouraged (e.g. regular prescribed burns in remaining oak savannah).

Table 12: Species of Regional Concern in the City of Mississauga, as classified by TRCA's Terrestrial Natural Heritage System Strategy.

Common Name	Scientific Name	Percent of Population	L - Rank
Sycamore	*Platanus occidentalis*	0.2	L1
White oak	*Quercus alba*	1.4	L2
Black oak	*Quercus velutina*	0.5	L2
Red pine	*Pinus resinosa*	1.8	L2
Native hawthorn	*Crategeous spp.*	0.7	L2 and L3
White spruce	*Picea glauca*	2.6	L3
Canada plum	*Prunus nigra*	0.5	L3
Tamarack	*Larix laricina*	0.9	L3

5.1.3 Tree Size Effects

The proportion of large trees in Mississauga is low, suggesting that the majority of trees are not surviving to full maturity (if tree size is used as a proxy for age). Less than 7 percent of all trees are greater than 38 cm in diameter.

Recognizing that tree size will naturally vary by species, it is important to understand the physiological requirements of different species in order to ensure that each newly planted tree reaches its full size potential. For example, foreseeing potential conflicts with power lines, sidewalks, and underground utilities during the planting stage will reduce premature mortality. To achieve a desirable age-class structure trees cannot be an after-thought in the municipal planning process, during which tree habitat needs are often relegated to a lower priority than grey infrastructure considerations.[11] Rather, it is necessary to take a progressive approach to urban design by providing adequate tree habitat in the initial stages of urban planning. For example, streetscapes must be designed in a manner that incorporates sufficient soil volume for healthy root development, which will in turn facilitate the growth of large, long-lived street trees. New residential developments must also meet minimum soil volume and quality standards that will enable newly planted trees to thrive and reach their genetic potential. Construction practices often leave soils compacted and degraded. Consequently, the mortality rate of new plantings in many new neighborhoods is unnecessarily high, which results in a low proportion of large trees indefinitely. Please see Section 5.2.4 for a further discussion of soil volume standards.

As urban trees increase in size, their environmental, social and economic benefits increase as well. Large trees provide much greater energy savings, air and water quality improvements, runoff reduction, visual impact, increase in property values, and carbon sequestration. While the tree population should maintain a substantial number of new plantings to offset reasonable establishment-related mortality,

[11] "Tree habitat" refers to the growing environment from which trees must derive all the essentials for their survival and growth (Urban Forest Innovations, Inc. and Kenney, 2008). Habitat includes the physical growing space in which a tree exists and includes the associated grey infrastructure, soil and all its constituents, air, climate, etc.

large trees should also represent a significant portion of the total population as they provide the highest benefit-cost ratio.

In Mississauga, an individual tree in diameter class 61-6-68.6cm removed approximately 8 times more pollution than a tree in diameter class 7.7-15.2cm, and 27 times more pollution than a tree in diameter class 2.5-7.6cm. Carbon storage capacity per tree increased with dbh, with an individual tree in the diameter class 61.6–68.6 cm storing 65 times the amount stored by a tree in diameter class 7.7–15.2cm. A similar trend was observed for per tree carbon sequestration. This trend is noteworthy in light of the existing diameter class distribution (Figure 18). Should the proportion of large trees in Mississauga's urban forest be increased, the total volume of carbon stored and sequestered would be expected to increase as well.

Large trees also provide greater infrastructure repair savings. Research conducted in Modesto, California, found that the shade from large-stature trees over city streets was projected to reduce costs for repaving by 58% (financial savings of $7.13/m^2) over the 30-year period when compared to unshaded streets (McPherson and Muchnick, 2005). In comparison, shade from small-stature trees was projected to save only 17% in repaving costs (financial savings of $2.04/ m^2).

Due to the highly modified and intensively managed nature of the urban forest resource, there is no appropriate historic / presettlement age-class distribution for which to strive. In other words, an urban forest in southern Ontario will necessarily maintain a very different diameter or age-class distribution than that observed in a rural woodland. Furthermore, defining an optimal age-class distribution in an urban forest is challenging given the variation in natural regeneration between land uses. Typically, rural mid-successional forests maintain a steep inverse j-shaped curve that reflects the abundance of small trees in the understorey as a result of natural regeneration[12]. This pattern was observed in the diameter class distribution in the natural cover / open space land use. However, with the exception of native remnants in protected areas and woodlots, natural regeneration occurs infrequently in the urban forest. Consequently, active management is needed in order to facilitate regeneration and renewal. In areas of the city where mature trees are dominant, managers should plan for future succession by planting replacement trees in advance of mature tree senescence.

A study conducted by Richards (1983) proposed the primary age diversity model, which suggests a diameter class distribution designed to ensure continuous canopy cover over time. The City of Davis, California, modified this model slightly to produce the following guidelines: 40 percent of municipal trees less than 15.2 cm dbh, 30 percent between 15.3 and 30.5 cm, 20 percent between 30.6 and 61cm, and 10 percent greater than 61 cm. The results of the i-Tree Eco analysis reveal the following diameter class distribution in Mississauga: 63 percent of municipal trees were less than 15.2 cm dbh, 24 percent were between 15.3 and 30.5 cm, 12 percent were between 30.6 and 61 cm, and less than 2 percent were greater than 61 cm. According to these guidelines the proportion of small trees was significantly higher than recommended and the proportion of large trees was significantly lower than recommended (Figure 28).

[12] The 'inverse j-shaped curve', or 'normal distribution', is commonly associated with natural multi-age forest stands with relatively constant recruitment and mortality rates. These populations are believed to persist indefinitely in the absence of exogenous disturbance (Oliver and Larson, 1996).

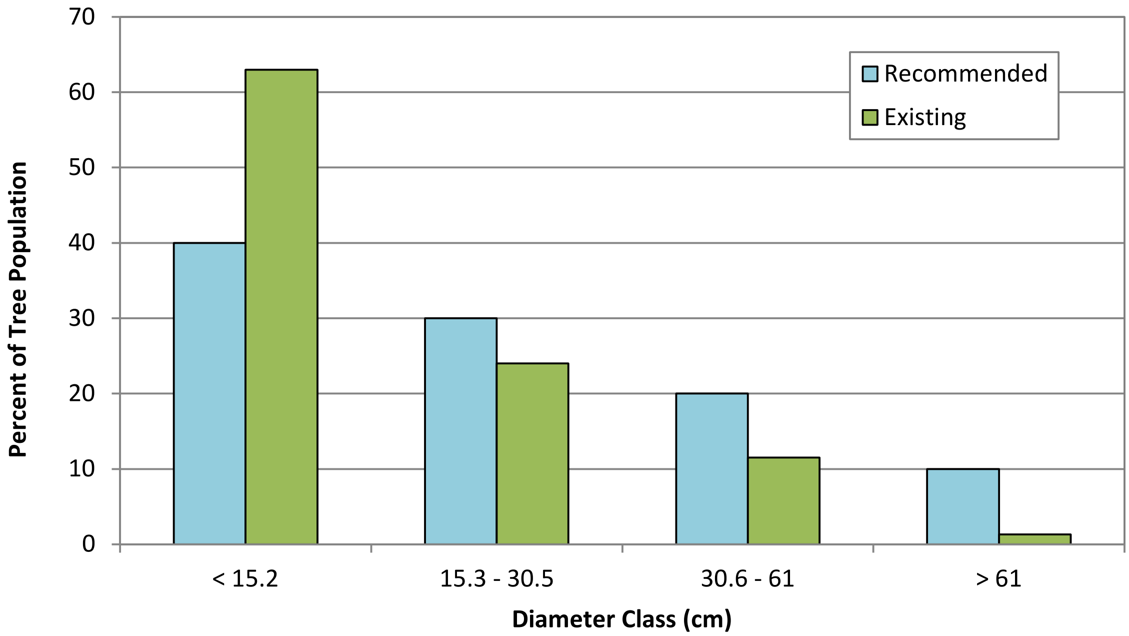

Figure 25: Guidelines for recommended diameter class distribution and actual diameter class distribution in the City of Mississauga.

Recommendation 8: Evaluate and develop the strategic steps necessary to increase the proportion of large, mature trees in the urban forest. Focus must be placed on long-term tree maintenance and by-law enforcement to ensure that healthy specimens can reach their genetic growth potential. The value of the services provided by mature trees must be effectively communicated to all residents.

When dbh is used as a proxy for age-class, species-related variations in tree size are not captured. For example, a large eastern cottonwood (*Populus deltoides)* will have a significantly larger dbh than an apple species (*Malus spp.)* of the same age. In contrast, *relative* dbh will reflect differences in size attributed to species.[13] Relative dbh can therefore be useful measure when setting age-class distribution targets. Kenney *et al.* (2011) state that an optimal age-class structure is achieved when the tree population is divided equally into the following four *relative* dbh classes: 0-25 percent; 26-50 percent; 51-75 percent; and 76-100 percent. In other words, 25 percent of the population will fall into the 0-25 percent relative dbh class, 25 percent will fall into the 26-50 percent, etc. In addition, an uneven age-class distribution must be sought at the municipal and neighbourhood / street segment scale. This distribution will positively impact management budgets, as an uneven-aged forest structure will allow managers to allocate annual maintenance costs uniformly over many years and will support long-term continuity in overall canopy cover. Exceptions to this proposed distribution should be made for woodlots, woodlands, and other natural areas under-going active restoration efforts (including invasive species control efforts).

Recommendation 9: Determine the relative dbh of the tree population in Mississauga; consider utilizing relative dbh as an indicator of urban forest health.

[13] Relative dbh is the ratio (percent) between a tree diameter and the maximum diameter for that species. The relative dbh can be used to compare the distribution of different species or to compare species that have different growth characteristics. A relative dbh near 100% indicates a mature tree.

5.1.4 Effect on Air Quality

Nitrogen dioxide removal by trees in Mississauga is equivalent to:

- Annual nitrogen dioxide emissions from 6,100automobiles or
- Annual nitrogen dioxide emissions from 4,000 single family houses

Sulfur dioxide removal by trees in Mississauga is equivalent to:

- Annual sulfur dioxide emissions from 19,100 automobiles or
- Annual sulfur dioxide emissions from 300 single family houses

Particulate matter less than 10 microns (PM_{10}) removal by trees in Mississauga is equivalent to:

- Annual PM_{10} emissions from 259,000 automobiles or
- Annual PM_{10} emissions from 25,000 single family houses

The negative health effects of acute exposure to common urban air pollutants have been well documented. Health effects examined include reduced lung function, acute bronchitis, asthma attacks, emergency room visits and hospitalizations for respiratory and cardiovascular conditions, and elevated rates of mortality (e.g. Burnett, 1999; Steib, 2002; Brook, 2002).

Trees and shrubs in Mississauga removed 429 tonnes of air pollution (CO, NO_2, O_3, PM_{10}, SO_2) annually, with an associated value of $4.8 million.[14] Pollution removal was greatest for ozone, accounting for 55 percent of total pollution removed. Ozone has been identified as the primary component of photochemical smog and is known to irritate and damage the respiratory system, reduce lung function, and increase susceptibility to respiratory infections (EPA, 2003). A recent study by Pollution Probe suggests that climate change could further exacerbate the degree of health effects associated with air pollution (Chiotti *et al*., 2002). For example, the occurrence of oppressive air masses which bring hot, humid and smoggy conditions, are projected to increase from the current level of 5 per cent of summer days to 23-39 per cent by 2080. This means that the Greater Golden Horseshoe Region will likely experience more frequent, more severe and possibly longer smog episodes in the future. Thus, by mitigating the human health risks associated with air pollution, in addition to mitigating both the causes and effects of climate change, Mississauga's urban forest plays an important role in community wellness, particularly for those more vulnerable members of the population.

The results revealed that large diameter trees removed greater volumes of pollution on a per tree basis than small diameter trees. Trees were found to remove greater volumes of pollution than shrubs. In both instances, pollution removal capacity was a direct function of leaf area. Thus, the pollution removal capacity of the urban forest can be maximized by increasing the extent of canopy cover as well as the volume of leaf area *within* canopied areas. Nowak *et al.* (2002) suggest that in areas with high levels of ground-based emissions (e.g., highways), tree / shrub cover located adjacent to the highway, with minimal overhead canopy, will allow pollutants to disperse upwards while increasing removal immediately adjacent to the sources. Planting species that require little maintenance, that are well adapted to local conditions, and that have long life spans will decrease emissions of air pollutants from maintenance and removal activities required for these species. In addition, managing for enhanced health and longevity of existing trees and shrubs through effective maintenance and stewardship will increase the urban forest's capacity to improve air quality.

Trees and shrubs emit biogenic volatile organic compounds (VOCs), including isoprene and monoterpenes. These compounds are natural chemicals that make up essential oils, resins, and other plant products; these compounds are believed to be useful in attracting pollinators or repelling

[14] The results of the analysis likely underestimated the total effect of the urban forest on the reduction of ground-level pollutants, as the effect of the forest canopy in preventing concentrations of upper air pollution from reaching ground-level air space was not accounted for (Nowak *et al.* 2002).

predators (Kramer and Kozlowski, 1979). VOCs emissions by trees can contribute to the formation of ground level ozone and carbon monoxide. However, this process is temperature dependent. Given that trees generally lower air temperature, the net result is often still positive with respect to the impact of trees on air quality.

5.1.5 Climate Change Mitigation

Trees can 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. In Mississauga, trees store approximately 203,000 tonnes of carbon (value of $5.8 million), and sequester approximately 10,000 tonnes of carbon annually (value of $285,000 annually).[15] The amount of carbon stored per hectare in Mississauga is lower than in most other Cities with comparable data (Table 13). This is likely due to the lower tree density, but may also be influenced by relative tree size and condition. Please see Appendix E for a complete list of comparisons.

Table 13: Tree density, carbon storage and annual carbon sequestration by urban forests in Canadian cities that have completed an i-Tree Eco analysis.

City	Tree Density (trees/ha)	Carbon Storage (tonnes/ha)	Carbon Sequestration (tonnes/ha/yr)
Calgary, AB	164.8	5.6	0.3
Brampton, ON	134.3	6.5	0.3
Mississauga, ON	73.1	7.0	0.3
Oakville, ON	192.9	13.4	0.6
London, ON	185.5	15.3	0.5
Toronto, ON	160.4	17.4	0.7

Structural factors that lead to increased carbon storage and gross sequestration per hectare include increased tree density and an increased proportion of large trees. Healthy trees with minimal dieback or decay also have higher gross sequestration rates than trees in poorer condition. Net carbon storage increases when forest growth (carbon accumulation) is greater than decomposition. Therefore, to further reduce CO_2 concentrations the following steps should be taken: sustain existing tree cover to avoid loss of carbon currently stored; increase the proportion of large trees to enhance per tree carbon storage and sequestration; increase tree cover and density to facilitate additional carbon storage; and replace dead and dying trees with young, healthy trees to increase sequestration capacity[16]. Furthermore, long-term carbon storage from forests can be increased when wood is used in long-term products (lumber) or where it is prevented from decaying, e.g., landfills (Nowak, 2000).

Nowak and Crane (2002) argue that carbon released through tree management activities must be accounted for when calculating the net effect of urban forestry on atmospheric carbon dioxide. Tree care practices often release carbon back into the atmosphere as a result of fossil fuel emissions from

[15] When estimated mortality rates and tree removal were considered, net annual carbon sequestration was approximately 7,400 tonnes annually.
[16] An exception should be made in natural areas/woodlots where substantial amounts of down-woody debris should be retained on site.

maintenance equipment. For example, vehicles and equipment such as chainsaws, backhoes, leaf blowers, chippers, and shredders emit CO_2 (approximately 0.7 kg/l of gasoline) (Graham *et al.*, 1992) as well as VOC, CO, nitrogen and sulfur oxides, and particulate matter (EPA, 1991). In order to compensate for the base carbon emissions associated with planting, establishment, pruning, and tree removal, trees planted in the urban landscape must live for a minimum amount of time.[17] If trees succumb to early mortality, sustaining the tree population will lead to net emissions of carbon throughout the life cycle of that population (Nowak and Crane, 2002). It follows that the greater the 'last positive point' (LPP)[18], the more beneficial a species and / or management activity is for reducing atmospheric carbon. Accordingly, tree life span was found to have the greatest positive effect on carbon LPP. However, given the same life span and growth, larger trees at maturity will sequester more carbon than smaller trees and will thus have higher LPPs. This observation further highlights the importance of selecting low maintenance, well-adapted native species with the goal of maximizing tree health and longevity. A reduction in the use of fossil fuel for urban forest maintenance will also have a positive impact on local CO_2 levels.

Recommendation 10: Conduct an assessment of municipal urban forest maintenance activities (e.g. pruning, tree planting) to determine areas where a reduction in fossil fuel use can be achieved.

The urban forest can also affect CO_2 levels by reducing the demand for heating and cooling in residential building, subsequently avoiding carbon emissions by power plants. In Mississauga the annual demand for heating and cooling was reduced by approximately 79,200 MBTUS and 7,300 MWH, with an associated annual financial savings of approximately $1,175,000. As a result of this reduced demand for heating and cooling the production of over 2,100 tonnes of carbon emissions were avoided annually (associated annual savings of $61,800).

However, a considerable opportunity exists to increase these savings through public education and outreach. For example, shading by trees during winter months can actually increase residential demand for heating. In Mississauga, this increase was partially off-set by the reduction in heating demand as a result of wind speed reductions and evapotranspiration. Yet the results highlight the importance of proper species selection and placement. Conifer species planted along the south facing wall of a building will block the heat transfer from the winter sun and will increase the need for daytime heating. In contrast, a large deciduous tree will shade buildings during hot summer months and will allow heat transfer in the winter. Public education can play a very influential role by providing direction for strategic planting around buildings to enhance energy savings. Maximizing energy savings will not only yield financial savings but will assist in efforts to mitigate climate change.

Carbon storage by trees in Mississauga is equivalent to:

- The amount of carbon emitted in the City in 20 days ;
- Annual carbon emissions from 134,000 automobiles or; or
- Annual carbon emissions from 67,400 single family houses.

Annual carbon sequestration by trees in Mississauga is equivalent to:

- Amount of carbon emitted in the City in 1 day;
- Annual carbon emissions from 6,600 automobiles; or
- Annual carbon emissions from 3,300 single family homes.

[17] According to Nowak and Crane (2002) the minimum necessary life span for a red maple (*Acer rubrum*) with conservative maintenance and mulching decomposition scenarios was between 5 and 10 years.
[18] LPP is defined as the point at which total carbon emission becomes greater than total carbon sequestered, or the last positive net carbon value (Nowak and Crane 2002).

Recommendation 11: Reduce energy consumption and associated carbon emissions by providing direction and assistance to residents and businesses for strategic tree planting and establishment around buildings.

5.1.6 Heat Island Mitigation

The urban heat island (UHI) effect occurs in urban and suburban areas where surface temperatures are significantly warmer than nearby rural areas. As cities replace natural land cover with pavement, buildings, and other infrastructure urban surface temperatures increase. Higher surface temperature can then lead to higher air temperatures, although the two variables are not directly correlated. Typically the spatial distribution of UHI intensity shows maximum differences at the urban centre with a large temperature gradient at the urban-rural edge (NRCan, 2009).

Research has shown that by increasing the amount of urban vegetation the effects of UHI can be mitigated (Rosenzweig *et. al.*, 2006; Solecki *et. al*., 2005). Specifically, the shade generated by tree canopies will reduce the amount of solar radiation transmitted to underlying surfaces. Consequently, increased canopy cover lessens the heat island effect by reducing heat transfer from these surfaces to the surrounding air. Furthermore, evapotranspiration by urban vegetation can result in peak summer temperature reductions of 1 - 5°C in urban areas (EPA, 2007). According to Simpson (1998), every 1 percent increase in canopy cover results in a maximum mid-day air temperature reduction of 0.04 to 0.2°C.

Natural Resources Canada has recently evaluated the potential to characterize and map UHI in the GTA using remote sensing data (NRCan, 2009). The research utilized both satellite imagery and in-situ air and surface temperature measurements. Although the study was not designed to directly evaluate the influence of urban trees and shrubs on UHI, the results are relevant to urban forest management. At a GTA-wide scale, suburban cover was found to have distinctly higher thermal admittance properties. Consequently, the suburban areas of Mississauga and Brampton recorded the highest surface cover temperatures and highest night time UHI intensities, significantly higher than the measurements recorded in the dense downtown core of the City of Toronto (Figure 29). Many of the areas with the highest recorded surface temperature in Mississauga directly correspond with the areas receiving the highest scores in the Priority Planting Index (Section 4.2). The lowest surface temperatures were recorded in the vegetated corridors of the Don and Humber river valleys. A direct relationship was also observed between urbanization and substantial increases in surface temperatures in extreme heat event conditions. It follows that high surface temperatures in Mississauga are more likely to produce high air temperatures, which can have a direct impact on human and wildlife mortality and morbidity.

Recommendation 12: Focus tree planting and establishment in "hot-spots" identified by thermal mapping analysis.

Effective heat island mitigation strategies will incorporate both sustainable "green" technology (e.g. green roofs) and natural infrastructure (e.g. urban forest) in order to successfully reduce impervious cover and increase urban vegetation.[19] Planting and establishing trees in the hot-spots identified by the thermal mapping exercise will likely reduce surface temperatures, thereby reducing the formation of

[19] Please visit the Sustainable Technologies Evaluation Program (STEP) for information on the local application of a variety of sustainable technologies: http://www.sustainabletechnologies.ca/.

VOCs and O_3, which will in turn have direct public health benefits. Furthermore, planting trees over impervious surface such as cement and asphalt has been found to increase the life span of these materials and reduce infrastructure maintenance costs.

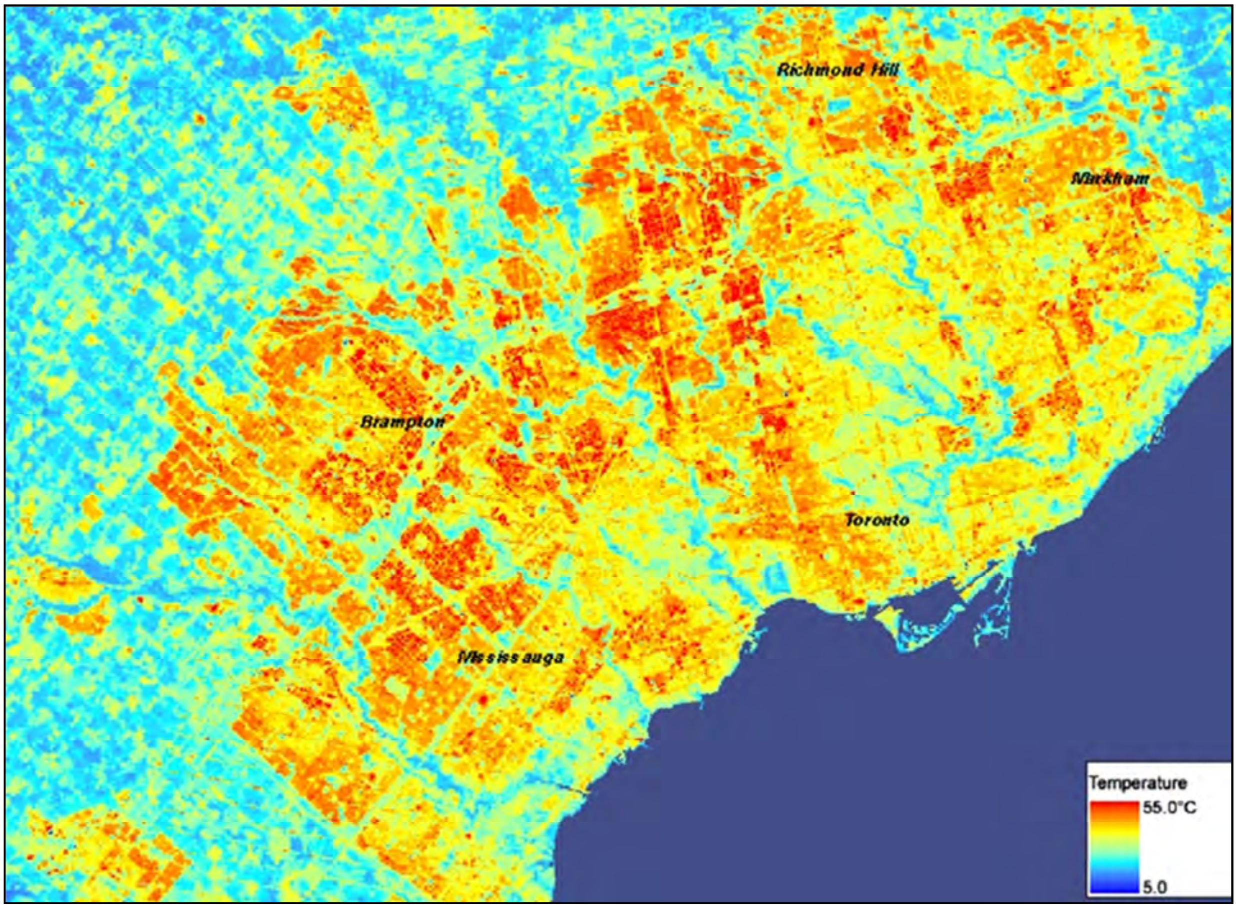

Figure 26: Land surface temperature map of the Greater Toronto Area in July, 2008. Image courtesy of Natural Resources Canada (2009).

