Markham Forest Study 2022: Technical Report

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Joanna Klees van Bommel, Toronto and Region Conservation Authority
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Michelle Bourdeau, York Region
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Executive Summary

The Regional Municipality of York (York Region) along with the City of Markham (Markham) are committed to assessing the distribution, structure, and function of Markham's forest every 10 years through a Forest Study. A Forest Study employs a combination of remote sensing, GIS tools, and plot-based field surveys to characterize the forest across the entire City and examines factors that may impact its health and function, such as invasive species and soil condition.

The Region in partnership with Markham retained Toronto and Region Conservation Authority (TRCA) to undertake the Markham Forest Study. This technical report examines the distribution of canopy cover by Municipal Property Assessment Corporation (MPAC) land use type, available planting opportunities, tree size and species composition, the structural and ecosystem services value of the forest, condition of the forest, and soil properties. Additionally, the report explores change since the last assessment, the potential future state of the forest, and climate vulnerability. Data for the past and current assessments were collected in 2009 and 2021, but this report refers to the publication years of 2012 and 2022, respectively, for clarity.

Markham's forest has an estimated 3.29 million trees with an estimated structural value of $1.09 billion. Trees in Markham sequester approximately 8,693 tonnes of carbon per year, with an associated annual value of $1.6 million and store 265,348 tonnes of carbon, valued at $50.1 million. Markham's forest removes 147.1 tonnes of air pollution annually; the benefit of this ecosystem service is valued at $2.7 million annually. In Markham the forest reduces the annual energy consumption of residential homes and low-rise apartments by approximately 416,089 MBTUs and 11,245 MWH, with an associated annual financial savings of approximately $1.89 million.

Canopy cover in Markham is at twenty-one percent, an increase of three percent since 2012 due to tree planting, natural regeneration, and growth of existing trees. A total of sixty-six percent (13,826 ha) of the City's land area could theoretically support additional canopy. However, much of this area is contained within active agricultural areas which in practice cannot be planted. Rouge National Urban Park also overlaps Markham's boundaries and presents opportunities to increase canopy and woodland cover.

Markham's forest is young, and seventy-nine percent of the trees are in excellent, good, and fair condition. Approximately, seventy-two percent of all trees are less than 15.2 cm diameter at breast height (DBH) – these trees will grow in future years, increasing both canopy cover and benefit provision. The top three species make up 49 percent of the population and efforts to diversify tree species composition and reduce planting of these three species is recommended. Limited species diversity reduces the resilience of the forest to impacts of climate change, pests, and diseases. Over the past 10 years Markham's forest has been significantly impacted by Emerald Ash Borer (EAB), slowing the City's efforts to increase canopy cover.

Soil and climate change impact the health of the forest – soil on private properties was found to have higher compaction, salinity, and pH than soil on public properties. 14 out of the top 20 species in Markham are expected to be moderately to extremely vulnerable to climatic changes that would occur by the 2050s, according to the Intergovernmental Panel on Climate Change's Representative Concentration Pathway (RCP) 8.5 (business-as-usual scenario).

Summary of Results

Through regular monitoring, this information can be used to track progress towards established goals, measure the effectiveness of efforts to maintain a healthy forest, and can guide future management decisions.

Tree Cover and Leaf Area

Markham's estimated 3.29 million trees (±470,000) provide Markham with 21 percent canopy cover. An additional 66 percent (13,826 ha) of the City's land area could theoretically support canopy cover, however, much of this area is currently cultivated and a significant proportion of these cultivated lands are designated for future urban development. Canopy cover has increased by three percent since 2012. Although trees have been lost to development, canopy has increased due to the planting and growth of existing trees, particularly in newer residential neighbourhoods. As Markham urbanizes, continuing tree planting requirements and restoration plans will help maintain canopy growth.

Leaf area in the City increased from 2012 to 2022, increasing tree benefits for Markham. Leaf area is approximately 23,912 hectares across a municipal area of 21,268 hectares, that is 1.12 m^2 of leaf area for every 1.0 m^2 of land, and the average tree density in Markham is 155 trees/hectare. The previous leaf area was 1.01m^2 of leaf area per 1.0 m^2 of land in Markham, with an average tree density of 148 trees/ha.

It is estimated that approximately 45 percent (±10.7%) of trees are located on publicly owned lands[1]. Public lands include municipal parks, rights-of-ways (ROWs), and protected areas, such as conservation authority lands. 55 percent (±10.9%) of trees are on private lands, which makes working with private landowners an essential component of maintaining and enhancing tree canopy.

Canopy Cover and Plantable Space by Land Use

Canopy cover was analyzed by land use type. Land use types were based on the Municipal Property Assessment Corporation's (MPAC) allocation of land use codes to properties for tax purposes (Figure i). The *Natural Cover* land use category has the highest canopy cover percent within a land use, with 49 percent tree cover. However, due to the relatively small size of this category, canopy cover within the *Natural Cover* category (411 ha) contributes to only 9 percent of the municipality's total canopy cover area. The greatest proportion of the existing canopy (1,171 ha) is found within the *residential low* category which contributes to 26.9 percent of Markham's total canopy cover area.

Agricultural lands have the largest available planting space (5,610 hectares), but it is not practical to plant on these lands. Canopy cover can be increased by planting on surfaces currently occupied by herbaceous/low shrubs and non-building or road paved surfaces that occur within residential areas and right-of-ways (ROWs) at 2,106 hectares and 1,898 hectares, respectively.

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[1] Including municipal, provincial, and federal, as well as well conservation authorities' lands

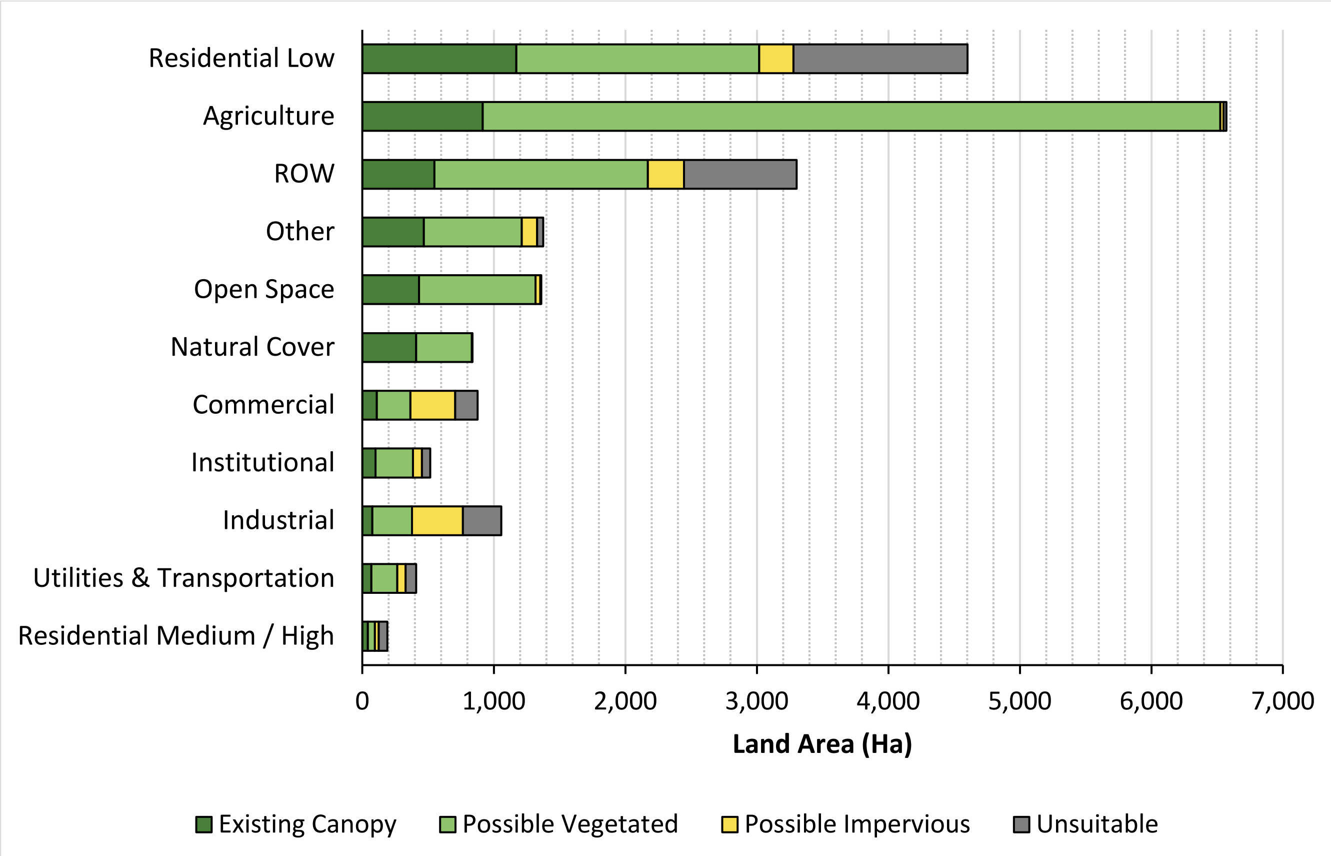

Figure i: The distribution of existing canopy cover and possible canopy cover[2] (ha) of MPAC land use land area in Markham 2022.

Species Composition

Between 2012 and 2022 there was a shift in the composition of the most common tree species in terms of population and leaf area (Table i and iii).

The Markham Forest is dominated by eastern white cedar (*Thuja occidentalis*), European buckthorn (*Rhamnus cathartica)* and sugar maple (*Acer saccharum*), and together, these species make up 49 percent of the tree population. The same species were dominant in 2012, then comprising 43 percent of the population. (Table i). These tree species are mostly found in residential areas; eastern buckthorn is found in all land use strata, while eastern white cedar is found in all strata except commercial-industrial, and sugar maple is found in all except agriculture (Table ii).

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[2] Possible Vegetated: plantable space occurring on herbaceous/low shrub land cover; Possible Impervious: plantable space occurring on paved surfaces other than roads and buildings.

Table i: Top three most abundant tree species in 2012 and 2022 in terms of tree population

2012		2022	
Species	**Percent of Population (%)**	**Species**	**Percent of Population (%)**
Eastern white cedar *(Thuja occidentalis)*	21	Eastern white cedar *(Thuja occidentalis)*	33
Sugar maple (*Acer saccharum*)	11	European buckthorn (*Rhamnus cathartica)*	9
European buckthorn (*Rhamnus cathartica)*	11	Sugar maple (*Acer saccharum*)	7

Table ii: Top 3 most abundant tree species in 2022 by land use stratum

Stratum	Species	Number of Trees	SE	Relative Percentage of Stratum (%)
Agriculture	European buckthorn	31,020	±28,505	53
	Eastern white cedar	10,340	±10,338	
Commercial – Industrial	Sugar maple	22,741	±22,737	55
	European buckthorn	63,170	±60,543	
Open Space – Natural Cover	Sugar maple	60,971	±29,227	29
	European buckthorn	84,829	±56,789	
	Eastern white cedar	55,669	±43,792	
Residential	Sugar maple	2,810	±2,809	69
	European buckthorn	47,770	±21,392	
	Eastern white cedar	890,763	±289,962	
Utilities – Transportation	Sugar maple	42,466	±33,598	35
	European buckthorn	7,078	±5,219	
	Eastern white cedar	58,981	±54,227	
Other – Institutional	Sugar maple	86,635	±62,109	34
	European buckthorn	72,773	±49,498	
	Eastern white cedar	79,704	±66,225	

In terms of leaf area, the forest is also homogeneous with the top three species – sugar maple, eastern white cedar, and Norway maple (*Acer platanoides*) – contributing to 44 percent of the leaf area. A forest with minimal species diversity is vulnerable to pests and diseases. Since 2012, a larger proportion of eastern white cedar and Norway maple contribute towards the total population and leaf area, indicating an increase in their dominance. (Table iii).