5.2 Creating a Sustainable Urban Forest

5.2.1 Tree Preservation and Protection

While tree planting initiatives are an important component of sustainable urban forestry, the protection and stewardship of existing trees is the most effective means of achieving future targets, including canopy cover, leaf area density, and age-class distribution. For example, the Grow Out scenarios presented in Section 4.4 highlight the influence that annual mortality rates can have on future canopy cover. Specifically, by reducing the average annual mortality rate to 1 percent, the Grow Out model estimates that the total canopy cover will theoretically increase from 16 to 25 percent in 50 years, with no new trees planted annually during that time period. Trees that grow to reach a large mature size provide the highest benefit-cost ratio with respect to leaf area and associated functional benefits. The most critical time for tree care, including water and mulching, is in the first few years following planting. In absence of this care and maintenance tree mortality will be high during the early stages of tree establishment and few trees will survive to reach their full size potential. To address this problem in street trees the Urban Forestry Unit has implemented a rejuvenation program for young trees that are no longer under warranty. However, this addresses only a small portion of the urban forest. Furthermore, in order to develop a more sustainable age-class distribution in which a greater proportion of large trees are present on the landscape, tree care and stewardship must continue for the entire lifetime of a tree. Given that the large majority of the urban forest is located on private lands, this task of long-term tree care falls to private land owners.

The City of Mississauga has available two complimentary avenues for ensuring retention and long-term health of trees on private property: strong legislation that is diligently enforced; and targeted outreach and education programs that foster an effective stewardship ethic. The former will be discussed here. The City of Mississauga's Tree Permit By-law (By-law 474-05) regulates the removal of trees on private property. The By-law states that property owners require a permit to remove 5 or more trees that are 15 cm in diameter or larger from their private property in a calendar year. Thus, the removal of up to 4 trees of any size is allowed without a permit. While this By-law represents a significant step forward in the protection of urban trees and the services they provide, there is still much room for improvement. If strengthened to include the protection of *all* trees that are 20 cm in diameter or greater, the By-law would more successfully ensure that the entire community will continue to benefit from the ecosystem services provided by the urban forest. Within the GTA both the Town of Markham and the Town of Richmond Hill have adopted by-laws that require a permit for the removal of any tree that is 20 cm in diameter or greater; these examples should be followed by the City of Mississauga. Furthermore, where the planting of a replacement tree(s) has been stipulated as a condition of tree removal the replacement must be made such that there is no net loss in leaf area, and no significant loss in associated ecosystem services.

The Tree Permit By-law was created by the municipality in recognition of the fact that "trees provide a wide variety of benefits to the community and enrich our lives" and therefore these benefits should be legally protected (City of Mississauga, 2010). Ultimately the protection of trees equates to the protection of ecosystem services that are essential to the health of humans and wildlife (e.g. clean air, cooler summer temperatures, etc.). Thus, the protection of these essential services becomes a matter of social justice. The services provided by the urban forest are an asset that belong to the entire community, and must be managed in a manner that ensures the equal and unrestricted access by all residents.

Recommendation 13: Review and enhance the Tree Permit By-law 474-05 to include the protection all trees that are 20 cm or greater in diameter at breast height.

Recommendation 14: Develop a comprehensive Public Tree By-law that provides protection to all trees on publically owned and managed lands.

Protection of root zones during construction activities can partially safeguard trees against damage and subsequent decline caused by soil compaction, root cutting and stem injury. Typically a tree protection barrier includes as a minimum the area within the drip line of the tree. However, protection to the drip line is rarely sufficient for large mature trees as tree roots commonly extend 2 to 3 times the distance of the drip line. Detailed guidelines for tree protection zones and barriers have been created by the City of

Toronto.[20] The City of Mississauga is strongly encouraged to expand on its existing guidelines to produce a more detailed and enforceable set of standards for all publically and privately owned trees.

Recommendation 15: Develop a Tree Protection Policy that outlines enforceable guidelines for tree protection zones and other protection measures to be undertaken for all publically and privately owned trees.

The enforcement of the Tree Permit By-law, and the proposed Public Tree By-law and Tree Protection Policy will determine the success of these measures. The City of Mississauga must therefore allocate sufficient funding to the Tree Preservation and Protection Section of the Urban Forestry Unit for the resources needed to successfully enforce the By-laws and polices.

Recommendation 16: Allocate additional funding to the Urban Forestry Unit for the resources necessary to ensure full public compliance with Urban Forestry By-laws and policies.

5.2.2 Stewardship and Education

The residents of Mississauga are the most influential stewards of the urban forest, and as such, their cooperation is essential to achieving all future urban forest targets. The UTC analysis determined that the largest proportion of both existing and potential tree cover was found within the residential land use. Recognizing that 1) the lack of tree care is a significant threat to tree health, and 2) municipal resources are finite, it is clear that the public must share the responsibility for tree care and preservation. While by-laws designed to prevent the damage and destruction of trees can serve as a critical safety net, it is ultimately a strong collective stewardship ethic that will ensure the growth and long-term health of the urban forest on both public and private property. For example, tenants and property owners can reduce the mortality of public trees planted in residential boulevards and along commercial right-of-ways by providing regular care and maintenance, such as watering and mulching. However, communicating the need for collective action and community stewardship is not simply a matter of delivering print materials as part of an information campaign. While such tools can be effective in creating public awareness they are limited in their ability to foster long-term behaviour change (Aronson *et al*., 1990; Costanzo *et al*. 1986).

Community-based social marketing (CBSM) emphasizes that effective program design must begin with an understanding of the barriers people perceive to engaging in an activity. According to McKenzie-Mohr and Smith (1999) CBSM is composed of four steps: uncovering barriers to behaviours and then, based on this information, selecting which behavior to promote; designing a program to overcome the barriers to the selected behaviour; piloting the program; and evaluating the program once it is broadly implemented. CBSM offers a means to increase the uptake and success of outreach activities and should therefore be incorporated into future stewardship programs.

Trees and vegetation in the private domain are managed by a socially diverse group of stakeholders including homeowners, community associations, utility companies, and businesses. It follows that the vertical complexity, species composition, health, and distribution patterns of the urban forest will reflect the variation in ownership patterns, professional training, aesthetic sensibilities and choices, perceived value of the vegetation, funding levels, and education of these diverse managers (Carreiro and Zipperer,

[20] Guidelines can be found on the City of Toronto website: http://www.toronto.ca/trees/pdfs/TreeProtSpecs.pdf

2008). Preferences for urban forest structure will naturally differ among user groups; these preferences will likely have a strong cultural dimension. Mississauga's social and cultural diversity must therefore be considered in the design and implementation of outreach programs. As an example, TRCA's Multicultural Environmental Stewardship Program engages new Canadians in environmental initiatives and stewardship projects by reducing language, cultural and economic barriers, traditionally limiting new Canadian participation.[21]

It is important to note that accessibility to the benefits associated with urban trees does not tend to be equally distributed among urban residents (Heynen, 2003). In Milwaukee, Wisconsin, homeowners and renters were targeted equally for an urban reforestation program that offered residents the opportunity to obtain a free tree. However, the vast majority of trees planted within this program were done so on owner-occupied land, reflecting that participation in urban reforestation programs is not proportionally divided between renters and homeowners (Perkins *et al.*, 2004). Thus, housing market inequalities led to uneven distribution of urban reforestation efforts biased toward owner-occupiers. Management plans that seek to address such inequalities can more effectively contribute to landscape sustainability. In designing such plans matching species to the social context may be as important as matching species to site conditions (Carreiro and Zipperer, 2008).

The City of Toronto's Community Animator program, a component of the Live Green Toronto program, is a working outreach model that could be implemented in Mississauga. Community Animators are situated throughout Toronto and provide the expertise, knowledge and capacity in community animation to launch grassroots action. Animators help community groups and neighbourhoods identify potential initiatives, organize their communities, identify potential funding sources, access expertise and partners, and build capacity for future projects. While the City of Mississauga currently offers numerous stewardship programs on public lands, community-based conservation activities must also be encouraged and facilitated on private lands.

Recommendation 17: Create a Community Animator Program that assists residents and groups acting at the neighbourhood scale in launching local conservation initiatives.

There are several organizations in the GTA that offer programs and resources designed to facilitate urban forest conservation at the community and neighbourhood level. For example, LEAF offers a backyard tree planting program in several municipalities throughout southern Ontario. This program offers native trees and shrubs to residents at a subsidized cost and assists residents in the selection, placement and planting of each specimen.[22] The City is encouraged to pursue a partnership with LEAF to provide the backyard tree planting program to the residents of Mississauga.

A complete discussion of public education and stewardship is beyond the scope of this study. Therefore, a full assessment of opportunities to enhance urban forest stewardship using CBSM should be conducted by the City of Mississauga.

Recommendation 18: Conduct a detailed assessment of opportunities to enhance urban forest stewardship through public outreach programs that utilize community-based social marketing.

[21] For more information visit: http://www.trca.on.ca/get-involved/stewardship/multicultural-environmental-stewardship-program.dot
[22] For more information visit: http://www.leaftoronto.org/node/178

Municipal staff must also be provided with the knowledge necessary to effectively manage the City's natural and grey infrastructure. Objectives for each form of infrastructure, whether natural or grey, should be made compatible at all scales and valued equally. For example, damage can unwittingly be done to publically (and in some instances privately) owned trees by municipal staff completing infrastructure upgrades or repairs. Such damage may be prevented through a more comprehensive understanding and appreciation of acceptable root protection zones during construction activities. A municipal staff training program should therefore be developed and implemented for all relevant employees that will highlight the role each department can play in protecting or enhancing the City's natural infrastructure.

In addition, information sharing sessions for municipal departments that are stakeholders in urban forest management should be provided. Stakeholders include, but are not limited to, those who are directly involved in urban forestry as well as those whose activities indirectly affect or are affected by the urban forest, including municipal parks, operations and planning departments, transportation and health departments, and school boards. The results of this urban forest study as well as the targets and objectives established in the ensuing Urban Forest Management Plan should be shared and distributed widely among all City employees.

Recommendation 19: Develop and implement a comprehensive municipal staff training program as well as information sharing sessions that target all departments and employees that are stakeholders in sustainable urban forest management.

5.2.3 Adaptive Urban Forest Management

The full impact of climate change on Mississauga's urban forest is uncertain. For example, the genetic structure of some flora populations may be affected by altered selection pressures resulting from a changed environment, and species with larger genetic variability are likely more adaptable to a variety of climate conditions and as a result may be more successful (Colombo *et al.*, 1998). Competitive abilities of flora species now present in Ontario's forests may change, increasing in some cases and decreasing in others (e.g., herbaceous plants are favoured by increased CO_2 compared to woody plants). Thus, managers of the urban forest must recognize this uncertainty and plan accordingly.

In order to manage for uncertainty and increase the adaptive capacity of the urban landscape ecological resilience must be built into the urban forest and the natural system.[23] A key strategy for building both resilience and adaptive capacity is to increase diversity at all scales (Burton *et al.,* 1992; Harris *et al.,* 2006; Maciver and Wheaton, 2005; Millar *et al.,* 2007; Rice and Emery, 2003). Species diversity targets have been discussed in Section 5.1.3. However there is also a need to increase genetic diversity within the urban forest. Genetic diversity within a species facilitates the survival of that species by increasing the likelihood that some individuals will be adapted to withstand a major stress or disturbance event. A reliance on clones in the urban forest will have the opposite effect and will increase the risk of catastrophic loss of leaf area and tree cover in the event of a pest or disease outbreak.

[23] Peterson *et al.* (1998) define ecological resilience as a measure of the amount of change required to transform a system from one that is maintained by one set of mutually reinforcing processes and structures to a different set of processes and structures. As such, ecosystems are resilient when ecological interactions reinforce one another and dampen disruption.

Recommendation 20: Increase genetic diversity in the urban forest by working with local growers to diversify stock and reduce reliance on clones.

Following an extensive review of academic literature addressing biodiversity management and adaption in the face of climate change, Heller and Zavaleta (2009) determined that increasing landscape connectivity was the most frequently sited recommendation for climate change adaptation. However, the authors also observed that connectivity strategies were often poorly developed and limited to very general actions (e.g. "build flexibility", "manage the matrix", "modify land use practices"), lacking identification of specific actions, actors and information gaps. Determining which species to manage for is challenging as some species are transient. If conditions are good many migratory birds will fly over the City without stopping; however, in inclement conditions many will seek trees in which to refuel, rest and find refuge. For these species, the more trees there are distributed across the municipality, the better. Other species reside in Mississauga, either permanently (Northern Mockingbird, Screech Owl and White-footed Mouse) or seasonally, and their demands for habitat require a slightly more strategic approach to urban forestry.

Most summer or breeding species, especially ground-dwelling bird and amphibian species, find few options for nesting and for local movement in urban regions. Similarly, plants of the forest floor are unable to find habitat within urban land uses. Therefore, most local movement of flora and fauna species will occur within the established natural systems, the wilder portions of the urban forest. Mapping of Mississauga's natural system can be found in the City's official plan as well as in TRCA's TNHSS and CVC's TEEM Program (introduced in Section 2.2).

One should not expect the urban forest in Mississauga to provide connectivity for all species, but it is reasonable to expect that the urban forest will assist in increasing the rate of breeding success of some, particularly canopy-dwellers, by providing them with additional resources. Swallows, Flycatchers, Tanagers, Grosbeaks, Woodpeckers, Orioles and Warblers feed on insects in "green" portions of urban areas during the breeding season. Furthermore, the placement of trees adjacent to the natural system can provide resources (foraging areas and refuge from predators) near their nest location that can increase the survival rate of young birds. This requires a more strategic distribution of trees to expand the leaf area density outward from natural areas, which will eventually serve to increase connectivity in Mississauga.

Recommendation 21: Utilize the UTC analysis together with natural cover mapping to identify priority planting and restoration areas within the urban matrix.

Matrix influence refers to the extent that the surrounding land use affects the integrity of the natural system. The character of the urban land use can either help to reduce negative impacts or intensify them. For example, the more mature neighbourhoods in the lower Etobicoke Creek and Credit Valley Watersheds with their open spaces and mature street trees help to soften the line between the edge of the natural features and the urban development. This makes the landscape more accessible and hospitable to resident and migrant fauna species. In contrast, industrial areas tend to have little or no open space or tree cover. These types of landscapes can be inhospitable to migratory birds and other species and do little to integrate the urban landscape with the remaining natural areas. Increasing leaf area and canopy cover in the *commercial* and *industrial* land use categories will reduce the negative matrix influence on the adjacent natural system, which will in turn increase the quality of habitat patches and the adaptive capacity of the species that inhabit them. The *Employment Land Planting Program* provided by the GTAA Partners in Project Green offers a means to increase leaf area in

Mississauga's commercial and industrial area, reduce the negative matrix influence, beautify the employment lands, and facilitate corporate team building and leadership development.[24]

Through the Target System Design process of the TNHSS, TRCA has identified the quantity and quality distribution of natural cover required to sustain regional biodiversity. Enhancing connectivity within the natural system will increase ecological function and adaptive capacity at the landscape scale. Please see the TNHSS for a complete discussion of the Target Natural System and associated land acquisition and restoration.

Recommendation 22: Implement the target natural heritage system in the Etobicoke and Mimico Creeks Watersheds; work with CVC to identify and implement the target natural heritage system in the Credit Valley Watershed.

Recognizing that a general trend towards north-ward migration of tree species is currently being observed and projected for the future (see for example, Colombo *et al.*, 1998), it may be advantageous to select native species that are currently at the northern limit of their range (e.g. Northern hackberry, *Celtis occidentalis* and tulip tree, *Liriodendron tulipifera*). However, careful monitoring of the urban forest resource will facilitate adaptive management. The City is encouraged to develop a comprehensive monitoring program that tracks trends in tree establishment and mortality, and more generally evaluates the distribution and structure of the urban forest over the next 20 years. The tools of analysis utilized for this Study should form the basis of this program. Specifically, both the i-Tree Eco analysis and the Urban Tree Canopy analysis should be repeated at regular 5-year intervals. The results of each successive analysis can be released publically via an "Urban Forest Report Card" in order to maintain on-going interest in sustainable urban forest management. The City should also consider incorporating the existing street tree inventory and a woodlot inventory into the proposed monitoring program.

Recommendation 23: Develop and implement an urban forest monitoring program that tracks trends in the structure and distribution of the urban forest using the i-Tree Eco analysis and Urban Tree Canopy analysis. The structure and distribution of the urban forest should be comprehensively evaluated at regular 5-year intervals and reported on publically.

Exploring research partnerships with local academic institutions will also be advantageous with respect to forecasting future conditions and selecting appropriate tree species. In addition, collaboration with a local arboretum, such as the Humber Arboretum, will offer opportunities to evaluate the survival of certain species under controlled conditions.

It is increasingly likely that EAB will not be contained and the existing ash population in Ontario will decline significantly. In the City of Mississauga approximately 16 percent of the urban forest is composed of ash species, all of which could therefore be lost. It follows that there is an urgent need to collect and store high quality seed from native ash species. Preserving seed from a wide range of healthy ash specimens in the local population will prevent the possible extinction of this species and facilitate reintroduction of native ash once adequate environmental control measures for EAB are developed or trees resistant to the insect are bred and introduced (NRCan, 2010). Breeding resistant ash trees will require an array of adapted parental populations. In anticipation of the need for ash seed

[24] For more information visit: www.partnersinprojectgreen.com

stock the City of Mississauga is advised to develop an ash seed collection program in partnership with TRCA, CVC and the National Tree Seed Centre of NRCan.

Recommendation 24: Develop a seed collection program for native ash species in partnership with TRCA, CVC and National Tree Seed Centre

5.2.4 Tree Habitat

Proper growing conditions are critical to long-term tree survival and are therefore fundamental to the success of programs that aim to increase canopy cover, diversify age class structure, and enhance overall forest sustainability. By increasing soil volume in tree habitat, improving soil moisture and fertility, and maintaining a healthy soil structure, the longevity of urban trees can be significantly extended. Soil compaction under pavement is required in order to safely bare surface weight. Consequently soil porosity is low and street tree roots are unable to penetrate the compacted soil. When the needs of the tree exceed the capacity of the soil, tree health will decline. As a result trees grown in typical urban streetscapes rarely reach their full growth potential. Compaction associated physiological dysfunctions cause systemic damage and decline, as well as failures in dealing with additional environmental changes (Coder, 2000). In highly compacted soil along roadways tree roots often grow in the small void space directly beneath the pavement; this results in sidewalk heaving. Pavement lifting and sidewalk heaving can then lead to public safety concerns and additional infrastructure repair costs.

When properly integrated into urban design, trees can deliver multiple engineering benefits including increased pavement life, and a reduction in stormwater flow and runoff. Careful below ground design is a necessary element of sustainable urban planning. In collaboration with the municipal planning department, the Urban Forestry Unit is advised to update or create (where applicable) guidelines and regulations for development applications for sustainable streetscape and subdivision design. Such regulations must serve to eliminate conflicts between natural and grey infrastructure by placing required soil volumes and urban forest targets on the same level as other site demands.

The Green Streets Program implemented by the City of Portland Oregon offers an example of sustainable streetscape design.[25] The Green Street design was first created for the purpose of stormwater management and has since evolved into an integrated application that provides multiple benefits, such as greenspace and habitat connectivity, enhancement of the bicycle and pedestrian environment, and neighbourhood liveability. Casey Trees, a nonprofit organization based in Washington DC, has created a matrix of recommended soil volumes based on sidewalk width as well as several streetscape design options to achieve the suggested soil volumes.[26] The Town of Markham's Streetscape Design Guidelines Manual provides specifications and required design features for applications for Site Plan and Subdivision as well as Town boulevard tree planting. The Manual was developed to ensure that adequate replacement and increased numbers of new tree plantings occur in a sustainable manner.

The projected population growth in Mississauga has created a demand for urban intensification, which will create a more compact, mixed-use city, with clear (i.e. non-sprawling) boundaries. This process may

[25] For more information visit: http://www.portlandonline.com/BES/index.cfm?c=44407
[26] For more information visit: http://www.caseytrees.org/planning/design-resources/for-designers/tree-space/index.php

entail increasing building density and developing on vacant land in order to accommodate growth and achieve a more compact and sustainable urban form. Urban intensification is also associated with increases in the amount of activity that takes place within cities – both increases in the population density, and the extent of economic and social activity. A more compact urban form will create both challenges and opportunities for urban forest managers. Provisions must be made for adequate tree habitat during the preliminary design stages of all new development activities. In other words, grey infrastructure spatial requirements cannot be met at the cost of natural infrastructure needs. A balance must be sought in order to create a healthy urban environment. Interdepartmental collaboration will be critical to achieving success in this regard.

Recommendation 25: Develop municipal guidelines and regulations for sustainable streetscape and subdivision design that 1) ensure adequate soil quality and quantity for tree establishment and 2) eliminate conflict between natural and grey infrastructure.

Technologies such as structural soils and subsurface cells will further enhance growing conditions and should be incorporated into urban design. To minimize costs, construction activities can be incorporated into planned capital works projects and other infrastructure maintenance, where possible.

Recommendation 26: Apply and monitor the use of structural soils, subsurface cells and other enhanced rooting environment techniques for street trees. Utilizing these technologies at selected test-sites in the short-term may provide a cost-effective means of integrating these systems into the municipal budget.

5.3 Criteria and Indicators for Sustainable Urban Forest Management

Kenney *et al.* (2011) have developed a comprehensive list of criteria and performance indicators for sustainable urban forest management. This list was derived from the work of Clark *et al.* (1997) and is intended to be used to assess the progress toward sustainable urban forest management and planning. The Urban Forestry Unit is advised to use the criteria and indicators to guide the creation of a strategic management plan. Achieving all objectives outlined in the framework simultaneously will not be feasible. Therefore, objectives should be prioritized as necessary. However, all 25 objectives should eventually be addressed through the management process. Please see Appendix F for the complete list of criteria and indicators.

Recommendation 27: Utilize the criteria and performance indicators developed by Kenney *et al.* (2011) to guide the creation of a strategic management plan and to assess the progress made towards sustainable urban forest management and planning.

6.0 Recommendations

The following recommendations reflect the actions needed in order to progress towards many of the short and long term objectives associated with the criteria and performance indicators for sustainable urban forest management presented by Kenney *et al.* (2011). To evaluate the City's performance for each of the 25 criteria is beyond the scope of this report. Such an extensive exercise should be conducted through the development of the City of Mississauga's Urban Forest Management Plan. It follows that the development of a Management Plan that will more fully explore the operational actions and resources required to achieve success is of the highest priority. The Management Plan should draw directly on the results of this study and incorporate the recommendations offered here.

6.1 Summary of Recommendations

28. Neighbourhoods identified by the Priority Planting Index should be targeted for strategic action that will increase tree cover and leaf area in these areas.

29. Use the parcel-based TC metrics together with the City's GIS database to identify and prioritize contiguous parcels that maintain a high proportion of impervious cover and a low percent canopy cover.

30. Increase leaf area in canopied areas by planting suitable tree and shrub species under existing tree cover. Planting efforts should be focused in areas where mature and aging trees are over-represented, including the older residential neighbourhoods located south of the Queensway. Neighbourhoods in these areas that maintain a high proportion of ash species should be prioritized.

31. Utilize the Pest Vulnerability Matrix during species selection for municipal tree and shrub planting.

32. Establish a diverse tree population in which no single species represents more than 5 percent of the tree population, no genus represents more than 10 percent of the tree population, and no family represents more than 20 percent of the intensively managed tree population both city-wide and the neighbourhood level.