Table iii: Top three tree species in 2012 and 2022 as a proportion of leaf area

2012		**2022**	
Species	**Percent of Leaf Area (%)**	**Species**	**Percent of Leaf Area (%)**
Sugar maple (*Acer saccharum*)	13	Sugar maple (*Acer saccharum*)	23
Eastern hemlock (*Tsuga canadensis*)	9	Eastern white cedar *(Thuja occidentalis)*	11
Eastern white cedar *(Thuja occidentalis)*	8	Norway maple (*Acer platanoides*)	10

Tree Size

Approximately 72 percent of all trees in Markham are less than 15.2 cm diameter at breast height (DBH), while just over 9 percent of trees have a DBH larger than 30.6 cm. Across all MPAC land use categories the trend is similar, with the smallest diameter classes containing the large majority of trees, while very few trees (<3.5% of the total) are found in the larger diameter classes (>45.7 cm). The average DBH across the forest in 2022 was 14.2 cm compared to 14.3 cm in 2012. While the young, small trees that make up Markham's forest will grow into larger trees, the size distribution will still be uneven so continued planting and maintenance efforts are necessary. Active planting needs to continue, and trees of all sizes require protection to ensure younger trees are present to replace older trees as they die. This is critical because older and larger trees provide significantly more ecosystem service benefits than smaller trees and take decades to replace with new plantings.

Condition

All trees measured were assigned a condition rating in the field based on the proportion of dieback in the crown canopy. Most trees in Markham are in good condition, with approximately 80 percent in excellent, good, or fair condition (<25% dieback). However, the percent of trees in poor, critical, dying, or dead condition has increased from 12 percent in 2012 to 20 percent in 2022. As shown in Figure ii below, *Open Space – Natural Cover* (21.2%) has the greatest proportion of dying and dead trees, followed by *Other – Institutional* (15.4%). The percentage of poor condition trees on *Other – Institutional* lands may be concerning. Ash (*Fraxinus spp*.) represents some of these trees, however other species are struggling as well. Black walnut (*Juglans nigra*) and yellow birch (*Betula alleghaniensis*) represent a high percentage of poor condition trees as well. On *Open Space – Natural Cover* land, the high percentage of poor condition trees also reflect dead ash on some sites but is also indicative of different management strategies. Dead trees within natural areas play an important role in the ecosystem, providing a variety of resources to other organisms, such as nesting opportunities or food sources. As a result, trees that are dead or in poor condition should be left in place in natural settings unless they pose a safety risk. However, in more urbanized settings, trees in poor health can present risk to infrastructure and public safety, and oftentimes need to be removed.

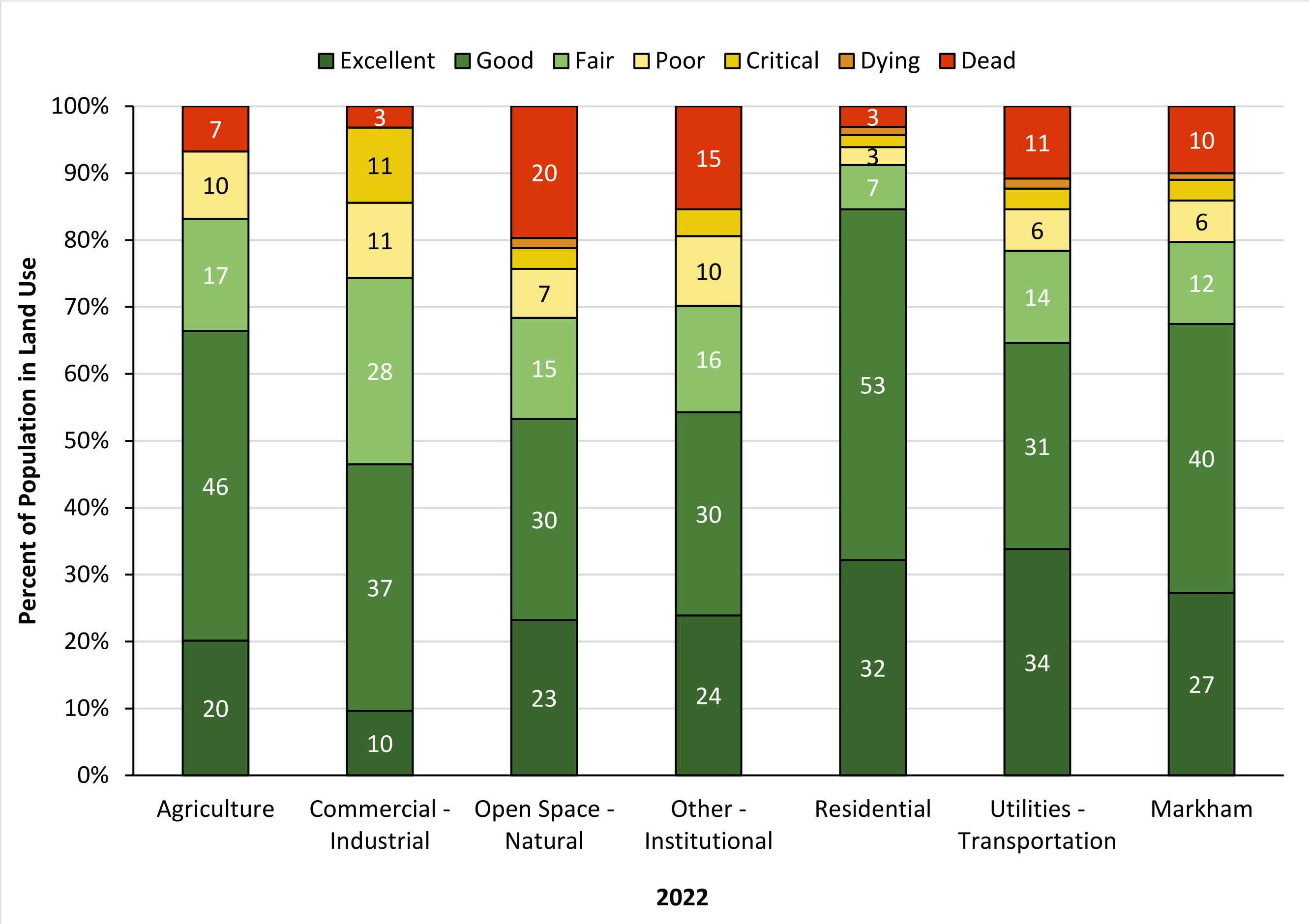


Figure ii: The proportion of trees in each condition category across Markham in 2022

Structural Value of Trees

The estimated structural value of all trees in Markham in 2022 is approximately $1.09 billion. This value does not include the ecological or societal value of the forest, but rather it represents an estimate of tree replacement costs or compensation value to tree owners for tree loss. This value is based on the Council of Tree and Landscape Appraisers (CTLA) Trunk Formula method, which considers species, DBH, condition, and location (Nowak, 2020).

Ecosystem Service Benefits

Carbon Storage and Sequestration

As a tree grows, it removes carbon dioxide from the atmosphere; this process is referred to as *carbon sequestration*, which is expressed as an annual rate of removal. Carbon is then stored in the woody biomass of the tree; this can be expressed as total *carbon storage*. When a tree dies, much of the stored carbon is released back to the atmosphere through decomposition. Trees in Markham sequester approximately 8,693 tonnes of carbon per year, with an associated annual value of $1.6 million and store 265,348 tonnes of carbon, valued at $50.1 million. Since 2012, gross annual carbon sequestration has remained roughly equivalent to the 9,200 tonnes of carbon per year in 2022, but net sequestration has decreased from 7,400 to 5,424 tonnes carbon per year. Decline in net sequestration is likely attributed to the increase of trees in critical, dying, or dead condition. In particular, dying and dead ash trees (*Fraxinus* spp.) are expected to emit carbon as they decompose (1,325 tC/year). Total storage increased from 230,000 tonnes. Sugar maple stores the greatest volume of carbon and the largest amount of carbon annually.

Air Pollution Removal

The forest can improve local air quality by absorbing and intercepting airborne pollutants. Markham's forest removes 147.1 tonnes of air pollution annually; the benefit of this ecosystem service is valued at $2.7 million annually. The forest removes the following pollutants:

- Ozone: 124.5 tonnes
- Particulate matter (2.5 microns): 7.1 tonnes
- Nitrogen dioxide: 12.6 tonnes
- Sulfur dioxide: 1.3 tonne
- Carbon monoxide: 1.6 tonne

Residential Energy Savings

Trees have a moderating effect on building temperatures by cooling the air through shade and the release of water vapor during evapotranspiration and retaining heat through wind speed reductions. Therefore, trees can reduce the demand for both heating and air conditioning depending on the season. In Markham, the forest reduces the annual energy consumption of residential homes and low-rise apartments by approximately 416,089 MBTUs and 11,245 MWH, with an associated annual financial savings of approximately $1.89 million.

Hydrological Benefits

The forest helps to prevent rainwater from entering the stormwater system, known as avoided runoff, by capturing rainwater, evapotranspiration, and facilitating the infiltration of water into the soil. Using 2019 rainfall data from Pearson International Airport, it was determined that Markham's forest avoided 742,449 m^3 runoff in 2019. This service has an associated value of just over $1.7 million per year.

Soil

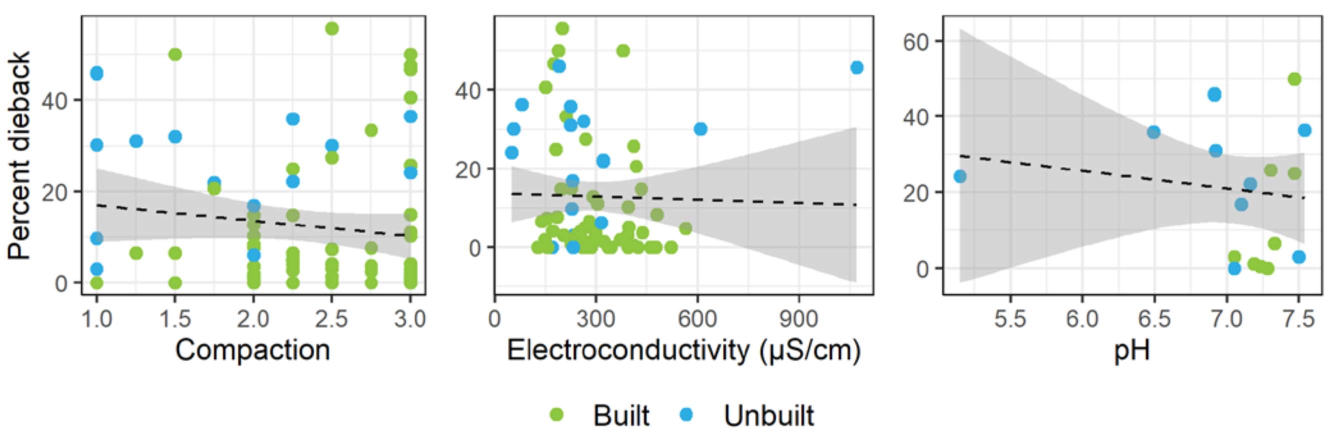
Soil is a vital component and indicator of forest health. The chemical and physical properties of soil influence its fertility and the capacity for plant growth. Urban soils are characterized by high levels of compaction, salinity, and alkalinity because of intensive human management and deposition of toxic elements from impermeable surfaces. The 2022 Markham Forest Study included the collection of data on soil health for the first time.