33. In collaboration with the Toronto Region Conservation Authority and Credit Valley Conservation, develop and implement an invasive species management strategy that will comprehensively address existing infestations as well as future threats posed by invasive insect pests, diseases and exotic plants.

34. Utilize native planting stock grown from locally adapted seed sources in both intensively and extensively managed areas.

35. Evaluate and develop the strategic steps necessary to increase the proportion of large, mature trees in the urban forest. Focus must be placed on long-term tree maintenance and by-law enforcement to ensure that healthy specimens can reach their genetic growth potential. The value of the services provided by mature trees must be effectively communicated to all residents.

36. Determine the relative dbh of the tree population in Mississauga; consider utilizing relative dbh as an indicator of urban forest health.

37. Conduct an assessment of municipal urban forest maintenance activities (e.g. pruning, tree planting) to determine areas where a reduction in fossil fuel use can be achieved.

38. Reduce energy consumption and associated carbon emissions by providing direction and assistance to residents and businesses for strategic tree planting and establishment around buildings.

39. Focus tree planting and establishment in “hot-spots” identified by thermal mapping analysis.

40. Review and enhance the Tree Permit By-law 474-05 to include the protection all trees that are 20 cm or greater in diameter at breast height.

41. Develop a comprehensive Public Tree By-law that provides protection to all trees on publically owned and managed lands.

42. Develop a Tree Protection Policy that outlines enforceable guidelines for tree protection zones and other protection measures to be undertaken for all publically and privately owned trees.

43. Allocate additional funding to the Urban Forestry Unit for the resources necessary to ensure full public compliance with Urban Forestry By-laws and policies.

44. Create a Community Animator Program that assists residents and groups acting at the neighbourhood scale in launching local conservation initiatives.

45. Conduct a detailed assessment of opportunities to enhance urban forest stewardship through public outreach programs that utilize community-based social marketing.

46. Develop and implement a comprehensive municipal staff training program as well as information sharing sessions that target all departments and employees that are stakeholders in sustainable urban forest management.

47. Increase genetic diversity in the urban forest by working with local growers to diversify stock and reduce reliance on clones.

48. Utilize the UTC analysis together with natural cover mapping to identify priority planting and restoration areas within the urban matrix.

49. Implement the target natural heritage system in the Etobicoke and Mimico Creeks Watersheds; work with CVC to identify and implement the target natural heritage system in the Credit Valley Watershed.

50. Develop and implement an urban forest monitoring program that tracks trends in the structure and distribution of the urban forest using the i-Tree Eco analysis and Urban Tree Canopy analysis. The structure and distribution of the urban forest should be comprehensively evaluated at regular 5-year intervals and reported on publically.

51. Develop a seed collection program for native ash species in partnership with TRCA, CVC and National Tree Seed Centre

52. Develop municipal guidelines and regulations for sustainable streetscape and subdivision design that 1) ensure adequate soil quality and quantity for tree establishment and 2) eliminate conflict between natural and grey infrastructure.

53. Apply and monitor the use of structural soils, subsurface cells and other enhanced rooting environment techniques for street trees. Utilizing these technologies at selected test-sites in the short-term may provide a cost-effective means of integrating these systems into the municipal budget.

54. Utilize the criteria and performance indicators developed by Kenney *et al.* (2011) to guide the creation of a strategic management plan and to assess the progress made towards sustainable urban forest management and planning.

References

Aronson, E., Ellsworth, P., Carslmith, J. M., and Gonzales, M. 1990. Methods of research in social psychology (2nd ed.). New York: McGraw-Hill.

Brook, R.D., Brook, J.R., Urch, B., Vincent, R., Rajagopalan, S. and F. Silverman. 2002. Inhalation of fine particulate air pollution and ozone causes acute arterial vasoconstriction in healthy adults. American Heart Association, Circulation, **April**, pp. 1534-1536.

Burnett, R.T., Smith-Doiron, M., Steib, D., Cakmak, S. and J.R. Brook. 1999. Effects of particulate and gaseous air pollution on cardiorespiratory hospitalization. Archives of Environmental Health, **54**, 2, pp. 130-139

Burton, P.J., Balisky, A.C., Coward, L.P., Cumming, S.G., Kneeshaw, D.D., 1992. The value of managing for biodiversity. Forestry Chronicle 68, 225–237.

Carreiro, M.M. and W.C. Zipperer. 2008. Urban forestry and the eco-city: Today and tomorrow. In Ecology, Planning, and Management of Urban Forests: International Perspectives. M.M. Carreiro *et al.* (eds). Springer.

Chiotti, Q., Morton, I., Ogilvie, K., Maarouf, A. and M. Kelleher. 2002. Towards an Adaptation Action Plan: Climate Change and Health in the Toronto-Niagara Region (Toronto: Pollution Probe) http://www.pollutionprobe.org/Reports/adaptation.pdf

City of Mississauga. 2004. By-law Number 0057-2004: A By-Law of The Corporation of the City of Mississauga regulating encroachments on public lands, to amend By-Law Number 277-96 and to exempt certain persons from By-Law Number 23-79. Retrieved from: http://www.mississauga.ca/file/COM/Encroachment_By_law.pdf

City of Mississauga. 2010. Mississauga Official Plan. Retrieved from: http://www.mississauga.ca/portal/residents/draftmississaugaofficialplan

Clark, J.R., Methany, N. P., Cross, G. and V. Wake. 1997. A model of urban forest sustainability. Journal of Arboriculture 23(1): 17-30.

Coder, K.D. 2000. Soil compaction impacts on tree roots. University of Georgia Warnell School of Forest Resources Extension Publication FOR00-8.

Colombo, S.J., M.L. Cherry, C. Graham, S. Greifenhagen, R.S. McAlpine, C.S. Papadopol, W.C. Parker, T. Scarr, M.T. Ter-Mikaelian and M.D. Flannigan. 1998. The impacts of climate change on Ontario's forests. Forest research information paper No. 143. Ontario Forest Research Institute.

Costanzo, M., Archer, D., Aronson, E., and T. Pettigrew. 1986. Energy conservation behavior: The difficult path from information to action. American Psychologist, 41(5), 521-528.

Elmendorf, W.F. and A.E. Luloff. 1999. Using ecosystem-based and traditional land-use planning to conserve greenspace. Journal of Arboriculture 25(5):264-273.

Endreny, T.A. 2005. Land Use and Land Cover Effects on Runoff Processes: Urban and Suburban Development. In: Encyclopedia of Hydrological Sciences, M.G. Anderson (Editor). Wiley, Chichester, United Kingdom, pp. 1775-1804.

EPA. 2007. Heat island effect: trees and vegetation. U.S. Environmental Protection Agency. http://www.epa.gov/hiri/strategies/vegetation.html.

Fischer, J., Lindenmayer, D.B., and A.D. Manning. 2006. Biodiversity, ecosystem function, and resilience: ten guiding principles for commodity production landscapes. Front Ecol Environ; 4(2): 80–86.

Graham, R.L., Wright, L.L., A.F. Turhollow. 1992. The potential for short-rotation woody crops to reduce U.S. CO_2 emissions. Climatic Change. 22: 223-238.

Harris, J.A., Hobbs, R.J., Higgs, E., and J. Aronson. 2006. Ecological restoration and global climate change. Restoration Ecology 14, 170–176.

Heller, N.E. and E.S. Zavaleta. 2009. Biodiversity management in the face of climate change: A review of 22 years of recommendations. Biological conservation 142:14-32.

Heynen, N. 2003. The scalar production of injustice within the urban forest. Antipode: A Journal of Radical Geography 35 (5): 980–98.

IPCC. 2007. Summary for Policymakers. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Kenney, W.A., van Wassenaer, P.J.E., A.L. Satel. 2011. Criteria and Indicators for Strategic Urban Forest Planning and Management. Arboriculture & Urban Forestry 2011. 37(3): 108–117.

Kramer. P. J., and T. T. Kozlowski. 1979. Physiology of woody plants. Academic Press, New York.

Laċan, I. and J.R. McBride. 2008. Pest vulnerability matrix: A graphic model for assessing the interaction between tree species diversity and urban forest susceptibility to insects and disease. Urban Forestry & Urban Greening 7:291-300.

Maciver, D.C., Wheaton, E., 2005. Tomorrow's forests: adapting to a changing climate. Climatic Change 70, 273–282.

McKenzie-Mohr, D., and Smith, W. 1999. Fostering sustainable behavior: An introduction to community-based social marketing (2nd ed.). Gabriola Island, British Columbia, Canada: New Society.

McPherson, E.G. 2003. A benefit-cost analysis of ten street tree species in Modesto, California, U.S. Journal of Arboriculture 29(1): 1-8.

McPherson, E.G., and J. Muchnick. 2005. Effects of street tree shade on asphalt concrete pavement performance. Journal of Arboriculture 31(6):303-310.

Millar, C.I., Stephenson, N.L., Stephens, S.L., 2007. Climate change and forests of the future: managing in the face of uncertainty. Ecological Applications 17, 2145–2151.

Nowak, D.J. 2000. The interactions between urban forests and global climate change. In: Abdollahi, K.; Ning, Z.H.; Appeaning, V.A.,eds. *Global climate change and the urban forest*. Baton Rouge, LA: GCRCC and Franklin Press: 31-44.

Nowak, D.J. 2006. Institutionalizing urban forestry as a "biotechnology" to improve environmental quality. Urban Forestry & Urban Greening 5:93–100.

Nowak, D.J. and D.E. Crane. 2002. Carbon storage and sequestration by urban trees in the USA. Environ. Poll. 116(3):381-389.

Nowak, D.J. Crane, D.E., Stevens, J.C., and M. Ibarra. 2002. Brooklyn's urban forest. USDA Forest Service, Northeastern Research Station. General Technical Report NE-290.

Nowak, D.J. and J.F. Dwyer. 2007. Understanding the costs and benefits of the urban forest. In *Urban and Community Forestry in the Northeast*, *2nd ed*. (J.E. Kuser, ed).

NRCan. 2004. The Atlas of Canada: Map of Forest Regions of Canada. Natural Resources Canada. Retrieved from: http://atlas.nrcan.gc.ca/site/english/learningresources/theme_modules/borealforest/forest_regions.jpg/image_view

NRCan. 2009. Thermal Remote Sensing of Urban Heat Islands: Greater Toronto Area. Natural Resources Canada.

NRCan. 2010. National Tree Seed Centre: Ash Seed Collection for Genetic Conservation. Natural Resources Canada. Retrieved from: http://cfs.nrcan.gc.ca/subsite/seedcentre/ashconservation.

Oliver, C. D, and B.C. Larson. 1996. Forest stand dynamics. New York, NY: Wiley.

Opdamm P. and D. Wascher. 2004. Climate change meets habitat fragmentation: linking landscape and biogeographical scale levels in research and conservation. Biological Conservation 117 (2004) 285–297

Pembina Institute and Credit Valley Conservation. 2009. Natural Capital: Estimating the Value of Natural Capital in the Credit River Watershed.

Perkins, H.A., Heynen, N., Wilson, J., 2004. Inequitable access to urban reforestation: the impact of urban political economy on housing tenure and urban forests. Cities 21 (4): 291–299.

Raupp. M.J., Cumming, A.B., and E.C. Raupp. 2006. Street tree diversity in eastern North America and its potential for tree loss to exotic borers. Arboriculture and Urban Forestry 32(6): 297-304.

Rice, K.J., and N.C. Emery. 2003. Managing microevolution: restoration in the face of global change. Frontiers in Ecology and the Environment 1, 469–478.

Richards, N. A. 1983. Diversity and stability in a street tree population. Urban Ecology **7**.

Riley, A.L. 1998. Restoring Streams in Cities: A Guide for Planners Policymakers and Citizens. Island Press, Washington, D.C.

Rosenzweig, C., Solecki, W., Parshall, L., Gaffin, S., Lynn, B., Goldberg, R., Cox, J., and S. Hodges. 2006. Mitigating New York City's heat island with urban forestry, living roofs, and light surfaces. A report to the New York State Energy Research and Development Authority (in press).

Santamour, F. S., Jr. 1990. Trees for Urban Planting: Diversity, Uniformity, and Common Sense. Proc. 7th.

Simpson, J.R. and E.G. McPherson. 1996. Potential of tree shade for reducing residential energy use in California. Journal of Arboriculture 22(1):10-18

Solecki, W.D., C. Rosenzweig, L. Parshall, G. Pope, M. Clark, J. Cox, and M. Wiencke, 2005. Mitigation of the heat island effect in urban New Jersey. Global Environ. Change B Environ. Hazards 6:30-49, doi:10.1016/j.hazards.2004.12.00.

Soulé, M.E., Mackey, B.G., Recher, H.F., Williams, J.E., Woinarski, J.C.Z., Driscoll, D., Dennison, W.C. and Jones, M.E.. 2004. The role of connectivity in Australian conservation. *Pacific Conservation Biology*, 10, 266–279.

Steib, D.M., Judek, S. and R.T. Burnett. 2002. Meta-analysis of time-series studies of air pollution and mortality: effects of gases and particles and the influence of cause of death, age and season. Journal of the Air and Waste Management Association, **52**, pp. 470-484.

Taylor, P.D., Fahrig, L., Henein, K. and Merriam, G. 1993. Connectivity is a vital element of landscape structure. Oikos, 68, 571–573.

USDA Forest Service. 2007. i-tree Software Suite v1.2: User's Manual.

Zipperer, W.C. 2008. Applying ecosystem management to urban forestry. In *Ecology, Planning, and Management of Urban Forests: International Perspectives.* M.M. Carreiro *et al.* (eds). Springer.

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Appendix A: Literature Review

Urban Forest Structure

Varying definitions of urban forest structure exist. Rowntree (1984) defines urban forest structure as the spatial arrangement of vegetation in relation to other objects within urban areas, while Sanders (1984) describes structure as the static assemblage of plant materials above, on, and below the ground surface within an urban area or its zone of influence. Generally, all such definitions refer to characteristics such as species composition, spatial distribution of vegetative cover, and tree size and condition.

Urban forest structure can be determined by a number of variables. McBride and Jacobs (1986) suggest that the structure of an urban forest can be tied directly to presettlement forest composition. Nowak (1994a) observed a direct relationship between presettlment forest cover and the extent of urban forest canopy in American cities, recording the highest tree cover in cities developed in naturally forested areas (32%), followed by grasslands (18%), and deserts (10%).[27] Sanders (1984) argues that urban vegetation patterns and their expected variations can be determined by the following three factors: urban morphology; the natural environment or natural processes that influence vegetation establishment, growth, competition, and decline; and human management systems. Nowak (1993) identifies four general forces that can alter urban forest structure: direct anthropogenic, e.g. planting and removals; indirect anthropogenic, e.g. war, economic depression; natural direct, e.g. storms, fire; and natural indirect, e.g. large earthquakes. Although forest managers have little control over indirect forces, proper planning will facilitate control over the direct forces of structural change. In the Greater Toronto Area population density and parcel size were not found to be related to the amount of vegetation cover (Conway and Hackworth, 2007), suggesting that other factors, such as land use policy, are influencing conditions on-the-ground.

Various socio-economic determinants of urban forest structure are also recognized. A direct correlation between neighbourhood wealth and the extent and diversity of urban vegetation cover has been observed (Iverson and Cook, 2000; Martin *et al.*, 2004; Heynen and Lindsay, 2003; Hope *et al.*, 2003). Education (Heynen and Lindsay, 2003), household age composition (Fung and Sui, 2000) and occupancy rates (Heynen *et al.*, 2006) have also been identified as determinants of the structure of urban vegetation. Fraser and Kenney (2000) found that the landscape traditions unique to various cultural groups in the City of Toronto directly affected preferences for urban forest structure. For example, the Mediterranean community, having evolved in a small-scale agrarian culture, demonstrated a preference for fruit trees and vegetable gardens. Chinese-Canadians expressed the greatest desire for treeless landscapes, while the British community responded the most positively to shade trees and naturalized parks. These cultural differences are largely consistent with the traditional use of trees in British, Mediterranean and Chinese landscaping, and appear to be maintained among North American immigrant populations (Fraser and Kenney, 2000).

Compositional differences in forest structure will directly influence the environmental services provided. For example, Beckett *et al.* (2000a) found that conifer species captured more particulate matter than

[27] No such determinations have been made for Canadian cities.

deciduous species when location and placement were controlled. The greater particulate capture was attributed to the finer, more complex structure of conifer species. Furthermore, structural properties of leaf and bark surfaces have been found to affect the capacity for particulate capture (Beckett *et al.*, 2000b). Rough, hairy leaf surfaces more effectively captured particles than smooth, waxy leaf surfaces. An understanding of the various attributes of different species can enhance the management capacity to direct urban forest structure to provide certain desired functions, such as particulate removal or stormwater interception.

Urban Forest Function

The urban forest provides a number of valuable ecosystem services. A non-exhaustive discussion of the relevant services is offered here.

Air Quality

Urban air pollution negatively impacts human health. Exposure to common transport-related air pollutants, such as particulate matter ($PM_{2.5}$ and PM_{10}), ozone (O_3), sulphur dioxide (SO_2), nitrogen dioxide (NO_2), and carbon monoxide (CO), has been linked to various health problems, including: inflammation of the respiratory tract; exacerbated allergic reactions in asthmatics; adverse outcomes in pregnancy; and increased mortality risk due to heart attack, cardiopulmonary and respiratory complications (Kuna-Dibbert and Krzyzanowski, 2005). These risks are not equally distributed across the population. Rather, children and elderly persons with pre-existing chronic disease have shown increased susceptibility to the adverse effects of exposure to air pollutants.

By significantly reducing the amount of airborne pollutants, trees can mitigate the potential health problems associated with poor air quality. Trees reduce the amount of airborne particulate matter by intercepting and storing large airborne particulate on outer leaf, branch, and bark surfaces (Nowak et al., 2006). In addition, trees improve air quality by binding or dissolving water-soluble pollutants onto moist leaf surfaces. Other gaseous air pollutants, such as carbon monoxide and sulphur dioxide, are removed primarily by leaf stomatal uptake (Smith, 1990).

Ground level ozone (O_3) is not emitted directly but is created by chemical reactions between oxides of nitrogen and volatile organic compounds (VOCs) in sunlight. Although trees are a source of VOC emissions, the net effect of tree cover on the landscape is usually positive with respect to O_3 formation (Cardelino and Chameides, 1990; Taha, 1996). Because VOC emissions are temperature-dependent and trees have been found to lower air temperatures, increased tree cover can lower overall VOC emissions and, subsequently reduce ozone levels in urban areas (Nowak and Dwyer, 2007). Furthermore, increasing tree cover over parking lots can reduce VOC emissions by shading parked cars and thereby reducing evaporative emissions (Scott et al., 1999). Thus, urban trees, particularly species that emit low levels of VOCs, can contribute to the reduction of urban O_3 levels (Nowak et al., 2000). It should be noted that VOC emissions do vary by species, air temperature and other environmental factors (Guenther et al., 1994).

Carbon Dioxide Reduction and Energy Conservation

Urban forests also play a role in climate change mitigation by reducing atmospheric carbon dioxide (CO_2) concentrations. This is achieved by sequestering and storing carbon as woody biomass, carbon sequestration and storage, reducing GHG emissions by conserving energy used for space heating and cooling, or displacing GHG emissions by using urban tree residue as bio-energy fuel.

Trees reduce atmospheric CO_2 levels through photosynthetic uptake and subsequent carbon sequestration in woody biomass. During photosynthesis, atmospheric CO_2 enters the leaf through surface pores, combines with water, and is converted into cellulose, sugars, and other materials in a chemical reaction catalyzed by sunlight. Most of these materials then become fixed as wood, while a small portion are respired back as CO_2 or are utilized in the production of leaves that are eventually shed by the tree (Larcher 1980). Nowak (1994b) found that the net annual carbon sequestration by trees in Chicago equaled the amount of carbon emitted from transportation in one week in the Chicago area. Furthermore, the amount of carbon emitted by the U.S. population over a 5.5 month period was equal to the estimated carbon storage by urban trees in the United States (Nowak and Crane, 2002).

Trees that are adjacent to buildings can reduce the demand for heating and air conditioning through their moderating influence on solar insolation and wind speed. In addition, trees ameliorate climate by transpiring water from their leaves, a process that has a cooling effect on the atmosphere. Thus, the effective placement of a tree or shrub can lower building temperatures. Simpson and McPherson (1999) report that by planting two large trees on the west side of a house, and one large tree on the east side of a house, homeowners can reduce their annual air conditioning costs by up to 30%. Potential GHG emission reductions from urban forestry are likely to be greatest in regions with large numbers of air-conditioned buildings and long cooling seasons. However, in colder regions where high energy demands are high during winter months, trees that are properly placed to create windbreaks can also substantially decrease heating requirements and can produce savings of up to 25% on winter heating costs (Heisler, 1986). This reduction in demand for heating and cooling in turn reduces the emissions associated with fossil fuel combustion (Simpson and McPherson, 2000).

Utilizing urban tree biomass as feedstock for bio-power plants eliminates GHGs that would have been emitted by combusting fossil fuels. The most common way to convert tree biomass to energy is by burning wood fuel to produce heat that powers turbines. However, the cost effectiveness of utilizing removed city trees as a bio-energy feedstock has not yet been well-researched. According to the California Climate Action Registry (2008) there can be costs associated with initial processing at the removal site, transporting to a transfer station, processing facility, or bio-energy facility, storing in open piles, and handling, usually through a combination of automatic conveyors and driver-operated front-end loaders. Research is also underway to develop more efficient processes for converting wood into fuels such as ethanol, bio-oil, and syngas (Zerbe 2006).

Stormwater Management

When stormwater hits impervious surfaces, the water is heated and various pollutants, including lawn fertilizers and oils on roadways, are picked up by the runoff. Water quality problems then arise when large volumes of polluted stormwater flow into receiving waters, posing threats to temperature sensitive species and providing suitable conditions for algal blooms and nutrient imbalances (Kollin, 2006). Leaves and branch surfaces intercept and store rainfall, thereby reducing runoff volumes and delaying the onset of peak flows. The urban canopy also filters pollutants that eventually flow to receiving waters. Once runoff is infiltrated into soils, plants and microbes can naturally filter and break down many common pollutants found in stormwater.

Tree roots also increase the rate at which rainfall infiltrates soil as well as the capacity of soil to store water, thereby reducing overland flow. Transpiration through tree leaves then reduces soil moisture, increasing the soil's capacity to store future rainfall. By increasing infiltration rates, urban vegetation also limits the frequency of sewer overflow events by reducing runoff volumes and by delaying stormwater discharges. In addition, tree canopies reduce soil erosion by diminishing the impact of rainfall on barren surfaces.

The trees and woody shrubs that comprise urban riparian buffers also improve water quality through filtration of sediment and contaminants, vegetative uptake of soluble nutrients, and infiltration of overland runoff from surrounding fields and hillslopes. Removal of over half the phosphorus, nitrogen and sediment inputs is typically achieved within the first 15 m of buffer width (Osborne and Kovacic, 1993; Castelle *et al*., 1994). Woody riparian vegetation also stabilizes banks and moderates stream temperature by providing shade.

Land use change associated with urbanization can negatively impact hydrologic processes. A summary of recent literature provided by Endreny (2005) concludes that conversion to urban cover results in the following: a reduction in stormwater interception as a consequence of the loss of tree and vegetative cover; a decrease in infiltration as a consequence of soil compaction and an increase in impervious cover; and, a decrease in evaporation due to reduced soil water volumes. The result is then an increase in peak runoff magnitude from precipitation events, which can scour and destabilize many urban channels (Riley, 1998). Although many models have been created to examine the effects of land use change on urban hydrology, i-Tree Hydro, created by the USDA Forest Service, is the only model designed to explicitly examine tree effects on stormwater. This model was therefore utilized in this study.

Social Benefits

Although more difficult to quantify, the urban forest provides a variety of important social benefits. Urban trees have been shown to reduce neighborhood crime levels. For example, Kuo and Sullivan (2001) found that apartment buildings with high levels of greenery witnessed 52% fewer crimes than those without trees. This research suggests that trees reduce crime in two ways: first, frequent encounters with nature can help to soothe violent temperaments; second, trees deter crime by increasing surveillance on city streets, as people tend to use treed spaces more than treeless spaces.

Hospital patients were found to recover from major surgery more quickly and with fewer complications when provided with a view of trees (Ulrich, 1984). Trees and urban parks also improve mental health and over all well-being by conveying a sense of calm and facilitating relaxation and outdoor activity. In addition, trees effectively reduce noise levels by absorbing unwanted sound (Aylor, 1972; Cook, 1978).

Traffic and Pedestrian Safety

Research suggests that trees may improve driving safety. Drivers seeing natural roadside views demonstrated lower levels of stress and frustration compared to those viewing all-built settings (Parsons *et al*. 1998). A study conducted by Mok *et al*. (2006) found a 46% decrease in crash rates across urban arterial and highway sites after landscape improvements were installed. Similarly, research conducted by Naderi (2003) found that placing trees and planters in urban arterial roadsides reduced mid-block crashes by 5% to 20%.

Economic Benefits

A healthy urban forest is a municipal capital investment that will appreciate in value over time. As urban forests grow, their environmental, social and economic benefits increase. The process of valuation of the goods and services provided by the urban forest and surrounding natural system is currently receiving considerable attention across all fields of conservation. A comprehensive assessment of this area of research is beyond the scope of this review; therefore, only a few key examples of this research are offered here.

DeGroot *et al.* (2002) proposed a framework for the valuation of ecosystem functions, goods and services that is based on the synthesis of complex ecological structures and processes into a more limited number of ecosystem functions that provide ecosystem goods and services valued by humans. This framework can be used at various scales; for example, to calculate the natural capital assets within TRCA jurisdiction, a watershed, or an individual site.

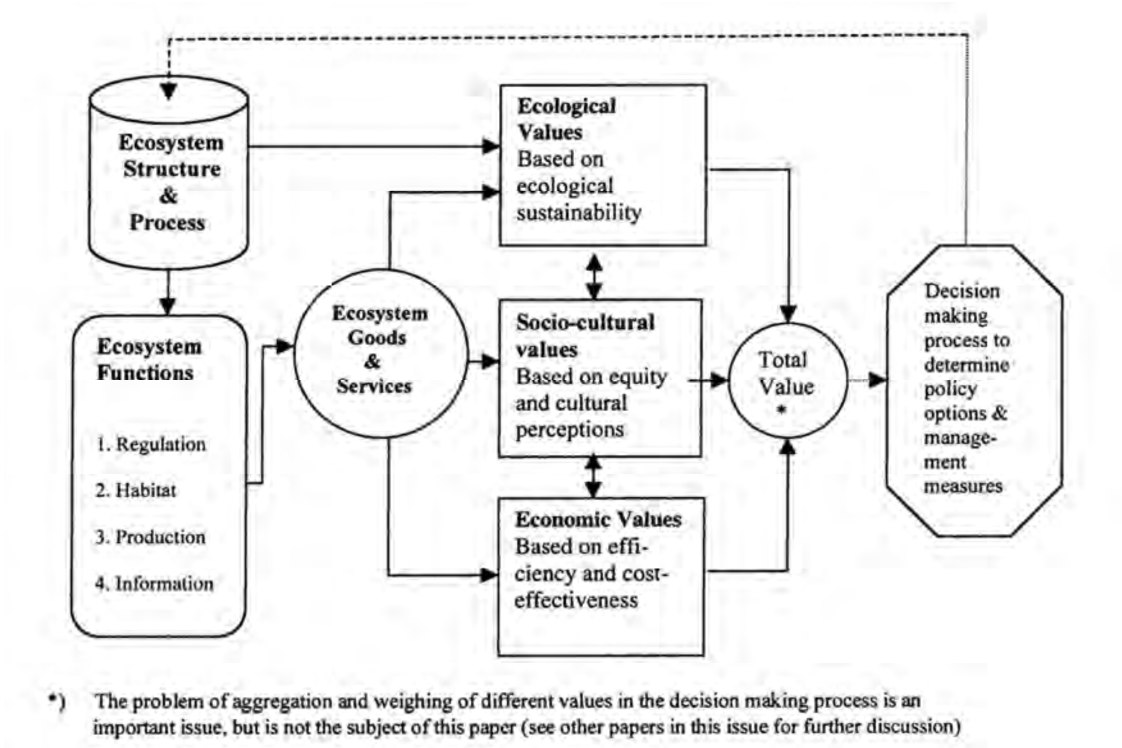

Figure 1: Framework for integrated assessment and valuation of ecosystem functions, goods and services (DeGroot *et al.*, 2002)

The Pembina Institute and Credit Valley Conservation (2009) estimated the value of ecosystem goods and services in the Credit River Watershed using a benefit transfer methodology that focused on the non-market value of ecosystem services; this non-market value was derived from a "willingness to pay" approach.[28] The report found that the value of the natural capital provided by the urban forest in the

[28] An individual's willingness to pay for an ecosystem service can be used to assign a value to a particular ecological good or service. Please see Pembina Institute and CVC (2009) for a more detailed discussion of this approach.

watershed was estimated at 18.7 million dollars annually.[29] This estimate included the value of the following services: climate regulation; gas regulation; water supply; pollination; recreation; and amenity and cultural.

There are numerous challenges associated with ecological valuation. For example, many ecosystem services are difficult to measure directly (e.g. gas exchange) and therefore require the use of surrogates or indicators (Cuperus *et al.*, 1996; Bond and Pompe, 2003). Furthermore, in the absence of local jurisdictional data, the best matching default values and parameters must be selected in order to calculate the value of ecosystem services. Consequently, values derived are often generalized for a large geographic area and are not site-specific. Thus, this field of research is still rapidly evolving in an effort to address these challenges.

A direct economic benefit of urban vegetation is observed in the relationship between tree cover and property value. Both residential tree cover and proximity to green space have been associated with higher property values in residential neighborhoods (Dombrow *et al*., 2000; Anderson and Cordell, 1988). The Center for Urban Forest Research (2005) estimates that properties with trees are valued five to fifteen percent higher than comparable properties without trees. Furthermore, research shows that shoppers in well-landscaped business districts were willing to pay more for both parking and goods and services (Wolf, 1999).

Urban tree cover can also increase the longevity of grey infrastructure thereby reducing the frequency of costly repairs. McPherson and Muchnick (2005) have demonstrated that tree shade is correlated with reduced pavement fatigue, cracking, rutting, shoving, and other distress. Subsequently, infrastructure maintenance costs can be reduced by increasing tree cover over asphalt. For example, repaving could be deferred ten years on a well-shaded street and potentially 25 years on a heavily shaded street.

An emerging valuation scheme in which urban forestry has begun to receive attention is the global carbon market. While carbon accounting through carbon offset programs has become a relatively well established protocol, in the past such programs generally operated outside the realm of urban forestry. In 2008 the California Climate Action Registry released the *Urban Forest Project Reporting Protocol Version 1.0*; this protocol was subsequently updated and rereleased as version 1.1 in March 2010. The Protocol provides guidance to account for and report greenhouse gas emission reductions associated with a planned set of tree planting and maintenance activities to permanently increase carbon storage in trees (Climate Action Reserve, 2010). This protocol is applicable to urban forest GHG projects undertaken by municipalities, educational campuses and Utilities. Only projects operating within the United States are eligible at the time of release of this report.

Wildlife Habitat

As rural forests are replaced with urban development, wildlife species are displaced or removed from the landscape completely. Construction activities destroy habitat and result in animals abandoning the area - eliminating these species both from the site, and from adjacent areas (Schaefer 1996). In Peel Region and southern Ontario as a whole, few large and connected woodlands remain to serve as habitat for native and migratory fauna species. Consequently, the urban forest now plays an increasingly important role in biodiversity conservation and habitat provision for these species.

[29] This value was considered the minimum lower bound of the natural capital value.

Sustainable Urban Forest Management

The structure and function of an urban forest will be influenced by a myriad of physical, biological, socioeconomic, cultural, and political factors; these factors are directly interconnected and cannot be viewed in isolation (Zipperer, 2008; Clark *et al.* 1997; Carreiro and Zipperer, 2008; Perkins *et al.*, 2004; Picket *et al.*, 1997). Moreover, these factors and the manner in which they interact with one and other must be taken into account when making management decisions. A growing body of research suggests that in order to successfully incorporate these diverse factors into management plans a holistic *ecosystem-based approach* to urban forest management is required (Zipperer, 2008; Carreiro and Zipperer, 2008; Elmendorf and Luloff, 1999).

The ecosystem-based approach found formal acceptance at the Earth Summit in Rio (1992), where it became the primary framework for action under the Convention on Biological Diversity. It is based on the application of appropriate scientific methodologies focused on levels of biological organization, which encompass the essential structures, processes, functions and interactions among organisms and their environment. The following themes are central to this approach: ecological rather than jurisdictional boundaries; ecological integrity; interagency and intermunicipal cooperation; humanity in nature; and environmental justice (Elmendorf and Luloff, 1999). To achieve an ecosystem-based approach to urban forest management Zipperer (2008) argues that consideration must be given to the broader context in which a management site occurs, as the site will effect and by effected by adjacent land uses and surrounding ecological processes. Ames and Dewald (2003) state that assembling a diverse base of expertise with multiple viewpoints into partnerships to address the management of a city's urban forest is integral to a ecosystem-based approach, as these partnerships can inform the creation and implementation of plans at the outset, thereby avoiding costly problems during and after project completion.

Urban forest managers typically alter the structure of the forest through single-tree management on public land only. However, this need not be a barrier to the use of a holistic ecosystem based management approach. Using the theory of vegetation dynamics developed by Pickett el al. (1987a,b), Zipperer (2008) demonstrates how managers may take a holistic approach through single-tree management. Three major drivers and explanatory categories for successional change are presented: site availability; species availability; and species performance (Figure 1). A non-exhaustive list of the factors that affect each these three variables is provided. By considering this hierarchy of factors in the management decisions made at the single-tree level, managers can better understand and direct urban forest change at a landscape level.

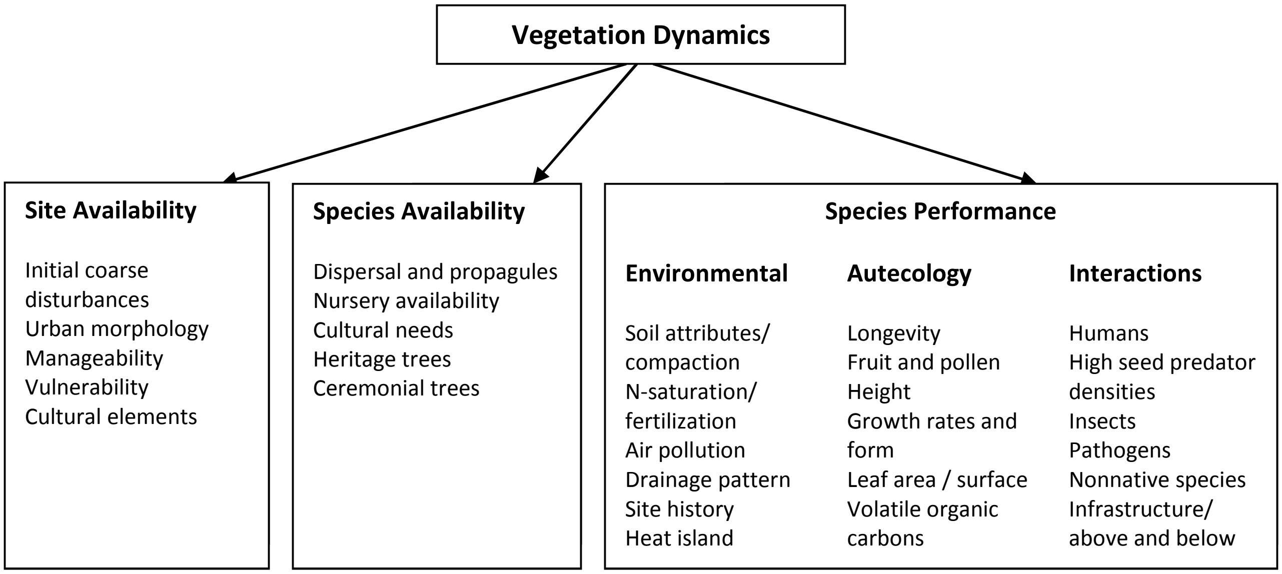

Figure 2: Theory of vegetation dynamics modified for application of ecosystem management in urban landscapes by incorporating elements of the urban ecosystem in the management-decision process (Zipperer, 2008).

In light of two observations, 1) urban environments are extremely heterogeneous in space and dynamic in time, and 2) areas containing urban trees and forest patches are often geographically fragmented, Wu (2008) argues that an urban forest may be most appropriately treated as a landscape that consists of a variety of changing and interacting patches of different shape, size, and history. Stated more explicitly, an urban forest is a dynamic patch mosaic system. The *urban landscape ecology approach* has been proposed by Wu (2008) in response to a growing awareness of the importance of considering spatial heterogeneity and its ecological consequences for understanding system processes. This approach emphasizes not only the diversity and interactions of the biological and socioeconomic components of a city, but also the spatial pattern of these elements and their ecological consequences from the scale of small patches to that of the entire urban landscape, and to the regional context in which the city resides (Pickett *et al.*, 1997; Zipperer *et al.*, 2000; Luck and Wu, 2002; Wu and David, 2002; Wu, 2008).

It is necessary to be able to assess progress relative to defined standards if sustainability is the ultimate landscape management goal. Recognizing this need, Clark *et al.* (1997) have developed a model of sustainability that provides a list of criteria and associated indicators for the evaluation of the following critical elements of urban forest management: the vegetation resource; community framework; and resource management approaches. Kenney *et al.* (2011) revised this model further to produce a more detailed set of criteria and measurable indicators. This revised model has been used in the Urban Forest Strategic Management Plan for the Town of Oakville to assess the Town's progress towards sustainability. Carreiro and Zipperer (2008) argue that the construction of urban sustainability indices and the valuation of ecosystem services will be critical particularly in the short-term, if we are to prevent undesirable trajectories and gauge the efficacy of collective actions in creating more ecologically sound cities.

Threats to the Urban Forest

Climate Change

Human activities occurring in the industrialized era, such as fossil fuel combustion, agricultural practices, land use change and deforestation, have released large quantities of heat trapping greenhouse gases into the atmosphere over a short period of time. As a consequence, the rising atmospheric greenhouse gas concentrations have been correlated with increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising sea levels (IPCC, 2007). Such climatic changes have had, and will continue to have, disastrous outcomes for the global biosphere.

Climate change is projected to impact the forests of Ontario by altering the frequency, intensity, duration, and timing of fire, drought, and insect and pathogen outbreaks (Dale *et al.*, 2001). In many areas, higher temperatures will alter moisture regimes and lead to increased drought stress for trees in urban settings; urban heat island effects are likely to magnify these stresses (Arnfield, 2003). Even a small rise in temperature during the growing season could increase evaporative demand, triggering drought stress (Dale *et al.*, 2001). In the Great Lakes basin soil moisture may decrease by as much as 30 percent in the summer and fall (de Loë and Berg, 2006). In areas where drought is not observed, rising levels of carbon dioxide may lead to increased water-use efficiency in trees, and consequently increased tree growth. Higher temperatures may also increase rates of photosynthesis and extend the growing season (Zhou *et al.*, 2001).

Extreme precipitation events in Southern Ontario are projected to increase in both frequency and intensity under future climate change scenarios (Hengeveld and Whitewood, 2005). Consequently, increased branch failure caused by ice storms and high winds will lead to higher rates of tree mortality. Furthermore, erosion associated with flooding following heavy rain and rapid snow melt will expose roots to pathogenic fungi and will weaken tree stability.

Warmer annual temperatures will provide less control over many insect populations, many of which are kept at low levels by cold winter temperatures (Volney and Fleming, 2000). The seasonal development of many insects such as the spruce budworm (*Choristoneura spp*) or forest tent caterpillar (*Malacosoma disstria*) will likely be accelerated and extended as climate change continues (Fleming and Volney, 1995; Cerezke and Volney, 1995). Stress caused by drought, heat and air pollution will, in turn, increase the susceptibility of urban trees to such insect pest outbreaks.

Changes in species composition in the urban forest may also be observed as a consequence of altered climatic conditions. For example, certain generalist species that tolerate a wide range of conditions and have several means of reproduction, such as poplar species, may prevail over those species that have narrow ecological tolerances (Thompson *et al.*, 1998). Drought tolerant species will likely possess a greater adaptive capacity, while populations of structurally weak species that are susceptible to ice damage may decline. In addition, northward migration of species as a result of shifting population ranges will create opportunities for increased planting of Carolinian species, while a loss of species at the southern edge of their present natural range may also be observed. For example, research suggests that species found in the oak-hickory forests of the central United States may migrate into what is currently the Great Lakes-St. Lawrence forest (Colombo *et al.*, 1998). However, differing migration rates and the reactions of individual species to new environmental conditions (e.g. modified soil moisture levels) could result in new species mixes for which inadequate forest management experience exists.

Malcolm *et al.* (2008) modeled current and future tree species distribution in the Credit River Watershed under projected climate change scenarios. The results showed a clear north – south pattern in potential tree community change, understood as a temperature analog perspective. Thus, under a moderate warming scenario the habitat conditions observed in the south of the watershed could be expected to shift into the north of the watershed. More specifically, under an A2 emissions scenario tree communities in the watershed would likely approximate those of Kentucky or northern Georgia in 2095 (depending on the model used).[30] However, the authors state that it is unlikely that these tree species will achieve the rates of northward migration necessary to accompany the rapidly shifting habitat conditions. Rather, the more probable outcome for the Credit River Watershed will be decreased species diversity, lower forest biomass, and a "weedier" (early successional) set of taxa.

The uncertainty associated with climate change highlights the need for decisions that emphasize ecological processes, rather than those based solely on structure and composition (Harris *et al.*, 2006). Millar *et al.* (2007) note that attempts to use historical ecosystem conditions as management targets may lead to the development of forests that are ill adapted to current conditions and more susceptible to undesirable changes. Thus, new management options must be considered.

Urbanization and Development Pressure

Population growth and the ensuing urbanization have transformed natural landscapes throughout the world and have contributed to the current crisis of biodiversity loss and deterioration of ecosystem services (Wu, 2008). The global urban population is growing three times faster than the rural population (Nilsson *et al.*, 1999). This trend is consistent with growth patterns in Canada. As of 2006, 80% of Canadian citizens lived in urban areas (Statistics Canada, 2008). The ecological footprints of growing Canadian cities are also increasing in size due to the demands for resources and the regional impacts of waste and emissions on soil, air, and water.

In southern Ontario, agriculture and urbanization have led to the conversion of presettlement forest cover and the subsequent loss of ecosystem services. The extent of such land use conversion in the southern areas of the Region is demonstrated in Table 1, which summarizes the amount of forest cover remaining in the Region as characterized in the *Peel – Caledon Significant Woodlands and Significant Habitat Wildlife Habitat Study* (North-South Environmental Inc. *et al.* 2009).

Table 1: Forest cover (all woodlands > 0.5ha) for municipalities in the Region of Peel (North-South Environmental Inc. *et al.*, 2009)

Municipality	Forest Cover in Each Municipality	Contribution to Regional Forest Cover (%)	Number of Forest Patches	Mean Patch Size
Peel	25,867 (20.6%)	100%	1,127	23.0
Caledon	21,954 (31.5 %)	84.9%	624	35.2
Brampton	1,972 (7.3%)	7.6%	251	7.7
Mississauga	1,940 (6.7%)	7.5%	263	7.4

[30] The A2 emissions scenario projects an estimated 3.4°C (range = 2.4 to 5.0°C) temperature increase by the end of the 21st century, relative to average temperatures recorded at the end of the 20th century.

If urban planning efforts fail to adequately include greenspace conservation, a community may see increased public costs for social and ecosystem services, increased public costs for disaster remediation, decreased community image and moral, lower property values, and increased public anxiety (Wilkinson, 1991). Moreover, a failure to incorporate greenspace conservation and urban forest management into community development early on will only amplify the complexities and costs of later efforts as land values increase concurrently with competition for land purchase (Elmendorh and Luloff, 1999).

Air Pollution

Air pollution contributes directly to urban forest degradation by inducing changes in tree condition, tree physiology, and biogeochemical cycling and by lowering tree resistance to insects and disease (Percy, 2002). Matyssek *et al.* (1992) found premature leaf discoloration and abscission in European white birch (*Betula pendula)* that were exposed to relatively low concentrations of ozone during the growing season. In addition, susceptibility to drought may also be increased by ozone and other gaseous pollutants. Evidence also suggests that air pollution can predispose some tree species to low temperature injury by reducing frost hardiness (Chappelka and Freer-Smith, 1995).

Air pollutants can have a more subtle effect on tree health by inducing changes to the reproductive success of particular genotypes or species. For example, acidic precipitation was shown to negatively affect the germination of pollen of a variety of species (Van Ryn *et al.*, 1986). Similarly, Scholz *et al.* (1985) and O'Connor *et al.* (1987) found that pollen germination in some species could be inhibited by sulphur dioxide.

Urban Forest Pests and Disease

Exotic insect pests pose a serious threat to the health of urban forests as no natural controls have developed to regulate these non-native species. Consequently, infestations commonly result in a substantial loss of canopy cover and associated ecosystem services, an increase in municipal maintenance costs, a loss of species diversity, and a shift to earlier age class distribution. Two exotic insect pests are of particular concern in this region: the emerald ash borer (*Agrilus planipennis*) and the Asian long-horned beetle (*Anoplophora glabripennis*).

The emerald ash borer (EAB) is an invasive beetle that attacks and kills all species of ash (genus: *Fraxinus*). The larvae tunnel beneath the bark and feed on the cambium, disrupting the flow of water and nutrients within the tree. The beetle was first identified in Michigan in 2002 and quickly became well established throughout much of Essex County and Chatham-Kent. Most recently the beetle has been detected in Mississauga, Oakville, Toronto, Pickering, Sault Ste Marie, and Ottawa. Ash species are very common in many urban forests of southern Ontario as they are tolerant of harsh urban conditions. The loss of existing ash trees will therefore translate to a significant loss of total canopy cover and associated services.

The Asian long-horned beetle (ALHB) is also an invasive beetle, native to eastern Asia. This exotic beetle attacks multiple hardwood species native to Canada. In particular, maple species (genus: *Acer*) are a preferred host tree. The beetle also attacks the following genera: horsechestnut (*Aesculus spp*), elm (*Ulmus spp*), birch (*Betula spp*), poplar (*Populus spp*), willow (*Salix spp*), mountain-ash (*Sorbus spp)* and common hackberry (*Celtic occidentalis*). The ALHB's presence in Canada was first detected in 2003 in an industrial area on the Toronto – Vaughan boundary. The Canadian Food Inspection Agency has launched an aggressive campaign to contain the infestation. The area is now regulated to prevent further spread.

Invasive Plant Species

Invasive plants are harmful non-native species whose introduction or spread threatens the environment, economy, and society, including human health. Such species reproduce aggressively and subsequently displace native vegetation, impede the natural regeneration of forest tree species, modify habitat, hybridize with other native species, and ultimately threaten biodiversity (Simberloff *et al.*, 1997). The agricultural and urban areas of temperate regions are among the most invaded biomes in the world (Lonsdale, 1999). Particularly persistent invasive species in the Greater Toronto Area include common and glossy buckthorn (*Rhamnus cathartica, R. frangula*), dog-strangling vine / swallowwart (*Cynanchum louiseae [Vincetoxicum nigram], C. rossicum*), garlic mustard (*Alliara petiolata*), and Norway maple (*Acer platanoides*).

Invasive plant species have few natural controls that prevent establishment. For example, Jogesh *et al.* (2008) found that several highly invasive plants common in the Ottawa region were more resistant to generalist herbivores, suggesting that these plants possess resistance traits to which native North American herbivores are poorly pre-adapted. Similarly, Cappuccino and Carpenter (2005) determined that nine common invasive plants found in Ontario, New York and Massachusetts experienced, on average, 96 percent less damage due to herbivory than non-invasive plant species.

In response to the serious threat to local biodiversity posed by invasive plants, coordinated efforts for early detection and rapid response are now underway at the municipal, provincial, and federal scale. Vital to the success of these efforts will be the prevention of new introductions. Within the urban forest many invasive species are horticultural plants that have escaped from residential gardens into adjacent natural systems. Thus, the utilization of non-invasive native species in urban gardens and yards will play an important role in invasive species management programs.