Soil on private properties was found to have higher compaction, salinity (using electroconductivity as a proxy), and pH than soil on public properties (including conservation authority lands) (Table iv). Soil in plots occurring in *Open Space – Natural Cover* land use category, and other undeveloped land uses, had lower compaction, salinity, and pH than plots in built or developed land uses. Greater compaction and salinity are associated with decreased tree health. Research by the United States Department of Agriculture (USDA) has shown that almost no roots can penetrate soil with a penetration resistance (psi) of 300 psi or more (Duiker, 2002). Plant tolerance to salinity is species-dependent, however as salinity increases there may be constraints on plant success. Lastly, optimal soil pH is typically between 6.0 – 7.0, where soil with pH levels that are too alkaline or acidic can hinder plant growth.

Table iv: Soil properties across Markham

Soil Property	Open Space – Natural Cover	Residential Areas	Other Built Land Uses
Uncompacted plots (% of plots)	48	15	8
Median salinity (µS/cm)	231	291	284
Median pH	6.6	7.7 (all developed classes)	

The relationship between soil compaction, salinity (indicated by electroconductivity), pH, and tree condition measured as percentage crown dieback was analyzed using correlation testing (Figure iii). While it would be expected that increased canopy dieback would be associated with increased average compaction, salinity and pH, the opposite was found through correlation testing. There are several likely reasons for these observations. Due to the soil data largely being collected from public lands, many of which falling into natural woodlands, the soil data is skewed to reflect conditions in public lands. For example, dead and dying trees, including ash trees, are important structural components and are typically left standing in natural forests to provide habitat space for wildlife unless they pose a hazard for the public. Hence, while natural areas tend to have less compaction and lower salinity levels, these areas tend to have more dead and dying trees representative of unmanaged natural areas.



Note: Line indicates a linear regression and grey shaded area is the standard error.

Figure iii: Scatterplots of crown dieback versus soil compaction, electroconductivity as an indicator of salinity, and pH

Invasive Species

Plants

Out of the 202 plots surveyed, 43 percent of plots had at least one invasive plant species present. Invasive plant species were most prevalent in the *Residential* land use category (80% of plots), followed by *Other – Institutional* (64% of plots). The most common invasive species in terms of the proportion of plots affected were European buckthorn (*Rhamnus cathartica*) (22%), Norway maple (*Acer platanoides*) (16%), dog strangling vine (*Cynanchum rossicum*) (14%), Manitoba maple (*Acer negundo*) (13%), wintercreeper euonymus (*Euonymus fortunei*) (12%), and garlic mustard (*Alliaria petiolata*) (10%).

Pests and Diseases

The presence and/or symptoms of spongy moth (*Lymantria dispar dispar*) were observed at 30 percent of plots surveyed in Markham, while emerald ash borer (EAB, *Agrilus planipennis*) was observed at 12 percent of plots. Beech bark disease (*Neonectria faginata*) was only found in 3 plots.

Climate Vulnerability

A climate vulnerability assessment of the top twenty most abundant species in Markham, revealed that all but six species (30%) were moderately to extremely vulnerable to climatic changes that would occur by the 2050s, according to RCP 8.5 (business-as-usual scenario). Under this scenario, Markham is expected to become warmer, drier in the summer, and experience more extreme weather events. Two of the six species that were assigned a low vulnerability score are not recommended for planting because they are invasive (Manitoba maple and black locust). Of the native species, eastern white cedar and sugar maple are highly and moderately vulnerable to climate change, respectively. This is of particular concern as they dominate the forest composition. The potential decline of these two species poses a threat to the wellbeing of Markham's forest and the services and benefits it provides. It is essential to increase the diversity of resilient native and non-native, non-invasive plant species. Species such as sugar maple, eastern hophornbeam (*Ostrya virginiana*), black gum (*Nyssa sylvatica)*, and honey locust (*Gleditsia triacanthos*) should be planted because they are anticipated to have low or moderate vulnerability to the impacts of climate change.

Summary of Recommendations

The following recommendations were developed based on the results of the report, the current municipal context (i.e., existing programs, plans, policies, etc.), and the capacity and priorities of the City of Markham. The recommendations below have been developed in alignment with Markham's existing planning and management documents. Some recommendations are included in multiple sections as the recommended actions are cross-applicable. These are indicated with an asterisk (*).

Existing and Possible Forest Distribution

Recommendation 1*: The City's Urban Forest Management Plan is a study to be undertaken starting in 2023 and should address: local canopy targets; species diversity; forest health, maintenance, and monitoring; invasive species management; soil conservation strategies; and climate change mitigation and adaptation.

Recommendation 2: The next Official Plan update should include a commitment to at least 30 percent canopy cover target to align with the Markham Greenprint Sustainability Plan. However, it is recommended to aim for a more ambitious target of 35 percent. Additionally, the development of a woodland cover target should be further explored as a component of an overall canopy target by assessing the feasible restoration potential in the Greenway System.

- Approximately 66 percent of the municipality (13,826 ha) has been identified as possible tree canopy (area theoretically available for additional tree establishment); the majority of this is identified as possible vegetated land cover (8,005 ha). While it is not practical to plant in all pervious vegetated areas due to site considerations, there is an opportunity to increase canopy cover to more than 30 percent.

Recommendation 3: Develop canopy cover targets for all land use types within the Official Plan.

Recommendation 4: Work with York Region to customize and utilize the Region's tree planting prioritization tool for Markham to improve equitable canopy cover distribution, the maximization of ecological benefits and ecosystem services, and target areas impacted by invasive pests.

Recommendation 5: Develop mechanisms to encourage and support private landowners (particularly commercial and industrial landowners, and property developers) to protect and enhance canopy and educate those landowners about maintenance best practices.

Recommendation 6: Continue to plant, prune and replace trees on municipal roads, parks and other municipal properties. Evaluate planting and maintenance budgets regularly as the City grows and assumes responsibility for new roads, parks and facilities.

Recommendation 7: Continue to carry out restoration plantings in the natural heritage system and other naturalized areas.

Improving Tree Diversity

See Recommendation 1.

Recommendation 8*: In line with current practices, continue to establish a diverse tree population in intensively managed urban areas, 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 intensively managed tree population both municipal-wide and at the neighbourhood level.