Additional Urban Forest Stressors

Urban forests are exposed to a host of additional biotic and abiotic stressors. Often multiple stressors combine to reduce a tree's vigour and increase vulnerability to additional problems. Moisture deficiency or excess are extremely common causes of urban tree decline. Soil saturation due to flooding or over-watering can decrease oxygen availability and lead to root suffocation (Iowa State University, 2008). Numerous factors may lead to soil-moisture-related drought stress, including restricted soil volumes, reduced rainfall infiltration, and soil compaction. Moisture stress can limit tree growth and reduce survival through direct and indirect effects on an array of physiological processes including photosynthesis (Cregg, 1995), respiration, protein synthesis, and secondary carbohydrate metabolism (Kramer, 1987). Moreover, reduced tree vigour caused by moisture stress may predispose trees to additional health problems including insect infestation (Mattson and Haack, 1987). Chemical injury caused by exposure to herbicides, insecticides, fungicides, and de-icing salts is also a common cause of urban tree decline (Fluckiger and Braun, 1981).

References

Ames, B. and S. Dewald. 2003. Working proactively with developers to preserve urban trees. Cities 20:95–100.

Anderson, L.M. and H.K. Cordell. 1988. Residential property values improved by landscaping with trees. Southern Journal of Applied Forestry 9: 162-166.

Arnfield, A.J. 2003. Two decades of urban climate research: a review of turbulence, exchanges of energy and water, and the urban heat island. International Journal of Climatology 23:1-26.

Aylor, D.E. 1972. Noise reduction by vegetation and ground. Journal of Acoust. Soc. Am. 51(1):197-205.

Beckett, P.K., Freer-Smith, P.H., and G. Taylor. 2000a. Particulate pollution capture by urban trees: Effect of species and windspeed. Global Change Biology 6(8): 995-1003.

Beckett, P.K., 2000b. Effective tree species for local air quality management. Journal of Arboriculture 26(1): 12-19.

Bonds, M.H. and J. Pompe. 2003. Calculating wetland mitigation banking credits; adjusting for function and location. *Natural Resources Journal* 43(4): 961-977.

California Climate Action Registry. 2008. Urban Forest Project Reporting Protocol. Version 1.0.

Cappuccino, N. and D. Carpenter. 2005. Invasive exotic plants suffer less herbivory than non invasive exotic plants. Biology Letters v.1 (4): 435–438.

Cardelino,C.A. and W.L. Chameides. 1990. Natural hydrocarbons, urbanization, and urban ozone. Journal of Geophysical Research 95(D9):13,971-13,979.

Carreiro, M.M. and W.C. Zipperer. 2008. Urban forestry and the eco-city: Today and tomorrow. In Ecology, Planning, and Management of Urban Forests: International Perspectives. M.M. Carreiro *et al.* (eds). Springer.

Castelle, A.J., A.W. Johnson, and C. Conolly. 1994. Wetlands and Stream Buffer Size Requirements: A Review. Journal of Environmental Quality 23: 878-882.

Cerezke, H.F. and W.J.A Volney. 1995. Forest insect pests in the Northwest region. In *Forest Insect Pests in Canada* (J.A. Armstrong and W.G.H. Ives, ed.). Canadian Forest Service, Science and Sustainable Development Directorate, Ottawa.

Chappelka, A.H., and P.H. Freer-Smith. 1995. Predisposition of trees by air pollutants to low temperatures and moisture stress. Environ. Pollut. 87: 105.117.

Clark, J.R., Methany, N. P., Cross, G. and V. Wake. 1997. A model of urban forest sustainability. Journal of Arboriculture 23(1): 17-30.

Climate Action Reserve. 2010. http://www.climateactionreserve.org/.

Colombo, S.J., M.L. Cherry, C. Graham, S. Greifenhagen, R.S. McAlpine, C.S. Papadopol, W.C. Parker, T. Scarr, M.T. Ter-Mikaelian and M.D. Flannigan. 1998. The impacts of climate change on Ontario's forests. Forest research information paper No. 143. Ontario Forest Research Institute.

Conway, T.M., and J. Hackworth. 2007. Urban pattern and land cover variation. The Canadian Geographer 51 (1): 43–57.

Cook, D.L. 1978. Trees, solid barriers, and combinations: Alternatives for noise control. In *Proceedings of the National Urban Forestry Conference* (G. Hopkins, ed.) SUNY College of Environmental Science and Forestry, Syracuse, NY, pp:330-339.

Cregg, B.M. 1995. Plant moisture stress of green ash trees in contrasting urban sites. J. Arboric. 2:271–276.

Cuperus, R., K.J. Canters, and A.A.G Piepers. Ecological compensation of the impacts of a road. Preliminary method for the A50 road link. Ecological Engineering Volume 7(4): 327-349.

Dale, V.H., Joyce, L.A., McNulty, S., Neilson, R.P., Ayres, M.P., Flannigan, M.D., Hanson, P.J., Irland, L.C., Lugo, A.E., Peterson, C.J., Simberloff, D., Swanson, F. J., Stocks, B.J., and M. Wotton. 2001. Climate change and forest disturbances. BioScience. 51(9): 723-734.

De Groot, R.S., M.A. Wilson, and R.M.J. Boumans. 2002. A typology for the classification, description and valuation of ecosystem functions, goods and services. Ecological Economics 41: 393–408.

De Loë R. and A.A Berg. 2006. Mainstreaming climate change in drinking water source protection in planning in Ontario. White paper prepared for the Canadian Water Resources Association and Pollution Probe. 42 Pages.

Dombrow, J. M. R. and C.F. Sirmans. 2000. The market value of mature trees in single-family housing markets. The Appraisal Journal 68: 39-43.

Elmendorf, W.F. and A.E. Luloff. 1999. Using ecosystem-based and traditional land-use planning to conserve greenspace. Journal of Arboriculture 25(5):264-273.

Endreny, T.A., 2005. Land Use and Land Cover Effects on Runoff Processes: Urban and Suburban Development. In: Encyclopedia of Hydrological Sciences, M.G. Anderson (Editor). Wiley, Chichester, United Kingdom, pp. 1775-1804.

Fleming, R.A. and W.J.A.Volney. 1995. Effects of climate change on insect defoliator population processes in Canada's boreal forest: some plausible scenarios. Water, Air, Soil Poll. 82: 445-454.

Fluckiger, W., and S. Braun. 1981. Perspectives of reducing the deleterious effect of de-icing salt upon vegetation. Plant Soil. 63:527529.

Fraser, E.D.G, and W.A. Kenney. 2000. Cultural background and landscape history as factors affecting perceptions of the urban forest. Journal of Arboriculture 26(2):106-113.

Fung, T., Sui, W., 2000. Environmental quality and its changes, an analysis using NDVI. International Journal of Remote Sensing 21, 1011–1024.

Guenther, A., Zimmerman, P., and M Wildermuth. 1994. Natural volatile organic compound emission rate estimates for U.S. woodland landscapes. Atmos. Environ. 28(6):1197-1210.

Harris, J. A., R. J. Hobbs, E. Higgs, and J. Aronson. 2006. Ecological restoration and global climate change. Restoration Ecology 14:170–176.

Heisler, G.M. 1986. Energy savings with trees. Journal of Arboriculture 12(5):113-125.

Hengeveld, H. and B. Whitewood. 2005. Understanding climate change — 2005; Environment Canada, Meteorological Service of Canada, 57 p.

Heynen, N.C., and G. Lindsay. 2003. Correlates of urban forest canopy cover: implications for local public works. Public Works Management and Policy 8 (1), 33–47.

Heynen, N., Perkins, H.A., and P. Roy. 2006. The political ecology of uneven green space: the impact of political economy on race and ethnicity in producing environmental inequality in Milwaukee. Urban Affairs Review 42 (1): 3–25.

Hope, D., Gies, C., Zhu, W., Fagab, W.F., Redman, C.L., Grimm, N.B., Nelson, A.L., Martin, C., and A Kinzig. 2003. Socioeconomics drive urban plant diversity. Proceedings of the National Academy of Science 100 (15), 8788–8792.

IPCC. 2007. Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland, 104 pp.

Iowa State University. 2008. Understanding decline in trees. Extension f**ile: Forestry 2, Pest Management 5. Retrieved from:** http://www.extension.iastate.edu/Publications/SUL2.pdf.

Iverson, L.R., and E.A. Cook. 2000. Urban forest cover of the Chicago region and its relation to household density and income. Urban Ecosystems 4: 105–124.

Kenney, W.A., van Wassenaer, P.J.E., A.L. Satel. 2011. Criteria and Indicators for Strategic Urban Forest Planning and Management. Arboriculture & Urban Forestry 2011. 37(3): 108–117.

Kollin, C. 2006. How green infrastructure measures up to structural stormwater service: Quantifying the contribution of trees and vegetation. Stormwater 7(5).

Kramer, P.J. 1987. The role of water stress in tree growth. J. Arboric. 13:33–38.

Kuo, F. and W. Sullivan. 2001. Environment and crime in the inner city: Does vegetation reduce crime? Environment and Behavior 33(3): 343-367.

Kuna-Dibbert, B. and M. Krzyzanowski. 2005. Health risk assessment of transport-related air pollultion. In *Health effects of transport-related air pollution*. (M. Krzyzanowski, ed.). World Health Organization.

Larcher, W. 1980. Physiological plant ecology. Springer-Verlag,Berlin, 303 p.

Lonsdale, W.M. (1999) Global patterns of Plants Invasions and the concept of invasibility. Ecology 80(5): 1522–1536.

Luck, M., and J. Wu. 2002. A gradient analysis of urban landscape pattern: A case study from the Phoenix metropolitan region, Arizona, USA. Landscape Ecology 17:327–339.

Martin, C.A., Warren, P.S., and A.P. 2004. Neighborhood socioeconomic status is a useful predictor of perennial landscape vegetation in residential neighborhoods and embedded small parks of Phoenix, AZ. Landscape and Urban Planning 69: 355–368.

Mattson, W.J., and R.A. Haack 1987. The role of drought in outbreaks of plant-eating insects. BioScience 37:110-118.

Matyssek, R., Günthardt-Goerg, M.S., Saurer, M., and T. Keller. 1992. Seasonal growth in leaves and stem, and phloem structure of birch (*Betula pendula*) under low ozone concentrations. Trees 6: 96–76.

Millar, C., Stephenson, N.L., and S.L. Stephens. 2007. Climate change and forests of the future: Managing in the face of uncertainty. Ecological Applications, 17(8): 2145–2151.

McPherson, E.G., and J. Muchnick. 2005. Effects of street tree shade on asphalt concrete pavement performance. Journal of Arboriculture 31(6):303-310.

Mok, J.-H., H.C. Landphair, and J.R. Naderi. 2006. Landscape Improvement Impacts on Roadside Safety in Texas. *Landscape and Urban Planning* 78:263-274.

Naderi, J.R. 2003. Landscape Design in the Clear Zone: Effect of Landscape Variables on Pedestrian Health and Driver Safety. *Transportation Research Record* 1851:119-130.

Nilsson, K., Konijnendijk, C.D., and T.B. Randrup. 1999. Urban forestry: Where people meet trees. In: Proceedings of International Conference on Community Forestry, December 7–8, 1999, London. http://www.communityforest.org.uk/tpsn.html.

Nowak, D.J. 1993. Historical vegetation change in Oakland and its implications for urban forest management. Journal of Arboriculture 9(15):313-319.

Nowak, D.J., D.E. Crane, and J.C. Stevens. 2006. Air pollution removal by urban trees and shrubs in the United States. Urban Forestry & Urban Greening 4.

O'Connor, C.J., Ashford, K.P. and D.J. Spedding. 1987. Germination and metabolism of *Pinus radiata* pollen in the presence of sulphur dioxide. J. Plant Physiol. 126: 373-8.

Osborne, L.L. and D.A. Kovacic. 1993. Riparian Vegetated Buffer Strips in Water-Quality Restoration and Stream Management. Freshwater Biology 29:243-258.

Parsons, R., L.G. Tassinary, R.S. Ulrich, M.R. Hebl, and M. Grossman-Alexander. 1998. The View From the Road: Implications for Stress Recovery and Immunization. *Journal of Environmental Psychology* 18, 2:113–140.

Pembina Institute and Credit Valley Conservation. 2009. Natural Credit: Estimating the Value of Natural Capital in the Credit River Watershed.

Percy, K.E., 2002. Is air pollution an important factor in forest health? pp. 23-42 In: R.C. Szaro, A. Bytnerowicz and J. Oszlanyi (Eds.), Effects of Air Pollution on Forest Health and Biodiversity in Forests of the Carpathian Mountains, IOS Press, Amsterdam

Perkins, H.A., Heynen, N., Wilson, J., 2004. Inequitable access to urban reforestation: the impact of urban political economy on housing tenure and urban forests. Cities 21 (4): 291–299.

Pickett, S.T.A., Collins, S.C., and J.J.Armesto. 1987a. A hierarchical consideration of causes and mechanisms of succession. Vegetatio 69:109–114.

Pickett, S.T.A., Collins, S.C., and J.J. Armesto. 1987b. Models, mechanisms and pathways of succession. Botanical Review 53:335–371.

Pickett, S.T.A., Burch, W.R., Jr., Dalton, S.E., Foresman, T.W., Grove, J.M., and R.A.Rowntree. 1997. A conceptual framework for the study of human ecosystems in urban areas. Urban Ecosystems 1:185–201.

Riley, A.L. 1998. Restoring Streams in Cities: A Guide for Planners Policymakers and Citizens. Island Press, Washington, D.C.

Rowntree, R.A. 1984. Ecology of the urban forest- Introduction to Part I. Urban Ecology 8(1/2):1-11.

Sanders, R.A. 1984. Urban vegetation impacts on the urban hydrology of Dayton Ohio, Urban Ecology 9:361-376.

Scott, K.I.,Simpson, J.R., and E.G. McPherson. 1999. Effects of tree cover on parking lot microclimate and vehicle emissions. Journal of Arboriculture 25(3):129-142.

Schaefer, R. R. 1996. Red-cockaded Woodpecker reproduction and provisioning of nestlings in relation to habitat. M.Sc. Thesis. Stephen F. Austin State University, Nacogdoches, TX. 78. pp.

Simberloff, D. with D.R. Towns and I.A.E. Atkinson. 1997. Restoration of New Zealand islands: Redressing the effects of introduced species. Pacific Conservation Biology 3:99-124.

Simpson, J.R. and E.G. McPherson. 1996. Potential of tree shade for reducing residential energy use in California. Journal of Arboriculture 22(1):10-18.

Simpson, J.R. and E.G. McPherson. 2000. Effects of urban trees on regional energy use and avoided carbon. In Preprints, 3rd urban environment symposium; 2000 August 14-18; Davis, CA. Washington, DC: American Meteorological Society:143-144.

Smith, W.H. 1990. Air pollution and forests, Springer-Verlag. New York.

Statistics Canada. 2009. 2006 Community Profiles: Ajax. Last modified: 2009-03-10.

Taha, H. 1996. Modeling the impacts of increased urban vegetation on the ozone air quality in the south coast air basin. Atmospheric Environment 30(20): 3423-3430.

Thompson, I.D., M.D. Flannigan, B. M. Wotton and R. Suffling. 1998. The effects of climate change on landscape diversity: An example in Ontario forests. Environmental Monitoring and Assessment 49: 213-233.

Ulrich, R. 1984. View through window may influence recovery from surgery. Science 224: 420-421.

Volney, W.J.A. and R.A. Fleming. 2000. Climate change and impacts of boreal forest insects. Agriculture, Ecosystems and Environment 82:283-294.

Wilkinson, K. 1991. *The Community in Rural America*. New York, NY: Greenwood Press

Wolf, K.L. 1999. Nature and commerce: Human ecology in business districts. In *Building Cities of Green* (C. Kollin, ed): Proceedings of the 9th National Urban Forest Conference. Washington, D.C: American Forests.

Wu. J. 2008. Toward and landscape ecology of cities: Beyond buildings, trees, and urban forests. In *Ecology, Planning, and Management of Urban Forests: International Perspectives*. M.M. Carreiro *et al.* (eds). Springer.

Wu, J., and J.L. David. 2002. A spatially explicit hierarchical approach to modeling complex ecological systems: theory and applications. Ecological Modeling 153:7–26.

Zerbe, J.I. 2006. Thermal Energy, Electricity, and Transportation Fuels from Wood. Forest Products Journal. 56 (1).

Zipperer, W.C. 2008. Applying ecosystem management to urban forestry. In *Ecology, Planning, and Management of Urban Forests: International Perspectives.* M.M. Carreiro *et al.* (eds). Springer.

Zipperer, W.C., Wu, J., Pouyat, R.V., and S.T.A Pickett. 2000. The application of ecological principles to urban and urbanizing landscapes. Ecological Applications 10:685–688.

Appendix B: Land Use Categories

MPAC Code	Description
	OPEN SPACE
103	Municipal park
490	Golf Course
702	Cemetery
491	Ski Resort
382	Mobile home park – more than one mobile home on a parcel of land, which is a mobile park operation.
486	Campground
109	Large land holdings, greater than 1000 acres
703	Cemetery with non-internment services
	RESIDENTIAL LOW
301	Single family detached (not on water)
302	More than one structure used for residential purposes with at least one of the structures occupied permanently
303	Residence with a commercial unit
304	Residence with a commercial/ industrial use building
305	Link home – are homes linked together at the footing or foundation by a wall above or below grade.
307	Community lifestyle (not a mobile home park) – Typically, a gated community under single ownership.
309	Freehold Townhouse/Row house – more than two units in a row with separate ownership
311	Semi-detached residential – two residential homes sharing a common center wall with separate ownership.
313	Single family detached on water – year round residence
314	Clergy Residence
322	Semi-detached residence with both units under one ownership – two residential homes sharing a common center wall.
332	Typically a Duplex – residential structure with two self-contained units.
363	House-keeping cottages - no American plan – typically a mini resort where you rent a cabin. No package plan available. All activities, meals, etc. are extra.
364	House-keeping cottages - less than 50% American plan – typically a mini resort where you rent a cabin and package plans are available. Activities, meals, etc. maybe included.
365	Group Home as defined in Claus 240(1) of the Municipal Act, 2001 – a residence licensed or funded under a federal or provincial statute for the accommodation of three to ten persons, exclusive of staff, living under supervision in a single housekeeping unit and who, by reason of their emotional, mental, social or physical condition or legal status, require a group living arrangement for their well being.
366	Student housing (off campus) – residential property licensed for rental by students.
381	Mobile home – one or more mobile home on a parcel of land, which is not a mobile home park operation.
382	Mobile home park – more than one mobile home on a parcel of land, which is a mobile park operation.
383	Bed and breakfast establishment
	RESIDENTIAL MEDIUM
127	Townhouse block - freehold units
350	Row housing, with three to six units under single ownership
352	Row housing, with seven or more units under single ownership
333	Residential property with three self-contained units
334	Residential property with four self-contained units
335	Residential property with five self-contained units

336	Residential property with six self-contained units
360	Rooming or boarding house – rental by room/bedroom , tenant(s) share a kitchen, bathroom and living quarters.
361	Bachelorette, typically a converted house with 7 or more self-contained units
373	Cooperative housing – equity – Equity Co-op corporations are owned by shareholders. The owners of shares do not receive title to a unit in the building, but acquire the exclusive use of a unit and are able to participate in the building's management.
	RESIDENTIAL HIGH
340	Multi-residential, with 7 or more self-contained units (excludes row-housing)
370	Residential Condominium Unit
341	Multi-residential, with 7 or more self-contained residential units, with small commercial unit(s)
378	Residential Leasehold Condominium Corporation – single ownership of the development where the units are leased.
	Commercial
400	Small Office building (generally single tenant or owner occupied under 7,500 s.f.)
401	Large office building (generally multi - tenanted, over 7,500 s.f.)
402	Small Medical/dental building (generally single tenant or owner occupied under 7,500 s.f.)
403	Large medical/dental building (generally multi - tenanted over 7,500 s.f.)
405	Office use converted from house
406	Retail use converted from house
407	Retail lumber yard
408	Freestanding Beer Store or LCBO - not associated with power or shopping centre
409	Retail - one storey, generally over 10,000 s.f.
410	Retail - one storey, generally under 10,000 s.f.
411	Restaurant - conventional
412	Restaurant - fast food
413	Restaurant - conventional, national chain
414	Restaurant - fast food, national chain
415	Cinema/movie house/drive-in
416	Concert hall/live theatre
417	Entertainment complex - with a large cinema as anchor tenant
419	Automotive service centre, highway - 400 series highways
420	Automotive fuel station with or without service facilities
421	Specialty automotive shop/auto repair/ collision service/car or truck wash
422	Auto dealership
423	Auto dealership - independent dealer or used vehicles
425	Neighbourhood shopping centre - with more than two stores attached, under one ownership, with anchor - generally less than 150,000 s.f.
426	Small box shopping centre less than 100,000 s.f. minimum 3 box stores with one anchor (large grocery or discount store)
427	Big box shopping/power centre greater than 100,000 s.f. with 2 or more main anchors such as discount or grocery stores with a collection of box or strip stores and in a commercial concentration concept
428	Regional shopping centre
429	Community shopping centre
430	Neighbourhood shopping centre - with more than 2 stores attached, under one ownership, without anchor - generally less than 150,000 s.f.

431	Department store
432	Banks and similar financial institutions, including credit unions - typically single tenanted, generally less than 7,500 s.f.
433	Banks and similar financial institutions, including credit unions - typically multi tenanted, generally greater than 7,500 s.f.
434	Freestanding supermarket
435	Large retail building centre, generally greater than 30,000 s.f.
436	Freestanding large retail store, national chain - generally greater than 30,000 s.f.
438	Neighbourhood shopping centre with offices above
441	Tavern/public house/small hotel
444	Full service hotel
445	Limited service hotel
446	Apartment hotel
447	Condominium Hotel Unit
450	Motel
451	Seasonal motel
460	Resort hotel
461	Resort lodge
462	Country inns & small inns
463	Fishing/hunting lodges/resorts
465	Child and community oriented camp/resort
470	Multi-type complex - defined as a large multi-use complex consisting of retail/office and other uses (multi res/condominium/hotel)
471	Retail or office with residential unit(s) above or behind - less than 10,000 s.f. gross building area (GBA), street or onsite parking, with 6 or less apartments, older downtown core
472	Retail or office with residential unit(s) above or behind - greater than 10,000 s.f. GBA, street or onsite parking, with 7 or more apartments, older downtown core
473	Retail with more than one non-retail use
475	Commercial condominium
476	Commercial condominium (live/work)
477	Retail with office(s) - less than 10,000 s.f., GBA with offices above
478	Retail with office(s) - greater than 10,000 s.f., GBA with offices above
480	Surface parking lot - excludes parking facilities that are used in conjunction with another property
481	Parking garage - excludes parking facilities that are used in conjunction with another property
482	Surface parking lot - used in conjunction with another property
483	Parking garage - used in conjunction with another property
705	Funeral Home
711	Bowling alley
713	Casino
704	Crematorium
105	Vacant commercial land
	UTILITIES AND TRANSPORTATION
496	Communication buildings
555	O.P.G. Hydraulic Generating Station
556	O.P.G. Nuclear Generating Station

557	O.P.G. Fossil Generating Station
558	Hydro One Transformer Station
559	MEU Generating Station
560	MEU Transformer Station
561	Hydro One Right-of-Way
562	Private Hydro Rights-of-Way
563	Private Hydraulic Generating Station
564	Private Nuclear Generating Station
565	Private Generating Station (Fossil Fuels and Cogen)
566	Private Transformer Station
567	Wind Turbine
741	Airport Authority
742	Public transportation - easements and rights
743	International bridge/tunnel
588	Pipelines - transmission, distribution, field & gathering and all other types including distribution connections
589	Compressor station - structures and turbines used in connection with transportation and distribution of gas
597	Railway right-of-way
598	Railway buildings and lands described as assessable in the Assessment Act
599	GO transit station/rail yard
737	Federal airport
738	Provincial airport
739	Local government airport
740	Airport leasehold
744	Private airport/hangar
745	Recreational airport
746	Subway station
748	Transit garage
749	Public transportation - other
755	Lighthouses
824	Government - wharves and harbours
826	Government - special educational facility
828	Government - canals and locks
830	Government - navigational facilities
832	Government - historic site or monument
840	Port authority - port activities
842	Port authority - other activities
495	Communication towers - with or without secondary communication structures
	INSTITUTIONAL
601	Post secondary education - university, community college, etc
602	Multiple occupancy educational institutional residence located on or off campus
605	School (elementary or secondary, including private)
608	Day Care
610	Other educational institution (e.g. schools for the blind, deaf, special education, training)

611	Other institutional residence
621	Hospital, private or public
623	Continuum of care seniors facility
624	Retirement/nursing home (combined)
625	Nursing home
626	Old age/retirement home
627	Other health care facility
630	Federal penitentiary or correctional facility
631	Provincial correctional facility
632	Other correctional facility
700	Place of worship - with a clergy residence
701	Place of Worship - without a clergy residence
730	Museum and/or art gallery
731	Library and/or literary institutions
733	Convention, conference, congress centre
734	Banquet hall
735	Assembly hall, community hall
736	Clubs - private, fraternal
750	Scientific, pharmaceutical, medical research facility (structures predominantly other than office)
760	Military base or camp (CFB)
761	Armoury
762	Military education facility
805	Post office or depot
806	Postal mechanical sorting facility
810	Fire Hall
812	Ambulance Station
815	Police Station
822	Government - agricultural research facility - predominantly non farm property (office building, laboratories)
	AGRICULTURE
200	Farm property without any buildings/structures
201	Farm with residence - with or without secondary structures; no farm outbuildings
210	Farm without residence - with secondary structures; with farm outbuildings
211	Farm with residence - with or without secondary structures; with farm outbuildings
220	Farm without residence - with commercial/industrial operation
221	Farm with residence - with commercial/industrial operation
222	Farm with a winery
223	Grain/seed and feed operation
224	Tobacco farm
225	Ginseng farm
226	Exotic farms i.e emu, ostrich, pheasant, bison, elk, deer
227	Nut Orchard
228	Farm with gravel pit
229	Farm with campground/mobile home park

230	Intensive farm operation - without residence
231	Intensive farm operation - with residence
232	Large scale greenhouse operation
233	Large scale swine operation
234	Large scale poultry operation
235	Government - agriculture research facility - predominately farm property
236	Farm with oil/gas well(s)
260	Vacant residential/commercial/ industrial land owned by a non-farmer with a portion being farmed
261	Land owned by a non-farmer improved with a non-farm residence with a portion being farmed
262	Land owned by a farmer improved with a non-farm residence with a portion being farmed
	NATURAL COVER
240	Managed forest property, vacant land not on water
241	Managed forest property, vacant land on water
242	Managed forest property, seasonal residence not on water
243	Managed forest property, seasonal residence on water
244	Managed forest property, residence not on water
245	Managed forest property, residence on water
107	Provincial park
108	Federal park
134	Land designated and zoned for open space
102	CA lands
	OTHER
120	Water lot (entirely under water)
492	Marina - located on waterfront - defined as a commercial facility for the maintenance, storage, service and/or sale of watercraft
493	Marina - not located on waterfront - defined as a commercial facility for the maintenance, storage, service and/or sale of watercraft
487	Billboard
111	Island under single ownership
385	Time-share, fee simple
386	Time share, right-to-use
391	Seasonal/recreational dwelling - first tier on water
392	Seasonal/recreational dwelling - second tier to water
395	Seasonal/recreational dwelling - not located on water
150	Mining lands - patented
151	Mining lands - unpatented
130	Non-buildable land (walkways, buffer/berm, storm water management pond,etc)
100	Vacant residential land not on water
101	Second tier vacant lot – refers to location not being directly on the water but one row back from the water
368	Residential Dockominium – owners receive a deed and title to the boat slip. Ownership is in fee simple title and includes submerged land and air rights associated with the slip. Similar to condominium properties, all common elements are detailed in the declaration.
306	Boathouse with residence above
110	Vacant residential/recreational land on water
140	Common land

375	Co-ownership – percentage interest/share in the co-operative housing.
371	Life Lease - No Redemption. Property where occupants have either no or limited redemption amounts. Typically Zero Balance or Declining Balance Life Lease Types.
372	Life Lease - Return on Invest. Property where occupants can receive either a guaranteed return or a market value based return on the investment. Typically, represented by Fixed Value, Indexed-Based, or Market Value Life Lease Types.
715	Race track, auto
716	Racetrack - horse, with slot facility
717	Racetrack - horse, without slot facility
718	Exhibition/fair grounds
720	Commercial sport complex
722	Professional sports complex
725	Amusement park
726	Amusement park - large/regional
710	Recreational sport club - non commercial (excludes golf clubs and ski resorts)
489	Driving range/golf centre - stand alone, not part of a regulation golf course
721	Non-commercial sports complex
112	Multi-residential vacant land
113	Condominium development land - residential (vacant lot)
114	Condominium development land - non residential (vacant lot)
115	Property in process of redevelopment utilizing existing structure(s)
125	Residential development land
379	Residential phased condominium corporation – condominium project is registered in phases.
369	Vacant land condominium (residential - improved) – condo plan registered against the land.
374	Cooperative housing - non-equity – Non-equity Co-op corporations are not owned by individual shareholders, the shares are often owned by groups such as unions or non-profit organizations which provide housing to the people they serve. The members who occupy the co-operative building do not hold equity in the corporation. Members are charged housing costs as a result of occupying a unit.
169	Vacant land condominium (residential)-defined land that's described by a condominium plan
377	Condominium parking space/unit – separately deeded.
376	Condominium locker unit – separately deeded.
380	Residential common elements condominium corporation – consists only of the common elements not units.

Appendix C: i-Tree Eco Model – Detailed Methodology

Adapted from: Nowak *et al.* 2008. A Ground-based Method of Assessing Urban Forest Structure and Ecosystem Services. Arboriculture and Urban Forestry. 34(6):347-358.

The i-tree Eco model uses a sampling procedure to estimate various measured structural attributes about the forest (e.g., species composition, number of trees, diameter distribution) within a known sampling error. The model uses the measured structural information to estimate other structural attributes (e.g., leaf area, tree and leaf biomass) and incorporates local environmental data to estimate several functional attributes (e.g., air pollution removal, carbon sequestration, building energy effects). Economic data from the literature is used to estimate the value of some of the functions. The model has 5 modules:

1: Urban Forest Structure

Urban forest structure is the spatial arrangement and characteristics of vegetation in relation to other objects (e.g., buildings) within urban areas (e.g., Nowak 1994a). This module quantifies urban forest structure (e.g., species composition, tree density, tree health, leaf area, leaf and tree biomass), value, diversity, and potential risk to pests.

Sampling

i-Tree Eco assessments have used two basic types of sampling to quantify urban forest structure: randomized grid and stratified random sampling. With the randomized grid sampling the study area is divided into equal-area grid cells based on the desired number of plots and then one plot is randomly located within each grid cell. The study area can then be subdivided into smaller units of analysis (i.e., strata) after the plots are distributed (post-stratification). Plot distribution among the strata will be proportional to the strata area. This random sampling approach allows for relatively easy assessment of changes through future measurements (urban forest monitoring), but likely at the cost of increased variance (uncertainty) of the population estimates.

With stratified random sampling, the study area is stratified prior to distributing the plots and plots are randomly distributed within each stratum (e.g., land use). This process allows the user to distribute the plots among the strata to potentially decrease the overall variance of the population estimate. For example, since tree effects are often the primary focus of sampling, the user can distribute more plots into strata that have more trees. The disadvantage of this approach is that it makes long-term change assessments more difficult due to the potential for strata to change through time.

There is no significant difference in cost or time to establish plots regardless of sampling methods for a fixed number of plots. However, there are likely differences in estimate precision. Prestratification, if done properly, can reduce overall variance as it can focus more plots in areas of higher variability. Any plot size can be used in i-Tree ECO, but the typical plot size used is 0.04 ha (0.1 ac). The number and size of plots will affect total cost of the data collection as well as the variance of the estimates (Nowak *et al.* 2008).

Data Collection Variables

There are four general types of data collected on a i-Tree ECO plot: 1) general plot information (Table 1) – used to identify the plot and its general characteristics, 2) shrub information (Table 2) - used to estimate shrub leaf area/biomass, pollution removal and volatile organic compound (VOC) emissions by shrubs, 3) tree information (Table 3) – used to estimate forest structural attributes, pollution removal, VOC emissions, carbon storage and sequestration, energy conservation effects, and potential pest impacts of trees, and 4) ground cover data - used to estimate the amount and distribution of various ground cover types in the study area.

Typically, shrubs are defined as woody material with a diameter at breast height (dbh; diameter of stem at height of 1.3m from ground) less than 2.54 cm, while trees have a dbh greater than or equal to 2.54 cm (1 in). Trees and shrubs can also be differentiated by species (i.e., certain species are always a tree or always a shrub), or with a different dbh minimum threshold. For example, in densely forested areas, increasing the minimum dbh to 12.7 cm (5 in.) can substantially reduce the field work by decreasing the number of trees measured, but less information on trees will be attained. Woody plants that are not 30.5 cm (12 in) in height are considered herbaceous cover (e.g., seedlings). Shrub masses within each plot are divided into groups of same species and size, and for each group, appropriate data are collected (Table 2). Tree variables (Table 3) are collected on every measured tree.

Field data are collected during the in-leaf season to help assess crown parameters and health. More detailed information on plot data collection methods and equipment can be found in the i-Tree User's Manual (i-Tree 2008).

Leaf area and leaf biomass

Leaf area and leaf biomass of individual open-grown trees (crown light exposure (CLE) of 4-5) are calculated using regression equations for deciduous urban species (Nowak 1996). If shading coefficients (percent light intensity intercepted by foliated tree crowns) used in the regression did not exist for an individual species, genus or hardwood averages are used. For deciduous trees that are too large to be used directly in the regression equation, average leaf-area index (LAI: m^2 leaf area per m^2 projected ground area of canopy) is calculated by the regression equation for the maximum tree size based on the appropriate height-width ratio and shading coefficient class of the tree. This LAI is applied to the ground area (m^2) projected by the tree's crown to calculate leaf area (m^2). For deciduous trees with height-to-width ratios that are too large or too small to be used directly in the regression equations, tree height or width is scaled downward to allow the crown to the reach maximum (2) or minimum (0.5) height-to-width ratio. Leaf area is calculated using the regression equation with the maximum or minimum ratio; leaf area is then scaled back proportionally to reach the original crown volume.

For conifer trees (excluding pines), average LAI per height-to-width ratio class for deciduous trees with a shading coefficient of 0.91 is applied to the tree's ground area to calculate leaf area. The 0.91 shading coefficient class is believed to be the best class to represent conifers as conifer forests typically have about 1.5 times more LAI than deciduous forests (Barbour *et al.* 1980) and 1.5 times the average shading coefficient for deciduous trees (0.83, see Nowak 1996) is equivalent to LAI of the 0.91 shading coefficient. Because pines have lower LAI than other conifers and LAI that are comparable to hardwoods (e.g., Jarvis and Leverenz 1983; Leverenz and Hinckley 1990), the average shading coefficient (0.83) is used to estimate pine leaf area.

Leaf biomass is calculated by converting leaf-area estimates using species-specific measurements of g leaf dry weight/m^2 of leaf area. Shrub leaf biomass is calculated as the product of the crown volume occupied by leaves (m^3) and measured leaf biomass factors ($g\ m^{-3}$) for individual species (e.g., Winer *et al.* 1983; Nowak 1991). Shrub leaf area is calculated by converting leaf biomass to leaf area based on measured species conversion ratios ($m^2\ g^{-1}$). Due to limitations in estimating shrub leaf area by the crown-volume approach, shrub leaf area is not allowed to exceed a LAI of 18. If there are no leaf-biomass-to-area or leaf-biomass-to-crown-volume conversion factors for an individual species, genus or hardwood/conifer averages are used.

For trees in more forest stand conditions (higher plant competition), leaf area index for more closed canopy positions (CLE = 0-1) is calculated using forest leaf area formula based on the Beer-Lambert Law:

$LAI = \ln(I/I_o)/-k$

where I = light intensity beneath canopy; I_o = light intensity above canopy; and k = light extinction coefficient (Smith *et al.* 1991). The light extinction coefficients are 0.52 for conifers and 0.65 for hardwoods (Jarvis and Leverenz, 1983). To estimate the tree leaf area (LA):

$$LA = [\ln((1-x_s)/-k\ ] \times \pi r^2$$

where x_s is average shading coefficient of the species and r is the crown radius. For CLE = 2-3: leaf area is calculated as the average of leaf area from the open-grown (CLE = 4-5) and closed canopy equations (CLE = 0-1).

Estimates of leaf area and leaf biomass are adjusted downward based on crown leaf dieback (tree condition). Trees are assigned to one of 7 condition classes: Excellent (< 1 dieback); Good (1-10 percent dieback); Fair (11-25 percent dieback); Poor (26-50 percent dieback); Critical (51-75 percent dieback); Dying (76-99); Dead (100 percent dieback). Condition ratings range between 1 indicating no dieback and 0 indicating 100-percent dieback (dead tree). Each class between excellent and dead is given a rating between 1 and 0 based on the mid-value of the class (e.g., fair = 11-25 percent dieback is given a rating of 0.82 or 82-percent healthy crown). Tree leaf area is multiplied by the tree condition factor to produce the final leaf area estimate.

Species Diversity

A species diversity index (Shannon-Wiener) and species richness (i.e., number of species) (e.g., Barbour 1980), are calculated for living trees for the entire city. The proportion of the tree population that originated from different parts of the country and world is calculated based on the native range of each species (e.g., Hough 1907; Grimm 1962; Platt 1968; Little 1971, 1976, 1977, 1978; Viereck and Little 1975; Preston 1976; Clark 1979; Burns and Honkala 1990a,b; Gleason and Cronquist 1991).

Structural Value

The structural value of the trees (Nowak *et al.*, 2002a) is based on methods from the Council of Tree and Landscape Appraisers (CTLA 1992). Compensatory value is based on four tree/site characteristics: trunk area (cross-sectional area at dbh), species, condition, and location. Trunk area and species are used to determine the basic value, which is then multiplied by condition and location ratings (0-1) to determine the final tree compensatory value. Local species factors, average replacement cost, and transplantable size and replacement prices are obtained from ISA publications. If no species data are available for the state, data from the nearest state are used. Condition factors are based on percent crown dieback. Available data required using location factors based on land use type (Int. Soc. of Arboric. 1988): golf course = 0.8; commercial/industrial, cemetery and institutional = 0.75; parks and residential = 0.6; transportation and forest = 0.5; agriculture = 0.4; vacant = 0.2; wetland = 0.1.

Insect Effects

The proportion of leaf area and live tree population, and estimated compensatory value in various susceptibility classes to gypsy moth (Liebhold *et al.,* 1995; Onstad *et al.*, 1997), Asian longhorned beetle (e.g., Nowak *et al.*, 2001) and emerald ash borer (ash species) are calculated to reveal potential urban forest damage associated with these pests.

2: Biogenic Emissions

Volatile organic compounds (VOCs) can contribute to the formation of O_3 and CO (e.g., Brasseur and Chatfield 1991). The amount of VOC emissions depends on tree species, leaf biomass, air temperature, and other environmental factors. This module estimates the hourly emission of isoprene (C_5H_8), monoterpenes (C_{10} terpenoids), and other volatile organic compounds (OVOC) by species for each land use and for the entire city. Species leaf biomass (from the structure module) is multiplied by genus-specific emission factors (Nowak *et al.,* 2002b) to produce emission levels standardized to 30^{o}C (86^{o}F) and photosynthetically active radiation (PAR) flux of 1,000 µmol m^{-2} s^{-1}. If genus-specific information is not available, then median emission values for the family, order, or superorder are used. Standardized emissions are converted to actual emissions based on light and temperature correction factors (Geron *et al.,* 1994) and local meteorological data. As PAR strongly controls the isoprene emission rate, PAR is estimated at 30 canopy levels as a function of above-canopy PAR using the sunfleck canopy environment model (A. Guenther, Nat. Cent. for Atmos. Res. pers. comm. 1998) with the LAI from the structure calculations.

Hourly inputs of air temperature are from measured National Climatic Data Center (NCDC) meteorological data. Total solar radiation is calculated based on the National Renewable Energy Laboratory Meteorological/Statistical Solar Radiation Model (METSTAT) with inputs from the NCDC data set (Maxwell 1994). PAR is calculated as 46 percent of total solar radiation input (Monteith and Unsworth 1990).

Because tree transpiration cools air and leaf temperatures and thus reduces biogenic VOC emissions, tree and shrub VOC emissions are reduced in the model based on air quality modeling results (Nowak *et al.,* 2000). For the modeling scenario analyzed (July 13-15, 1995) increased tree cover reduced air temperatures by 0.3^{o} to 1.0^{o}C resulting in hourly reductions in biogenic VOC emissions of 3.3 to 11.4 percent. These hourly reductions in VOC emissions are applied to the tree and shrub emissions during the in-leaf season to account for tree effects on air temperature and its consequent impact on VOC emissions.

3: Carbon Storage and Annual Sequestration

This module calculates total stored carbon, and gross and net carbon sequestered annually by the urban forest. Biomass for each measured tree is calculated using allometric equations from the literature (see Nowak 1994c; Nowak *et al.,* 2002b). Equations that predict above-ground biomass are converted to whole tree biomass based on root-to-shoot ratio of 0.26 (Cairns *et al.,* 1997). Equations that compute fresh-weight biomass are multiplied by species- or genus- specific-conversion factors to yield dry-weight biomass. These conversion factors, derived from average moisture contents of species given in the literature, averaged 0.48 for conifers and 0.56 for hardwoods (see Nowak *et al.,* 2002b).

Open-grown, maintained trees tend to have less above-ground biomass than predicted by forest-derived biomass equations for trees of the same dbh (Nowak 1994c). To adjust for this difference, biomass results for urban trees are multiplied by a factor 0.8 (Nowak 1994c). No adjustment is made for trees found in more natural stand conditions (e.g., on vacant lands or in forest preserves). Since deciduous trees drop their leaves annually, only carbon stored in wood biomass is calculated for these trees. Total tree dry-weight biomass is converted to total stored carbon by multiplying by 0.5 (Forest Products Lab 1952; Chow and Rolfe 1989).

The multiple equations used for individual species were combined together to produce one predictive equation for a wide range of diameters for individual species. The process of combining the individual formulas (with limited diameter ranges) into one, more general, species formula produced results that were typically within 2% of the original estimates for total carbon storage of the urban forest (i.e., the estimates using the multiple equations). Formulas were combined to prevent disjointed sequestration estimates that can occur when calculations switch between individual biomass equations.

If no allometric equation could be found for an individual species the average of results from equations of the same genus is used. If no genus equations are found, the average of results from all broadleaf or conifer equations is used.

To estimate monetary value associated with urban tree carbon storage and sequestration, carbon values are multiplied by $22.8/tonne of carbon ($20.7/ton of carbon) based on the estimated marginal social costs of carbon dioxide emissions for 2001-2010 (Fankhauser 1994).

Urban Tree Growth and Carbon Sequestration

To determine a base growth rate based on length of growing season, urban street tree (Frelich, 1992; Fleming 1988; and Nowak 1994c), park tree (DeVries 1987), and forest growth estimates (Smith and Shifley 1984) 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).

Average standardized growth rates for street (open-grown) trees were 0.83 cm/yr (0.33 in/yr). Growth rates of trees of the same species or genera were then compared to determine the average difference between standardized street tree growth and standardized park and forest growth rates. Park growth averaged 1.78 times less than street trees, and forest growth averaged 2.29 times less than street tree growth. Crown light exposure measurements of 0-1 were used to represent forest growth conditions; 2-3 for park conditions; and 4-5 for open-grown conditions. Thus, the standardized growth equations are:

Standardized growth (SG) = 0.83 cm/yr (0.33 in/yr) x number of frost free days / 153 and for: CLE 0-1: Base growth = SG / 2.26; CLE 2-3: Base growth = SG / 1.78; and CLE 4-5: Base growth = SG.

Base growth rates are adjusted based on tree condition. For trees in fair to excellent condition, base growth rates are multiplied by 1 (no adjustment), poor trees' growth rates are multiplied by 0.76, critical trees by 0.42, dying trees by 0.15, and dead trees by 0. Adjustment factors are based on percent crown dieback and the assumption that less than 25-percent crown dieback had a limited effect on dbh growth rates. The difference in estimates of carbon storage between year *x* and year *x+1* is the gross amount of carbon sequestered annually.

4: Air Pollution Removal

This module quantifies the hourly amount of pollution removed by the urban forest, its value, and associated percent improvement in air quality throughout a year. Pollution removal and percent air quality improvement are calculated based on field, pollution concentration, and meteorological data.

This module is used to estimate dry deposition of air pollution (i.e., pollution removal during nonprecipitation periods) to trees and shrubs (Nowak *et al.,* 1998, 2000). This module calculates the hourly dry deposition of ozone (O_3), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), and particulate matter less than 10 microns (PM10) to tree and shrub canopies throughout the year based on tree-cover data, hourly Ontario Ministry of the Environment weather data, and U.S. Environmental Protection Agency (EPA) pollution-concentration monitoring data.

The pollutant flux (F; in g m^{-2} s^{-1}) is calculated as the product of the deposition velocity (V_d; in m s^{-1}) and the pollutant concentration (C; in g m^{-3}):

$$F = V_d \times C$$

Deposition velocity is calculated as the inverse of the sum of the aerodynamic (R_a), quasi-laminar boundary layer (R_b) and canopy (R_c) resistances (Baldocchi *et al.,* 1987):

$$V_d = (R_a + R_b + R_c)^{-1}$$

Hourly meteorological data from the closest weather station (usually airport weather stations) are used in estimating R_a and R_b. In-leaf, hourly tree canopy resistances for O_3, SO_2, and NO_2 are calculated based on a modified hybrid of big-leaf and multilayer canopy deposition models (Baldocchi *et al.,* 1987; Baldocchi 1988).

As CO and removal of particulate matter by vegetation are not directly related to transpiration, R_c for CO is set to a constant for in-leaf season (50,000 s m^{-1} (15,240 s ft^{-1})) and leaf-off season (1,000,000 s m^{-1} (304,800 s ft^{-1})) based on data from Bidwell and Fraser (1972). For particles, the median deposition velocity from the literature (Lovett 1994) is 0.0128 m s^{-1} (0.042 ft s^{-1}) for the in-leaf season. Base particle V_d is set to 0.064 m s^{-1} (0.021 ft s^{-1}) based on a LAI of 6 and a 50-percent resuspension rate of particles back to the atmosphere (Zinke 1967). The base V_d is adjusted according to actual LAI and in-leaf vs. leaf-off season parameters. Bounds of total tree removal of O_3, NO_2, SO_2, and PM10 are estimated using the typical range of published in-leaf dry deposition velocities (Lovett 1994). Percent air quality improvement is estimated by incorporating local or regional boundary layer height data (height of the pollutant mixing layer). More detailed methods on module can be found in Nowak *et al.* 2006a.

The monetary value of pollution removal by trees is estimated using the median externality values for the United States for each pollutant. These values, in dollars per tonne (metric ton: mt) are: NO_2 = \$6,752 mt^{-1} (\$6,127 t^{-1}), PM10 = \$4,508 mt^{-1} (\$4,091 t^{-1}), SO_2 = \$1,653 mt^{-1} (\$1,500 t^{-1}), and CO = \$959 mt^{-1} (\$870 t^{-1}) (Murray *et al.,* 1994). Recently, these values were adjusted to 2007 values based on the producer's price index (Capital District Planning Commission 2008) and are now (in dollars per metric ton (t)): NO_2 = \$9,906 mt^{-1} (\$8,989 t^{-1}), PM10 = \$6,614 mt^{-1} (\$6,002 t^{-1}), SO_2 = \$2,425 mt^{-1} (\$2,201 t^{-1}), and CO = \$1,407 mt^{-1} (\$1,277 t^{-1}). Externality values for O_3 are set to equal the value for NO_2.

5: Building Energy Effects

This module estimates the effects of trees on building energy use and consequent emissions of carbon from power plants. Methods for these estimates are based on a report by McPherson and Simpson (1999). Distance and direction to the building is recorded for each tree within 18.3 m (60 ft) of two or one-story residential buildings. Any tree that is smaller than 6.1 meters (20 ft) in height or farther than 18.3 meters (60 ft) from a building is considered to have no effect on building energy use.

Using the tree size, distance, direction to building, climate region, leaf type (deciduous or evergreen) and percent cover of buildings and trees on the plot, the amount of carbon avoided from power plants due to the presence of trees is calculated. The amount of carbon avoided is categorized into the amount of MWh (cooling), and MBtus and MWh (heating) avoided due to tree energy effects. Default energy effects per tree are set for each climate region, vintage building types (period of construction), tree size class, distance from building, energy use (heating or cooling) and/or leaf type (deciduous or evergreen) depending upon the energy effect of the tree (tree shade, windbreak effects, and local climate effect) (McPherson and Simpson 1999). Default shading and climate effect values are applied to all trees; heating windbreak energy effects are assigned to each evergreen tree. As shading effect default values are given for only one vintage building type (post-1980), vintage adjustment factors (McPherson and Simpson 1999) are applied to obtain shading effect values for all other vintage types.