- In 2012, the above recommendation was made to guide the establishment of a diverse tree population in Markham. The current composition of the City's forest does not yet reflect this ratio, however it should be noted that planting and management changes since the last study require sufficient establishment time frames which may not yet be reflected in this iteration of the Forest Studies. Each of the top three species represent more than five percent of the tree population (eastern white cedar (*Thuja occidentalis,* 21%), sugar maple (*Acer saccharum,* 11%), European buckthorn (*Rhamnus cathartica,* 11%)). The two most common genera each represent more than 10 percent of the tree population (Cedars and junipers (*Cupressoideae* sub-family, 33.7%) and maple (*Acer spp.,* 11.8%)). It should be noted the third most common genus is largely made up of European buckthorn (Rhamnus spp. 9.7%), an invasive species.

Recommendation 9*: Investigate the utility and potential application of pest vulnerability tools, such as the Pest Vulnerability Matrix (PVM)[3] during species selection for municipal tree and shrub planting.

- This recommendation was made in the 2012 report and has been updated for the 2022 report. Given the anticipated increase in invasive pest outbreaks due to climate change, it is essential to enhance the diversity of the forest to ensure it is resilient to insect and disease outbreaks. The PVM is a model developed to visualize and assess the susceptibility of the forest to insects and diseases (Laçan & McBride, 2008). Using a model such as the PVM during tree species selection will help account for potential damage by future pest outbreaks, particularly by multi-host pests.

Recommendation 10: Consider the development of an education campaign focused on educating private landowners about the importance of species diversity for a resilient forest, particularly in the context of climate change.

Recommendation 11*: Utilize native and appropriate non-native, non-invasive planting stock in both intensively and extensively managed areas. Increase genetic diversity of tree populations by using the guidance provided by the Ontario Tree Seed Transfer Policy. This policy is intended to help managers source seed based on the projected changes in climate to increase the likelihood of producing trees well-adapted to current and future conditions.

- Given the sensitivity of native species to climate change establishing a diverse forest composed of both native and suitable non-native non-invasive species will support the resiliency of the forest to stressors.

Increasing the number of large, mature trees

See Recommendation 1.

Recommendation 12: Evaluate and develop the strategic steps required to increase the number and proportion of large, mature trees across Markham's forest including the City's Greenway System, street and park trees and trees on private lands.

- As urban trees increase in size, their environmental, social, and economic benefits increase exponentially. Large trees provide much greater energy savings, air and water quality improvements, runoff reduction, visual impact, increase in property values, and carbon sequestration.

Recommendation 13*: Review and enhance tree preservation requirements in municipal guidelines (Trees for Tomorrow Streetscape Manual) and regulations for sustainable streetscape and subdivision design standards (and particularly soil volume) to support tree establishment and eliminate conflict between natural and grey infrastructure.

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[3] For detailed methodology, please see Laçan and McBride (2008). The PVM tool can be obtained by contacting the author. Additionally, see research conducted by Vander Vecht, & Conway (2015) which applied the PVM to explore pest vulnerability of the species in Toronto's urban forest.

- Integrating green infrastructure, like trees, along side grey infrastructure has many benefits for urban populations, however for trees to survive and establish, appropriate design is necessary to optimize their growing conditions.

Effect on Air Quality

See Recommendation 1.

Recommendation 14: Where appropriate, select and plant long lived, low maintenance, and low volatile organic compound (VOC) emitting tree species.

- Since larger, long-lived individuals provide the greatest per-tree effects, they should be selected to provide long-term benefits. Similarly, having low maintenance trees will reduce the associated emissions from arborist maintenance by use of gas-powered equipment.

Recommendation 15: Bolster evergreen tree population across the municipality to improve year-round pollution removal services.

- By planting evergreen species, which have foliage all year round, Markham's trees can provide air pollution removal benefits during the leaf-off seasons (late fall to early spring) where deciduous trees don't provide air pollution associated benefits.

Recommendation 16: Engage in strategic tree planting in high emissions zones.

- Areas with dense pollution emissions should be targeted as high priority planting sites. For example, planting adjacent to highways or high emission industrial sites would be beneficial to offsetting immediate emissions.

Recommendation 17*: Consider developing an education campaign within the City's Trees for Tomorrow Program focused on educating the public about the ecosystem benefits Markham's forest provides.

- Green infrastructure, like trees, provide a wide variety of ecosystem services. Services can be grouped into four categories: provisioning (e.g., providing food), regulating (e.g., regulating climate), supporting (e.g., biodiversity) and cultural (e.g., providing recreation opportunities). These services translate to numerous benefits for humans and can be attributed a monetary value indicating how important these benefits are to people. Educating the public about the many benefits provided by urban trees will promote stewardship of the forest.

Effect on Stormwater Runoff

See Recommendation 1.

See Recommendation 13.

See Recommendation 17.

Recommendation 18: Continue to apply subsurface (Silva) cells on a project-by-project basis and other enhanced rooting environment techniques for street trees, particularly in constrained spaces such as intensification areas.

- Green infrastructure should be incorporated into grey infrastructure planning and development as it can function to intercept precipitation, cool paved surfaces, directly remove air pollution, and improve soil content available for runoff capture in urbanized areas.

- Utilizing these technologies at selected sites in the short-term may provide a cost-effective means of integrating these systems into the municipal budget. Silva cells can function to improve stormwater runoff channels.

Recommendation 19: Explore the opportunity to utilize the Sustainable Technology Evaluation Program Treatment Train Tool to evaluate and quantify the stormwater benefits of planting trees.

- The Low Impact Development Treatment Train Tool provides the ability to design and evaluate different urban tree planting scenarios at the site level to determine stormwater management benefits and can be a very effective way to demonstrate the benefits of urban tree planting.

Effect on Residential Energy Bills

See Recommendation 1.

See Recommendation 17.

Recommendation 20: Following the City of Markham's Official Plan recommendation to encourage tree planting to reduce the urban heat island effect (Section 6.2.3.1. c), consider including the potential of trees to provide energy savings when developing planting guidelines or standards. Consider the use of Letters of Credit or other tools to ensure tree establishment and success in the implementation of the Sustainability Metrics as a green development standard in Markham.