Tree Condition Adjustment

The default energy effect values (McPherson and Simpson 1999) are adjusted for the tree condition as follows:

$$\text{Energy adjustment} = 0.5 + (0.5 \times \text{tree condition})$$

where tree condition = 1 - % dieback. This adjustment factor is applied to all tree energy effects for cooling, but only evergreen trees for the heating energy use effects as deciduous trees are typically out-of leaf during the heating season.

Local Climate Effects

The individual tree effect on climate diminishes as tree cover increases in an area, though the total effect of all trees can increase. Base climate effect values for a tree are given for plots of 10, 30 and 60 % cover (McPherson and Simpson 1999). Interpolation formulas (McPherson and Simpson 1999) are used to determine the actual tree value based on the specific plot percent tree and building cover. For plots with less than 10% cover, the slope between the 10 and 30 % cover values are used for the interpolation. Plots with percent cover greater than 60 % used the slope between 30 and 60 % cover with a minimum individual tree climate effect of one-third the effect at 60% cover. This minimum is set to prevent a tree from obtaining a negative effect at high cover.

The total shading, windbreak, and climate energy effects due to trees on a plot are calculated by summing the individual tree's energy effects for the particular energy use and housing vintage. These values are adjusted for the distribution of the different vintage types within the climate region (McPherson and Simpson 1999).

Since the default cooling energy effects are determined based on the climate regions' electricity emissions factors it is necessary to convert the cooling energy effects to the state specific equivalent. This conversion is accomplished by multiplying the plot cooling energy effects by the ratio of the state specific electricity emissions factor to the climate region's electricity emissions factor (McPherson & Simpson 1999).

Home heating source distribution (e.g., fuel oil, heat pump, electricity, and natural gas) for the region is used to partition the carbon emissions from heating to the appropriate energy source. Standard conversion factors (t CO_2 / MWh, t CO_2 / MBtu) are used to convert the energy effect from t CO_2 to units of energy saved (MBtus, MWh). Cooling and heating electricity use (MWh) had state specific conversion factors; non-electrical heating fuels (MBtus) used a standard conversion factor because this factor does not vary by region (McPherson and Simpson 1999). Total plot effects are combined to yield the total energy and associated carbon effect due to the urban forest.

References:

Barbour, M.G, J.H. Burk, and W.D. Pitts. 1980. Terrestrial plant ecology. Menlo Park, CA: Benjamin/Cummings. 604 p.

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

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

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

Boyd, J.B. 1983. Natural Reproduction of Exotic and Indigenous Trees in Three Urban Environments. M.S. Thesis, Univ. of Wisconsin, Milwaukee, WI. 97 pp.

Brasseur, G.P. and R.B. Chatfield. 1991. The fate of biogenic trace gases in the atmosphere. In: Sharkey, T.D., E.A. Holland, and H.A. Mooney, eds. Trace gas emissions by plants. New York: Academic Press: 1-27.

Burns, R.M. and B.H. Honkala. 1990a. Silvics of North America. Vol. 1. Conifers. Agric. Handb. 654. Washington, DC: U.S. Department of Agriculture. 675 p.

Burns, R.M. and B.H. Honkala. 1990b. Silvics of North America. Vol. 2. Hardwoods. Agric. Handb. 654. Washington, DC: U.S. Department of Agriculture. 877 p.

Buckelew Cumming, A., D.J. Nowak, D.B. Twardus, R. Hoehn, M. Mielke, and R. Rideout. 2007. Urban Forests of Wisconsin 2002: Pilot Monitoring Project 2002. USDA Forest Service, Northeastern Area State and Private Forestry Report, NA-FR-05-07. 33 p. http://www.treesearch.fs.fed.us/pubs/12685 Last accessed June 2008.

Cairns, M.A., S. Brown, E.H. Helmer, and G.A. Baumgardner. 1997. Root biomass allocation in the world's upland forests. Oecologia. 111: 1-11.

The Capital District Regional Planning Commission. 2008. Consumer and producer price indices. http://www.cdrpc.org/CPI_PPI.html Last accessed June 2008.

Chow, P. and G.L. Rolfe. 1989. Carbon and hydrogen contents of short-rotation biomass of five hardwood species. Wood and Fiber Science. 21(1): 30-36.

Clark, D.E. 1979. Sunset New Western Garden Book. Menlo Park, CA: Lane Publ. Co. 512 p.
Council of Tree and Landscape Appraisers. 1992. Guide for plant appraisal. Savoy, IL: International Society of Arboriculture. 103 p.

Derrenbacher, W.E. 1969. Plants and Landscape: An Analysis of Ornamental Planting in Four Berkeley Neighborhoods. Masters thesis, University of California, Berkeley, CA. 231 pp.

deVries, R.E. 1987. A preliminary investigation of the growth and longevity of trees in Central Park. New Brunswick, NJ: Rutgers University 95 p. M.S. thesis.

Dorney, J.R., G.R. Guntenspergen, J.R. Keough, and F. Stearns. 1984. Composition and structure of an urban woody plant community. Urban Ecology. 8:69-90.

Duncan, J.S. Jr. 1973. Landscape taste as a symbol of group identity. Geographical Review 63:334-355.

Dwyer, J.F., E.G. McPherson, H.W. Schroeder, and R.A. Rowntree. 1992. Assessing the benefits and costs of the urban forest. Journal of Arboriculture 18(5):227-234.

Energy Information Administration. 2003a. Sales Revenue Data. 27 Jan 2003. http://www.eia.doe.gov/electricity/page/sales_revenue.xls. Last accessed April 2003.

Energy Information Administration. 2003b. Energy Markets and End Use. http://www.eia.doe.gov/emeu/states/_states.html. Last accessed April 2003.

Energy Information Administration. 2003c. Natural Gas Monthly. 16 Apr 2003. http://www.eia.doe.gov/pub/oil_gas/natural_gas/data_publications/natural_gas_monthly/current/pdf/table_15.pdf. Last accessed April 2003.

Energy Information Administration. 2003d. Petroleum Marketing Monthly. Feb 2003. http://www.eia.doe.gov/pub/oil_gas/petroleum/data_publications/petroleum_marketing_monthly/current/pdf/pmmtab18.pdf. Last accessed April 2003.

Energy Information Administration. 2003e. Residential Energy Consumption Survey. 27 Feb 2001. http://www.eia.doe.gov/emeu/consumptionbriefs/recs/heating_oil/region_oil.html. Last accessed April 2003.

Energy Information Administration 2003f. Residential Energy Consumption Survey. 27 Feb 2001. http://eia.doe.gov/emeu/recs/glossary.html. Last accessed April 2003.

Escobedo, F.J, D.J. Nowak, J.E. Wagner, C. Luz de la Maza, and M. Rodriguez. 2006. The socioeconomics and management of Santiago de Chile's public urban forest. Urban Forestry and Urban Greening. 4:105-114.

Fankhauser, S. 1994. The social costs of greenhouse gas emissions: an expected value approach. The Energy Journal. 15(2): 157-184.

Fleming, L.E. 1988. Growth estimation of street trees in central New Jersey. New Brunswick, NJ: Rutgers University. 143 p. M.S. thesis.

Forest Products Laboratory. 1952. Chemical analyses of wood. Tech. Note 235. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 4 p.

Frelich, L.E. 1992. Predicting dimensional relationships for Twin Cities shade trees. St. Paul, MN: University of Minnesota, Department of Forest Resources. 33 p.

Geron, C.D., A.B. Guenther, and T.E. Pierce. 1994. An improved model for estimating emissions of volatile organic compounds from forests in the eastern United States. Journal of Geophysical Research. 99(D6): 12,773-12,791.

Gilbert, O.L. 1989. The Ecology of Urban Habitats. Chapman and Hall, London. 369 pp.

Gleason, H.A. and A. Cronquist. 1991. Manual of vascular plants of Northeastern United States and Adjacent Canada. Bronx, NY: New York Botanical Garden. 910 p.

Grimm, W.C. 1962. The book of trees. Harrisburg, PA: Stackpole Co. 487 p.

Ham, D., C. Post, D. Vanblaricom, D. Lipscomb, D. Hargett, and D.J. Nowak 2003. Analysis of the explosively urbanizing South Carolina Interstate 85 corridor. Proc. of the 2003 National Urban Forest Conference. San Antonio, TX.

Hough, R.B. 1907. Handbook of the trees of the Northern States and Canada. Lowville, NY: R.B. Hough. 470 p.

Hyams, E.S. 1970. English cottage gardens. Nelson, London, 234 p.

International Society of Arboriculture. 1988. Valuation of landscape trees, shrubs, and other plants. Champaign, IL: International Society of Arboriculture. 50 p.

i-Tree. 2008. i-Tree software suite v2.0. 239 p. http://www.itreetools.org/resource_learning_center/elements/i-Tree_v20_UsersManual.pdf Last accessed June 2008.

Iizumi, S. 1983. The urban vegetation of Tokyo and Sendai, Japan. In: Holzner, W., Werger, M.J., and Ikusima, I. (Eds.) Man's impact on vegetation. Dr. W. Junk Publishers, The Hague. p. 335-340.

Jarvis, P.G. and J.W. Leverenz. 1983. Productivity of temperate, deciduous and evergreen forests. In: Lange, O.L., P.S. Nobel, C.B. Osmond, and H. Ziegler, eds. Physiological plant ecology IV, encyclopedia of plant physiology, volume 12D. Springer-Verlag, Berlin: 233-280.

Jones, A.W. 1957. The flora of the city of London bombed sites. The London Naturalist. 37:189-210.

Jim, C.Y. 1989. The distribution and configuration of tree cover in urban Hong Kong. GeoJournal. 18(2):175-188.

Kinnee, E., C. Geron, and T. Pierce. 1997. United States land use inventory for estimating biogenic ozone precursor emissions. Ecological Applications 7(1):46-58.

Kunick, W. 1982. Comparison of the flora of some cities of the central European lowlands. In: Bornkamm, R., Lee, J.A., and Seaward, M.R. (Eds.) Urban Ecology. Blackwell Science Publication, Oxford. p. 13-22.

Kuo, F.E. and Sullivan, W.C. 2001. Environment and crime in the inner city: does vegetation reduce crime? Environmental Behavior 33(3):343-365.

Leverenz, J.W. and T.M. Hinckley. 1990. Shoot structure, leaf area index and productivity of evergreen conifer stands. Tree Physiology. 6: 135-149.

Liebhold, A.M., K.W. Gottschalk, R. Muzika, M.E. Montgomery, R. Young, K. O'Day, and B. Kelley. 1995. Suitability of North American tree species to the gypsy moth: a summary of field and laboratory tests. Gen. Tech. Rep. NE-211. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 34 p.

Little, E.L. 1971. Atlas of United States trees. Vol. 1. Conifers and important hardwoods. Misc. Pub. 1146. Washington, DC: U.S. Department of Agriculture, Forest Service. 400 p.

Little, E.L. 1976. Atlas of United States trees. Vol. 3. Minor western hardwoods. Misc. Pub. 1314. Washington, DC: U.S. Department of Agriculture, Forest Service. 300 p.

Little, E.L. 1977. Atlas of United States trees. Vol. 4. Minor eastern hardwoods. Misc. Pub. 1342. Washington, DC: U.S. Department of Agriculture, Forest Service. 235 p.

Little, E.L. 1978. Atlas of United States trees. Vol. 5. Florida. Misc. Pub. 1361. Washington, DC: U.S. Department of Agriculture, Forest Service. 138 p.

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

Lozano, J.V. 2004. Distribucion del arbolado urbano en la ciudad de Fuenlabrada y su contribucion a la calidad del aire. Ciudad y Territorio, Estudios Territoriales 36(140):419-427.

Maxwell, E.L. 1994. A meteorological/statistical solar radiation model. In: Proceedings of the 1994 annual conference of the American Solar Energy Society. San Jose, CA: American Solar Energy Society: 421-426.

McBride, J.R., and D.F. Jacobs 1976. Urban forest development: a case study, Menlo Park, California. Urban Ecology. 2:1-14.

McBride, J.R., and D.F. Jacobs 1986. Presettlement forest structure as a factor in urban forest development. Urban Ecology. 9:245-266.

McNeil, J. and C. Vava. 2006. Oakville's urban forest: Our solution to our pollution. Town of Oakville Report, Oakville, Ontario. 67 p. http://www.oakville.ca/Media_Files/forestry/UFORE.pdf Last accessed June 2008.

McPherson, E.G., 1998. Structure and sustainability of Sacramento's urban forest. Journal of Arboriculture. 24(4):174-190.

McPherson, E.G. and J.R. Simpson.. 1999. Carbon dioxide reduction through urban forestry: Guidelines for professional and volunteer tree planters. Gen. Tech. Rep. PSW-171. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 237 p.

Miller, P.R., and A.M. Winer 1984. Composition and dominance in Los Angeles Basin urban vegetation.. Urban Ecology. 8:29-54.

Monteith, J.L. and M.H. Unsworth. 1990. Principles of environmental physics. New York: Edward Arnold. 291 p.

Moran, M.A. 1984. Influence of adjacent land use on understory vegetation of New York forests. Urban Ecology. 8:329-340.

Murray F.J., L. Marsh, and P.A. Bradford 1994. New York State Energy Plan, Vol. II: Issue Reports. New York State Energy Office, Albany, NY.

National Center for Atmospheric Research (NCAR). 2008. Model of Emissions of Gases and Aerosols from Nature (MEGAN). http://bai.acd.ucar.edu/Megan/ Last accessed June 2008.

National Climatic Data Center. 2008. Integrated surface hourly observations. http://ols.nndc.noaa.gov/plolstore/plsql/olstore.prodspecific?prodnum=C00353-CDR-S0001 Last accessed June 2008.

National Oceanic and Atmospheric Administration / U.S. Environmental Protection Agency. 2008. Biogenic Emissions Inventory System (BEIS) Modeling. http://www.epa.gov/asmdnerl/biogen.html. Last accessed June 2008.

New Jersey Department of Environmental Protection. 2002. DEP Announces $1 Million Urban Airshed Reforestation Project From Conectiv Enforcement Settlement. Press release 02/111, 10/26/02. http://www.state.nj.us/dep/newsrel/releases/02_0111.htm. Last accessed June 2008.

Nowak, D.J. 1991. Urban forest development and structure: analysis of Oakland, California. Berkeley, CA: University of California. 232 p. Ph.D. dissertation.

Nowak, D.J. 1994a. Understanding the structure of urban forests. Journal of Forestry. 92(10): 42-46.

Nowak, D.J. 1994b. Urban forest structure: the state of Chicago's urban forest. In: McPherson, E.G, D.J. Nowak and R.A. Rowntree. Chicago's Urban Forest Ecosystem: Results of the Chicago Urban Forest Climate Project. USDA Forest Service General Technical Report NE-186. pp. 3-18; 140-164.

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

Nowak, D.J. 1996. Estimating leaf area and leaf biomass of open-grown deciduous urban trees. Forest Science. 42(4): 504-507.

Nowak, D.J., K.L. Civerolo, S.T. Rao, G. Sistla, C.J. Luley, and D.E. Crane. 2000. A modeling study of the impact of urban trees on ozone. Atmospheric Environment. 34: 1601-1613.

Nowak, D.J. and D.E. Crane. 2000. The urban forest effects (UFORE) model: quantifying urban forest structure and functions. In Hansen M. and T. Burk (Eds.), Proceedings: Integrated tools for natural resources inventories in the 21st century. IUFRO Conference, 16-20 August 1998, Boise, ID. General Technical Report NC-212, U.S. Department of Agriculture, Forest Service, North Central Research Station, St. Paul, MN. pp. 714-720.

Nowak, D.J. and D.E. Crane. 2002. Carbon storage and sequestration by urban trees in the USA. Environmental Pollution 116(3):381-389.

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

Nowak, D.J., D.E. Crane, and J.C. Stevens. 2006a. Air pollution removal by urban trees and shrubs in the United States. Urban Forestry and Urban Greening 4:115-123.

Nowak, D.J., D.E. Crane, J.C. Stevens, and M. Ibarra. 2002b. Brooklyn's urban forest. General Technical Report NE-290, U.S. Department of Agriculture, Forest Service, Northeastern Research Station, Newtown Square, PA. 107.

Nowak, D.J. and J.F. Dwyer. 2007. Understanding the benefits and costs of urban forest ecosystems. In: Kuser, J. (ed.) Urban and Community Forestry in the Northeast. Springer Science and Business Media. New York. pp. 25-46.

Nowak, D.J., R.H. Hoehn, and D.E. Crane. 2007a. Oxygen production by urban trees in the United States. Arboriculture and Urban Forestry 33(3):220-226

Nowak, D.J., R. Hoehn, D.E. Crane, J.C. Stevens, and J.T. Walton. 2006b. Assessing urban forest effects and values: Minneapolis' urban forest. Resource Bulletin NE-166. U.S. Department of Agriculture, Forest Service, Northeastern Research Station, Newtown Square, PA. 20 p.

Nowak, D.J., R. Hoehn, D.E. Crane, J.C. Stevens, and J.T. Walton. 2006c. Assessing urban forest effects and values: Washington DC's urban forest. Resource Bulletin NRS-1. U.S. Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, PA. 24 p.

Nowak, D.J., R. Hoehn, D.E. Crane, J.C. Stevens, and J.T. Walton. 2006d. Assessing urban forest effects and values: Casper's urban forest. Resource Bulletin NRS-4. U.S. Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, PA. 20 p.

Nowak, D.J., R. Hoehn, D.E. Crane, J.C. Stevens, and J.T. Walton. 2007b. Assessing urban forest effects and values: Philadelphia's urban forest. Resource Bulletin NRS-7. U.S. Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, PA. 22 p.

Nowak, D.J., R. Hoehn, D.E. Crane, J.C. Stevens, and J.T. Walton. 2007c. Assessing urban forest effects and values: San Francisco's urban forest. Resource Bulletin NRS-8. U.S. Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, PA. 22 p.

Nowak, D.J., R. Hoehn, D.E. Crane, J.C. Stevens, and J.T. Walton. 2007d. Assessing urban forest effects and values: New York City's urban forest. Resource Bulletin NRS-9. U.S. Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, PA. 22 p.

Nowak, D.J., P.J. McHale, M. Ibarra, D. Crane, J. Stevens, and C. Luley. 1998. Modeling the effects of urban vegetation on air pollution. In: Gryning, S.E. and N. Chaumerliac (eds.) *Air Pollution Modeling and Its Application XII*. Plenum Press, New York. pp. 399-407.

Nowak, D.J. and P. O'Connor. 2001. Syracuse urban forest master plan: guiding the city's forest resource in the 21st century. *USDA Forest Service General Technical Report*. 50 p.

Nowak, D.J., J. Pasek, R. Sequeira, D.E. Crane, and V. Mastro. 2001. Potential effect of Anoplophora glabripennis (Coleoptera: Cerambycidae) on urban trees in the United States. Journal of Economic Entomology. 94(1):116-122.

Nowak, D.J., R.A. Rowntree, E.G. McPherson, S.M. Sisinni, E. Kerkmann and J.C. Stevens. 1996. Measuring and analyzing urban tree cover. Landscape and Urban Planning 36:49-57.

Nowak, D.J., J.T Walton, J.C. Stevens, D.E. Crane, and R.E. Hoehn. 2008. Effect of plot and sample size on timing and precision of urban forest assessments. Arboriculture and Urban Forestry (in press).

Numata, M. 1977. The impact of urbanization on vegetation in Japan. In: Miyawaki, A., and Tuxen, R. (Eds.) Vegetation Science and Environmental Protection. Maruzen Co. Ltd., Tokyo. p. 161-171.

Onstad, D.W., D.J. Nowak, and M.R. Jeffords. 1997. Potential defoliation of trees by outbreak populations of gypsy moth in the Chicago area. Journal of Arboriculture. 23(2): 57-64.

Peper, P.J. and E.G. McPherson. 1998. Comparison of five methods for estimating leaf area index of open-grown deciduous trees. Journal of Arboriculture. 24(2):98-111.

Platt, R. 1968. Discover American trees. New York: Dodd, Mead and Co. 256 p.

Preston, R.J. 1976. North American trees. Ames, IA: Iowa State University Press. 399 p.

Profous, G. 1984. Forest changes in the Bronx. Journal of Forestry. 82:559-560.

Profous, G., R.A. Rowntree, and R.E. Loeb 1988. The urban forest landscape of Athens, Greece: aspects of structure, planning and management. Arboricultural Journal. 12:83-107.

Richards, N.A., J.R. Mallette, R.J. Simpson, and E.A. Macie. 1984. Residential greenspace and vegetation in a mature city: Syracuse, New York. Urban Ecology. 8:99-125.

Rowntree, R.A. 1984. Forest canopy cover and land use in four eastern United States cities. Urban Ecology. 8:55-67.

Sanders, R.A. 1983. Configuration of tree canopy cover in urban land uses. Geographical Perspectives. 51:49-53.

Santamour, F.S. Jr. 1983. Woody-plant succession in the urban forest: filling cracks and crevices. Journal of Arboriculture. 9:267-270.

Schmid, J.A. 1975. Urban Vegetation: A Review and Chicago Case Study. Research Paper, Dept. of Geography, Univ. of Chicago, Chicago. vol. 161, 266 pp.

Smith, F.W., D.A. Sampson, and J.N. Long. 1991. Comparison of leaf area index estimates from allometrics and measured light interception. Forest Science. 37(6): 1682-1688.

Smith, W.B. and S.R. Shifley. 1984. Diameter growth, survival, and volume estimates for trees in Indiana and Illinois. Res. Pap. NC-257. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 10 p.

Sukopp, H., H.P. Blume, and W. Kunick 1979. The soil, flora, and vegetation of Berlin's waste lands. In: Laurie, I. (Eds.) Nature in Cities. John Wiley and Sons, New York, NY. p. 115-132.

U.S. Department of Labor and Statistics. 2003. Consumer Price Indices. 16 Apr 2003. http://www.ftp.bls.gov/pub/special.requests/cpi/cpiai.txt. Last accessed April 2003.

U.S. Environmental Protection Agency. 2008. Technology Transfer Network (TTN) Air Quality System (AQS). http://www.epa.gov/ttn/airs/airsaqs/detaildata/downloadaqsdata.htm Last accessed June 2008.

Viereck, L.A. and E.L Little. 1975. Atlas of United States trees. Vol. 2. Alaska trees and common shrubs. Misc. Publ. 1293. Washington, DC: U.S. Department of Agriculture, Forest Service. 109 p.

Westphal, L.M.. 2003. Urban greening and social benefits: a study of empowerment outcomes. Journal of Arboriculture. 29(3):137-147.

Whitney, G.G. 1985. A quantitative analysis of the flora and plant communities of a representative midwestern U.S. town. Urban Ecology. 9:143-160.

Winer, A.M.; D.R. Fitz, P.R. Miller, R. Atkinson, D.E. Brown, W.P. Carter, M.C. Dodd, C.W. Johnson, M.A. Myers, K.R. Neisess, M.P. Poe, and E.R. Stephens. 1983. Investigation of the role of natural hydrocarbons in photochemical smog formation in California. Riverside, CA: Statewide Air Pollution Research Center.

Wolf, K.M. 2003. Public response to the urban forest in inner-city business districts. Journal of Arboriculture. 29(3):117-126.

Yang, J., J. McBride, J. Zhou, and Z. Sun. 2005. The urban forest in Beijing and its role in air pollution reduction. Urban Forests and Urban Greening. 3(2): 65-78.

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

Appendix D: i-Tree Hydro Model – Detailed Methodology

Data and Model Calibration

Precipitation data for the Fletcher's Creek analysis were collected from the CVC Firehall and weather data were collected from Toronto Pearson International Airport (WBAN: 716240 99999). For the Spring Creek analysis the precipitation data were collected from weather stations at Heart Lake CA (PRCP0085) and Mississauga Works Yard (PRCP0115). Digital elevation model data were obtained from the Toronto Regional Conservation Authority. Tree and impervious cover parameters were derived for each watershed from photo-interpretation of Google Earth imagery using 1,000 randomly located points (Table 1).