- Research has shown that trees planted 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. Therefore, tree species selection and placement should be targeted to provide summer shade and reduce winter wind speeds around residential buildings.

Climate Change Mitigation and Adaptation

See Recommendation 1.

Recommendation 21: Consider including species' capacity for carbon storage and sequestration when developing planting lists or guidelines and future Urban Forest Management Plans.

- Trees are considered a natural climate solution. Trees can mitigate climate change by sequestering atmospheric carbon and then storing it long-term as woody biomass. Additionally, as climate change worsens, the role of trees, and to a larger extent the forest, will become increasingly more important as a means to mitigate heat stress especially in urban areas which are already warmer than surrounding regions due to the urban heat island effect.

Soil Health

See Recommendation 1.

See Recommendation 13.

Recommendation 22: Ensure best practices for healthy soils, are implemented in Markham's public and private urban areas in the planning of planting programs, from site selection and assessment to species selection.

Reference tools and programs such as the Sustainability Metrics and Trees for Tomorrow Standards relating to soil health.

Recommendation 23: Manage compaction, salinity, and pH on public property through amendments and remedial measures like mulching and planting of herbaceous cover and shrubs.

- The chemical and physical properties of soil influence its fertility and the capacity for tree growth (Pickett et al. 2011). Urban soils are highly vulnerable to disturbances, and often become modified due to direct effects, such as construction activities, and indirect effects, such as pollution (Lehmann & Stahr, 2007; Pouyat et al. 2019; Foldal et al. 2022).

Recommendation 24: Educate private homeowners and industrial and commercial landowners about soil best practices.

Invasive Plant Species, Pests and Diseases

See Recommendation 1.

See Recommendation 8.

See Recommendation 9.

Recommendation 25: Promote the implementation of natural buffers and fencing along the edges of urban woodlots to protect against the encroachment of invasive species.

Recommendation 26: Continue targeted removal of high priority invasive plant species at high priority sites following best practices.

Recommendation 27: Explore the development and implementation of an invasive plant, pest, and disease education and volunteer program to enhance awareness of invasive plants, pests, and pathogens and proper removal practices.

Recommendation 28: Develop a monitoring and action strategy for invasive species, including pests and diseases, and continue taking proactive approaches to address new and emerging invasive species, such as hemlock woolly adelgid and oak wilt.

- Invasive plants, pests and diseases pose a threat to the health of the forest, and their spread is expected to be exacerbated by climate change.

Monitoring Trends in the Markham Forest

See Recommendation 1.

See Recommendation 8.

Recommendation 29: Reassess tree care and maintenance practices for trees in highly urbanized areas. Indicators associated with street tree mortality should be considered, including plant hardiness and tolerances to harsher urban conditions, tree pit enhancements, direct tree care/stewardship, and assessing local traffic and building conditions.

Recommendation 30: Monitor stand level dynamics and patterns to select species, specifically sugar maple, targeting Carolinian forest stands across Markham.

Recommendation 31: Continue assessing forest structure, function, and distribution every 10 years through the Forest Studies.

- The Forest Studies provide an opportunity to compare change through time, given they involve the reassessment of the same randomly distributed plots every 10 years. The capacity to assess change over time allows for the chance to see the successes and opportunities in the City's forest maintenance, management, and monitoring.

Trajectory and Future Projections

See Recommendation 1.

Recommendation 32: Develop a post-tree planting management and monitoring strategy to complement the tree maintenance program in order to ensure tree survivorship and mitigate common stressors in the urban environment.

- In order to sustain and enhance Markham's forest, the City should continue to engage in tree planting, and proactive monitoring and management.

Climate Vulnerability and Resilience

See Recommendation 1.

See Recommendation 11.

Recommendation 33: Increase proactive, long-term monitoring of species identified as highly and extremely vulnerable to climate change to assess and evaluate the condition of the at-risk species as incremental climate change impacts advance.

- Changes in climate conditions are expected to profoundly alter the environmental conditions across Southern Ontario, limiting the capacity of many tree species to cope as their optimal climatic ranges shift. The resilience of Markham's forest to climate change can be improved via the City's existing policies and plans.

Recommendation 34: Assess the City's current recommended planting list based on the climate vulnerability of each species. Shift recommendations to native and appropriate non-native, non-invasive species that have a higher tolerance and lower vulnerability to climate change impacts.

Recommendation 35: Educate and incentivize private landowners to plant a greater diversity of native, resilient species as part of the Markham Trees for Tomorrow Program, to increase the functional diversity of species planted in Markham. Encourage private landowners to plant alternatives to eastern white cedar, given its high vulnerability to climate change.

Recommendation 36: Assisted range expansion and assisted migration should be further investigated. The City should undertake systematic testing of species from warmer ecodistricts that could be suitable to replace the eleven highly vulnerable and extremely vulnerable species that are at the greatest risk as a result of climate change.

Forestry and Asset Management

Recommendation 37: Continue to integrate green infrastructure into asset management planning, particularly for other municipal natural assets like woodlands and wetlands that have not yet been incorporated.

Table v: Recommendations by Cross-applicable sections

Markham Forest Study Summary of Cross-applicable Recommendations (2022)

	Existing and Possible Forest Dist.	Improving Tree Diversity	Increasing the number of large, mature Trees	Effects on Air Quality	Effects on Stormwater Runoff	Effects on Residential Energy Bills	Climate Change Mitigation and Adaptation	Soil Health	Invasive Plant Species, Pests and Diseases	Monitoring Trends in the Markham Forest	Trajectory and Future Projections	Climate Vulnerability and Resilience	Forestry and Asset Management
Rec. 1	■	■	■	■	■	■	■	■	■	■	■	■	
Rec. 2	■												
Rec. 3	■												
Rec. 4	■												
Rec. 5	■												
Rec. 6	■												
Rec. 7	■												
Rec. 8		■							■	■			
Rec. 9		■							■				
Rec. 10		■											
Rec. 11		■										■	
Rec. 12			■										
Rec. 13			■		■			■					
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1.0 INTRODUCTION

In Markham, the forest is fundamental to social, economic, public, and environmental health, and the resilience of the city. All the trees, shrubs, and woodlands located on public and private property make up the City's forest and provide vital services to the community. A healthy forest cleans the air, reduces stormwater run-off, moderates extreme heat, sequesters carbon, provides habitat for local wildlife, and makes a community more attractive and livable. The value of these services increases exponentially as healthy trees grow and thrive.