Table 1. Cover estimates for the Fletcher's Creek and Spring Creek Watersheds

	Percent Cover			
Area	**Impervious**	**Tree**	**Grass/shrub**	**Bare Soil**
Fletcher Creek Watershed	42.6%	10.6%	43.3%	4.2%
Spring Creek Watershed	48.2%	14.3%	36.6%	3.2%

Model results were calibrated against measured stream flow to yield the best fit between model and measured stream flow results. The model was calibrated using hourly stream flow data collected at the gauge at Fletcher's Creek over two seasons (May 1st, 2007 to November 30th, 2007 Spring Creek; May 1st, 2008 to November 18th, 2008). For the Spring Creek analysis the model was calibrated using data from the gauge at Spring Creek (STRM0085) from April 8th 2008 to November 30th 2008, and again for April 11th 2006 to November 30th 2006. Calibration coefficients (0-1 with 1.0 = perfect fit) were calculated for peak flow, base flow, and balance flow (peak and base) (Table 2). Calibrations can often be off, particularly for peak flows, due to mismatching of steam flow and weather data as the weather stations are often outside of the watershed area. Tree canopy leaf area index (LAI) was estimated at 5.1 and 5.0 for Fletcher's Creek and Spring Creek respectively; these estimates were based on field studies. The amount of percent of impervious cover connected to the stream was estimated at 65 percent and 30 percent for Fletcher's Creek and Spring Creek, respectively.

Table 2. Calibration coefficients for model estimates and gauging station data

	Calibration Coefficients		
Watershed	**Peak Flow**	**Base Flow**	**Balanced Flow**
Fletcher Creek (2007 data)	0.77	0.55	0.73
Fletcher Creek (2008 data)	0.50	0.42	0.55
Spring Creek (2008 data)	0.71	0.56	0.72

Model Scenarios

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 at the original value with tree cover varying between 0 and 100%. 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% tree cover, all impervious land is cover by trees. This assumption is unreasonable as all buildings, road and parking lots would be cover by trees, but 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 at the original value with impervious cover varying between 0 and 100%. 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% 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% impervious cover, all (100%) impervious cover is connected to the stream. Reductions in impervious cover were assumed to be filled with grass and shrub cover.

Water Quality Effects – Event Mean Concentration to Calculate Pollution Load

The term event mean concentration (EMC) is a statistical parameter used to represent the flow-proportional average concentration of a given parameter during a storm event. It is defined as the total constituent mass divided by the total runoff volume, although EMC estimates are usually obtained from a flow-weighted composite of concentration samples taken during a storm. Mathematically (Sansalone and Buchberger, 1997; Charbeneau and Barretti, 1998):

$$EMC = \overline{C} = \frac{M}{V} = \frac{\int C(t)\, Q(t) dt}{\int Q(t) dt} \approx \frac{\sum C(t)\, Q(t) \Delta t}{\sum Q(t) \Delta t} \qquad (1)$$

where $C(t)$ and $Q(t)$ are the time-variable concentration and flow measured during the runoff event, and *M* and *V* are pollutant mass and runoff volume as defined in Equation 1. It is clear that the EMC results from a flow-weighted average, not simply a time average of the concentration. EMC data is used for estimating pollutant loading into watersheds. EMCs are reported as a mass of pollutant per unit volume of water (usually mg/L).

The pollution Load (L) calculation from the EMC method is:

$$L = EMC * Q = EMC * d_r * A \qquad (2)$$

Where EMC is event mean concentration (mg/l, mg/m^3, …), Q is runoff of a time period associated with EMC (l/h, m^3 /day…), d_r is runoff depth of unit area (mm/h, m/h, m/day…), A is the land area (m^2, …) which is catchment area in i-Tree / UFORE-Hydro.

Thus, when the EMC is multiplied by the runoff volume, an estimate of the loading to the receiving water is provided. As is evident from Figure 2, the instantaneous concentration during a storm can be higher or lower than the EMC, but the use of the EMC as an event characterisation replaces the actual time variation of *C* versus *t* in a storm with a pulse of constant concentration having equal mass and duration as the actual event. This process ensures that mass loadings from storms will be correctly represented. EMCs represent the concentration of a specific pollutant contained in stormwater runoff coming from a particular land use type or from the whole watershed. Under most circumstances, the EMC provides the most useful means for quantifying the level of pollution resulting from a runoff event (USEPA, 2002).

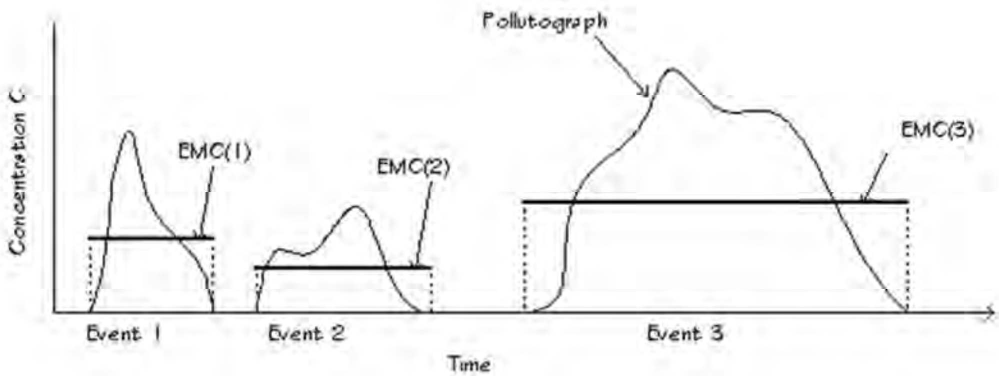

Figure 2. Interstorm variation of pollutographs and EMCs

Since collecting the data necessary for calculating site-specific EMCs can be cost-prohibitive, researchers or regulators will often use values that are already available in the literature. If site-specific numbers are not available, regional or national averages can be used, although the accuracy of using these numbers is questionable. Due to the specific climatological and physiographic characteristics of individual watersheds, agricultural and urban land uses can exhibit a wide range of variability in nutrient export (Beaulac and Reckhow 1982).

To understand and control urban runoff pollution, The U.S. Congress included the establishment of the Nationwide Urban Runoff Program (NURP) in the 1977 Amendments of the Clean Water Act (PL 95-217). The U.S. Environmental Protection Agency developed the NURP to expand the state knowledge of urban runoff pollution by applying research projects and instituting data collection in selected urban areas throughout the country.

In 1983, the U.S. Environmental Protection Agency (U.S. EPA, 1983) published the results of the NURP, which nationally characterizes urban runoff for 10 standard water quality pollutants, based on data from 2,300 station-storms at 81 urban sites in 28 metropolitan areas.

Two important conclusions from NURP investigations:

- The variance of the EMCs when data from sites are grouped by land use type or geographic region is so great that difference in measures of central tendency among groups statistically are not significant;
- Statistically, the entire sample of EMCs, and the medians of all EMCs among sites, are lognormally distributed.

Thus the numbers in Table 3 do not distinguish between different urban land use types.

Subsequently, the USGS created another urban stormwater runoff base (Driver et al. 1985), based on data measured through mid-1980s for over 1,100 stations at 97 urban sites located in 21 metropolitan areas. Additionally, many major cities in the United States collected urban runoff quality data as part of the application requirements for stormwater discharge permits under the National Pollutant Discharge

Elimination System (NPDES). The NPDES data are from over 30 cities and more than 800 station-storms for over 150 paramaters (Smullen et al, 1999).

The data from the three sources (NURP, USGS and NPDES) were used to compute new estimates of EMC population means and medians for the 10 pollutants with many more degrees of freedom than were available to the NURP investigators (Smullen et al, 1999). A “pooled” mean was calculated representing the mean of the total population of sample data. The NURP and pooled mean EMCs for the 10 constitutes are listed in Table 3 (Smullen et al, 1999). NURP or pooled mean EMCs were selected because they are based on field data collected from thousands of storm events. These estimates are based on nationwide data, however, so they do not account for regional variation in soil types, climate, and other factors.

Table 3. National Pooled EMCs and NURP EMCs

Constitute	Data Source	EMCs (mg/l)		No. of Events
		Mean	Median	
Total Suspended Solids: TSS	Pooled NURP	78.4 17.4	54.5 113	3047 2000
Biochemical Oxygen Demand: BOD_5	Pooled NURP	14.1 10.4	11.5 8.39	1035 474
Chemical Oxygen Demand: COD	Pooled NURP	52.8 66.1	44.7 55	2639 1538
Total phosphorus: TP	Pooled NURP	0.315 0.337	0.259 0.266	3094 1902
Soluble phosphorus: Soluble P	Pooled NURP	0.129 0.1	0.103 0.078	1091 767
Total Kjeldhal nitrogen: TKN	Pooled NURP	1.73 1.67	1.47 1.41	2693 1601
Nitrite and Nitrate: NO_2 and NO_3	Pooled NURP	0.658 0.837	0.533 0.666	2016 1234
Copper: Cu	Pooled NURP	13.5 66.6	11.1 54.8	1657 849
Lead: Pb	Pooled NURP	67.5 175	50.7 131	2713 1579
Zinc: Zn	Pooled NURP	162 176	129 140	2234 1281

Note;

(1) Polled data sources include: NURP, USGS, NPDES
(2) No BOD_5 data available in the USGS dataset - polled includes NURP+NPDES
(3) NO TSP data available in NPDES dataset - polled includes NURP+USGS

For i-Tree Hydro, the pooled median and mean EMC value for each pollutant (Table 3) were applied to the runoff regenerated from pervious and impervious surface flow, not the base flow values, to estimate effects on pollutant load across the entire modeling time frame. All rain events are treated equally using the EMC value, which mean some events may be over-estimated and others underestimated. In addition, local management actions (e.g., street sweeping) can affect these values. However, across the entire season, if the EMC value is representative of the watershed, the estimate of cumulative effects on water quality should be relatively accurate. Accuracy of pollution estimates will be increased by using locally derived coefficients. It is not known how well the national EMC values represent local conditions.

References

Beaulac, M. N. and Reckhow, K. H. 1982. An examination of land use-nutrient export relationships. *Water Resources Bulletin*, 18(6), 1013-1024.

Charbeneau RJ, Barretti M. 1998. Evaluation of methods for estimating stormwater pollutant loads. *Water Environ Res*. 70: 1295 –1302.

Driver, N. E., Mustard, M. H., Rhinesmith, R. B., and Middelburg, R. F. 1985. U.S. Geological Survey urban-stormwater data base for 22 metropolitan areas throughout the United States. United States Geological Survey, Open-File Report 85-337, Lakewood, CO.

Sansalone J.J., Buchberger S.G. 1997. Partitioning and first flush of metals in urban roadway storm water. *J Environ Eng ASCE* 123: 134 –143.

Smullen, J. T., Shallcross, A. L., and Cave, K. A. 1999. Updating the U.S. nationwide urban runoff quality database. *Water Science Technology* 39(12), 9-16.

U.S. Environmental Protection Agency (USEPA). 1983. "Results of the Nationwide Urban Runoff Program: Volume I – final report," U.S. Environmental Protection Agency, PB84-185552, Washington, DC.

U.S. Environmental Protection Agency (USEPA). 2002. Urban Stormwater BMP Performance Monitoring, A Guidance Manual for Meeting the National Stormwater BMP Database Requirements.

Wang, J., T.A. Endreny, and D.J. Nowak. 2008. Mechanistic simulation of urban tree effects in an urban water balance model. *Journal of American Water Resource Association*. 44(1):75-85.

Appendix E: City Comparisons

Table 1: City totals for trees only

City	% Tree Cover	# of Trees	Carbon Storage (tonnes)	Carbon Sequestration (tonnes /yr)	Pollution Removal (tonnes / yr)[1]	Pollution Value ($ CAN)[2]
Calgary, Alberta[a]	7.2	11,889,000	404,000	19,400	296	2,946,000
Toronto, ON[a*]	19.9	10,220,000	1,108,000	46,700	1,164	13,093,000
Atlanta, GA[b]	36.7	9,415,000	1,220,000	42,100	1,509	15,266,000
London, ON[c]	24.7	4,376,000	360,000	12,500	370	4,481,000
New York, NY[b]	20.9	5,212,000	1,225,000	38,400	1,521	14,793,000
Brampton, ON[e*]	15.2	3,618,000	175,000	7,700	184	2,050,000
Baltimore, MD[d]	21.0	2,627,000	542,000	14,700	390	3,904,000
Philadelphia, PA[b]	15.7	2,113,000	481,000	14,600	522	5,188,000
Mississauga, ON[e*]	**19.0**	**2,104,000**	**203,000**	**10,000**	**336**	**3,761,000**
Washington, DC[f]	28.6	1,928,000	477,000	14,700	379	3,573,000
Oakville, ON[a]	29.1	1,908,000	133,000	6,000	172	1,776,000
Ajax, ON[e*]	18.4	1,366,000	106,000	3,500	39	443,000
Boston, MA[b]	22.3	1,183,000	290,000	9,500	257	2,615,000
Woodbridge, NJ[g]	29.5	986,000	145,000	5,000	191	1,906,000
Minneapolis, MN[h]	26.4	979,000	227,000	8,100	277	2,803,000
Syracuse, NY[d]	23.1	876,000	157,000	4,900	99	1,045,000
San Francisco, CA[a]	11.9	668,000	176,000	4,600	128	1,273,000
Morgantown, WV[i]	35.5	658,000	84,000	2,600	65	606,000
Moorestown, NJ[g]	28.0	583,000	106,000	3,400	107	1,051,000
Jersey City, NJ[g]	11.5	136,000	19,000	800	37	365,000
Casper, WY[a]	8.9	123,000	34,000	1,100	34	344,000
Freehold, NJ[g]	34.4	48,000	18,000	500	20	203,000

[1] 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.
[2] Pollution values updated to 2007 values. Values are given in Canadian dollars (CND = 0.8 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

Table 2: Per hectare value of trees

City	No. of trees (trees/ha)	Carbon Storage (tonnes/ha)	Carbon sequestration (tonnes/ha/yr)	Pollution removal (kg/ha/yr)[1]	Pollution value Can. $/ha[2]
Calgary, Alberta[a]	164.8	5.6	0.3	4.1	40.8
Toronto, ON[a]	160.4	17.4	0.7	18.3	205.5
Atlanta, GA[b]	275.8	35.7	1.2	44.2	447.2
London, ON[c]	185.5	15.3	0.5	15.7	189.9
New York, NY[b]	65.2	15.3	0.5	19.0	185.1
Brampton, ON[e]	134.3	6.5	0.3	6.8	76.1
Baltimore, MD[d]	125.6	25.9	0.7	18.6	186.6
Philadelphia, PA[b]	61.9	14.1	0.4	15.3	151.9
Mississauga, ON[e]	**73.1**	**7.0**	**0.3**	**11.7**	**130.6**
Washington, DC[f]	121.1	30.0	0.9	23.8	224.5
Oakville, ON[a]	192.9	13.4	0.6	17.4	179.5
Ajax, ON[e]	202.5	15.7	0.5	5.8	65.7
Boston, MA[b]	82.9	20.3	0.7	18.0	183.1
Woodbridge, NJ[g]	164.4	24.2	0.8	31.9	317.9
Minneapolis, MN[h]	64.8	15.0	0.5	18.3	185.4
Syracuse, NY[d]	134.7	24.2	0.8	15.2	160.7
San Francisco, CA[a]	55.7	14.7	0.4	10.7	106.1
Morgantown, WV[i]	294.5	37.7	1.2	29.1	271.2
Moorestown, NJ[g]	153.4	27.9	0.9	28.1	276.5
Jersey City, NJ[g]	35.5	5.0	0.2	9.6	95.1
Casper, WY[a]	22.5	6.2	0.2	6.2	62.9
Freehold, NJ[g]	94.6	35.9	1.0	39.6	401.0

Appendix F: Criteria and Indicators for Sustainable Urban Forest Management

Source: Kenney, W.A., van Wassenaer, P.J.E, and A.L. Satel. 2011. Criteria and Indicators for Strategic Urban Forest Management and Planning

Vegetation Resource					
Criteria	**Performance Indictors**				**Key Objective**
	Low	**Moderate**	**Good**	**Optimal**	
Relative Canopy Cover	The existing canopy cover equals 0 - 25% of the potential	The existing canopy cover equals 25-50% of the potential	The existing canopy cover equals 50-75% of the potential	The existing canopy cover equals 75-100% of the potential	Achieve climate-appropriate degree of tree cover, community wide
Age distribution of trees in the community	Any Relative DBH (RDBH) class (0-25% RDBH, 26-50% RDBH, etc.) represents more than 75% of the tree population.	Any RDBH class represents between 50% and 75% of the tree po pulation.	No RDBH class represents more than 50% of the tree population	25% of the tree population is in each of four RDBH classes.	Provide for uneven-aged distribution city-wide as well as at the neighbourhood and/or street segment level.
Species suitability	Less than 50% of trees are of species considered suitable for the area.	50% to 75% of trees are of species considered suitable for the area.	More than 75% of trees are of species considered suitable for the area.	All trees are of species considered suitable for the area.	Establish a tree population suitable for the urban environment and adapted to the regional environment.
Species distribution	Fewer than 5 species dominate the entire tree population city-wide.	No species represents more than 10% of the entire tree population city-wide.	No species represents more than 5% of the entire tree population city-wide.	No species represents more than 5% of the entire tree population city-wide or at the neighbourhood /street segment level.	Establish a genetically diverse tree population city-wide as well as at the neighbourhood and/or street segment level.
Condition of Publicly-owned Trees (trees managed intensively)	No tree maintenance or risk assessment. Request based/reactive system. The condition of the urban forest is unknown	Sample-based inventory indicating tree condition and risk level is in place.	Complete tree inventory which includes detailed tree condition ratings.	Complete tree inventory which includes detailed tree condition and risk ratings.	Detailed understanding of the condition and risk potential of all publicly- owned trees
Publicly-owned natural areas (trees managed extensively, e.g. woodlands, ravine lands, etc.)	No information about publicly-owned natural areas.	Publicly-owned natural areas identified in a "natural areas survey" or similar document.	The level and type of public use in publicly-owned natural areas is documented	The ecological structure and function of all publicly-owned natural areas are documented and included in the city-wide GIS	Detailed understanding of the ecological structure and function of all publicly-owned natural areas.
Native vegetation	No program of integration	Voluntary use of native species on publicly and privately- owned lands.	The use of native species is *encouraged* on a project-appropriate basis in both intensively and extensively managed areas.	The use of native species is *required* on a project-appropriate basis in both intensively and extensively managed areas.	Preservation and enhancement of local natural biodiversity

Community Framework					
Criteria	Performance Indictors				Key Objective
	Low	Moderate	Good	Optimal	
Public agency cooperation	Conflicting goals among departments and or agencies.	Common goals but no cooperation among departments and/or agencies.	Informal teams among departments and or agencies are functioning and implementing common goals on a project-specific basis.	Municipal policy implemented by formal interdepartmental/ interagency working teams on ALL municipal projects.	Insure all city departments cooperate with common goals and objectives
Involvement of large private and institutional land holders	Ignorance of issues	Educational materials and advice available to landholders.	Clear goals for tree resource by landholders. Incentives for preservation of private trees.	Landholders develop comprehensive tree management plans (including funding).	Large private landholders embrace city-wide goals and objectives through specific resource management plans.
Green industry cooperation	No cooperation among segments of the green industry (nurseries, tree care companies, etc.) No adherence to industry standards.	General cooperation among nurseries, tree care companies, etc.	Specific cooperative arrangements such as purchase certificates for "right tree in the right place"	Shared vision and goals including the use of professional standards.	The green industry operates with high professional standards and commits to city-wide goals and objectives.
Neighbourhood action	No action	Isolated or limited number of active groups.	City-wide coverage and interaction.	All neighbourhoods organized and cooperating.	At the neighbourhood level, citizens understand and cooperate in urban forest management.
Citizen-municipality-business interaction	Conflicting goals among constituencies	No interaction among constituencies.	Informal and/or general cooperation.	Formal interaction e.g. Tree board with staff coordination.	All constituencies in the community interact for the benefit of the urban forest.
General awareness of trees as a community resource	Trees seen as a problem, a drain on budgets.	Trees seen as important to the community.	Trees acknowledged as providing environmental, social and economic services.	Urban forest recognized as vital to the communities environmental, social and economic well-being.	The general public understanding the role of the urban forest.
Regional cooperation	Communities cooperate independently.	Communities share similar policy vehicles.	Regional planning is in effect	Regional planning, coordination and /or management plans	Provide for cooperation and interaction among neighbouring communities and regional groups.

Resource Management Approach					
Criteria	**Performance Indictors**				**Key Objective**
	Low	**Moderate**	**Good**	**Optimal**	
Tree Inventory	No inventory	Complete or sample-based inventory of publicly-owned trees	Complete inventory of publicly-owned trees AND sample-based inventory of privately-owned trees.	Complete inventory of publicly-owned trees AND sample-based inventory of privately-owned trees included in city-wide GIS	Complete inventory of the tree resource to direct its management. This includes: age distribution, species mix, tree condition, risk assessment.
Canopy Cover Inventory	No inventory	Visual assessment	Sampling of tree cover using aerial photographs or satellite imagery.	Sampling of tree cover using aerial photographs or satellite imagery included in city-wide GIS	High resolution assessments of the existing and potential canopy cover for the entire community.
City-wide management plan	No plan	Existing plan limited in scope and implementation	Comprehensive plan for publicly-owned intensively and extensively managed forest resources accepted and implemented	Strategic multi-tiered plan for public and private intensively and extensively managed forest resources accepted and implemented with adaptive management mechanisms	Develop and implement a comprehensive urban forest management plan for private and public property.
Municipality-wide funding	Funding for reactive management	Funding to optimize *existing* urban forest.	Funding to provide for net increase in urban forest benefits.	Adequate private and public funding to sustain maximum urban forest benefits.	Develop and maintain adequate funding to implement a city-wide urban forest management plan
City staffing	No staff.	No training of existing staff.	Certified arborists and professional foresters on staff with regular professional development.	Multi-disciplinary team within the urban forestry unit.	Employ and train adequate staff to implement city-wide urban forestry plan
Tree establishment planning and implementation	Tree establishment is *ad hoc*	Tree establishment occurs on an annual basis	Tree establishment is directed by needs derived from a tree inventory	Tree establishment is directed by needs derived from a tree inventory and is sufficient to meet canopy cover objectives	Urban Forest renewal is ensured through a comprehensive tree establishment program driven by canopy cover, species diversity, and species distribution objectives
Tree habitat suitability	Trees planted without consideration of the site conditions.	Tree species are considered in planting site selection.	Community wide guidelines are in place for the improvement of planting sites and the selection of suitable species.	All trees planted with adequate soil quality and quantity, and growing space to achieve their genetic potential.	All publically owned trees are planted in habitats that will maximize current and future benefits provided to the site.

Maintenance of publicly-owned, intensively managed trees	No maintenance of publicly-owned trees	Publicly-owned trees are maintained on a request/reactive basis. No systematic (block) pruning.	All publicly-owned trees are systematically maintained on a cycle longer than five years.	All mature publicly-owned trees are maintained on a 5-year cycle. All immature trees are structurally pruned.	All publicly-owned trees are maintained to maximize current and future benefits. Tree health and condition ensure maximum longevity.
Tree Risk management	No tree risk assessment/ remediation program. Request based/reactive system. The condition of the urban forest is unknown	Sample-based tree inventory which includes general tree risk information; Request based/reactive risk abatement program system.	Complete tree inventory which includes detailed tree failure risk ratings; risk abatement program is in effect eliminating hazards within a maximum of one month from confirmation of hazard potential.	Complete tree inventory which includes detailed tree failure risk ratings; risk abatement program is in effect eliminating hazards within a maximum of one week from confirmation of hazard potential.	All publicly owned trees are safe.
Tree Protection Policy Development and Enforcement	No tree protection policy	Policies in place to protect public trees.	Policies in place to protect public and private trees with enforcement.	Integrated municipal wide policies that ensure the protection of trees on public and private land are consistently enforced and supported by significant deterrents	The benefits derived from large-stature trees are ensured by the enforcement of municipal wide policies.
Publicly-owned natural areas management planning and implementation	No stewardship plans or implementation in effect.	Reactionary stewardship in effect to facilitate public use (e.g. hazard abatement, trail maintenance, etc.)	Stewardship plan in effect for each publicly-owned natural area to facilitate public use (e.g. hazard abatement, trail maintenance, etc.)	Stewardship plan in effect for each publicly-owned natural area focused on sustaining the ecological structure and function of the feature.	The ecological structure and function of all publicly-owned natural areas are protected and, where appropriate, enhanced.