Trees and woodlands are adaptable to change, but in urban areas they often require special planning, management, and stewardship to ensure they are protected, maintained, replaced, and integrated properly into the built environment.

The capacity of Markham's forest to support a healthy and resilient community is under threat. Stressors such as climate change impacts, urban development pressures, difficult growing conditions, altered soils, and invasive species continue to challenge the health of the forest. If the forest is to continue to provide consistent services, Markham and its partners must address these challenges in a cost-effective, coordinated way. This requires a comprehensive understanding of forest distribution, structure, and function.

1.1 Purpose

This Forest Study is a resource for use by City and Regional staff to help track and evaluate progress towards established goals, adapt goals and strategies as needed, and make informed management decisions about the forest. The York Region Forest Management Plan has a target of achieving 40 percent canopy cover by 2051 and recommends a canopy cover range of 20 percent to 35 percent for Markham. The Greenprint, Markham's Sustainability Plan has a target of 30 percent tree canopy cover.

The first city-wide analysis of Markham's forest was conducted through a collaboration between Toronto and Region Conservation Authority (TRCA), Markham, and York Region. Data was collected in 2009 and the results were published in the *Markham Urban Forest Study: Technical Report* (TRCA, 2012). The 2012 study now forms a baseline against which change can be measured. The 2022 Forest Study is also an opportunity to analyze issues that were emerging in 2012 and have become more crucial to assess in the intervening years. Specifically, this study will include more detailed information on invasive plant species, pest and disease presence, soil quality, and climate vulnerability for Markham's forest.

To track progress, study partners committed to conducting sample-based field surveys every ten years, and a GIS-based canopy cover assessment every five years. These timelines have been formally established in the York Region Forest Management Plan. For this Forest Study, the canopy cover assessment was completed in 2020 and the field data was collected in 2021.

1.2 Objectives

The objectives of the 2022 Markham Forest Study are to:

- Assess canopy cover distribution and track progress towards canopy cover goals;
- Quantify the current species composition, size, and condition of Markham's forest;
- Quantify ecosystem services and benefits provided by the forest;
- Assess the change in distribution and structure since the 2012 study;
- Analyze key factors relating to forest health, specifically soil health, invasive plant cover, and presence of invasive pests and diseases;
- Conduct an i-Tree Eco Forecast analysis to estimate the tree planting needed to maintain existing canopy cover and to meet the recommended canopy cover goals;
- Assess climate change risks and forest vulnerability; and
- Provide recommendations to support the protection and enhancement of Markham's forest.

2.0 CONTEXT

2.1 Demographic and Ecological Context

The City of Markham is a lower-tier municipality within the Regional Municipality of York. Markham is bounded by the Town of Whitchurch-Stouffville to the north, the City of Pickering to the east, the City of Toronto to the south and the City of Vaughan and City of Richmond Hill to the west. The City falls within five watersheds: Rouge River Watershed; Don River Watershed; Highland Creek Watershed; Petticoat Creek Watershed; and Duffins Creek Watershed. The Provincial Greenbelt (protected Countryside) extends along the northern and western boundaries of the municipality, covering approximately 24 percent of the municipal land area.

Rouge National Urban Park (RNUP) overlaps Markham's boundaries and is Canada's first national urban park, encompassing natural, cultural, and agricultural landscapes rich in biodiversity. The park sits at the northern edge of the Carolinian Zone and is home to numerous habitat types including forests, thickets, meadows, wetlands, rivers, and agricultural fields. RNUP presents promising opportunities to increase canopy and woodland cover.

Population growth in Markham has slowed in the past five years, only increasing by 2.9 percent between 2016 and 2021 compared to a 9 percent increase between 2011 and 2016, and a 25 percent increase from 2006 to 2011 (Statistics Canada, 2021). The current growth rate of the city is lower than the provincial average of 5.8 percent and the national average of 5.2 percent. Despite the slowing population growth, intensification has continued across the municipality. Based on the 2021 census, the total population in Markham is 338,503 and the population density is approximately 1,604 people per square kilometer (Statistics Canada, 2021).

Markham is located within Plant Hardiness Zone 5b according to the Natural Resources Canada Plant Hardiness Zone Map. The City is bordered by the Oak Ridges Moraine to the north and dominated by the Peel Plain and South Slope physiographic regions. Markham is situated almost entirely within ecodistrict 7E-4, which corresponds to the Carolinian Forest Region. The Carolinian Forest Region covers the southern-most portion of the province in a broad band along Lake Erie that extends up along the edge of Lake Ontario. This ecoregion includes many species commonly found in other parts of Ontario, such as sugar maple (*Acer saccharum*) and American beech (*Fagus grandifolia*), as well as regionally rare species such as the Kentucky coffee tree (*Gymnocladus dioicus*), tulip tree (*Liriodendron tulipifera*), and American sycamore (*Platanus occidentialis*). Markham sits at the northern most limit of the Carolinian Forest ecodistrict.

Prior to European settlement Markham and most of southern Ontario was covered by forests and wetlands. The City's 1990 Natural Features Study identified woodland cover had fallen to as low as 5 percent in the early 1900s. 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 due to 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. Today, the most pressing challenges facing the natural systems in Markham are urban development, the effects of climate change, and the threat of invasive diseases and pests. Urban intensification and infill development threaten the retention of trees and reduces the space available for future trees in urban areas. The effects of climate change are already being felt in Markham and are expected to threaten the health and sustainability of the natural environment. Recognizing these challenges, Markham is taking proactive steps to protect and enhance the City's natural systems and mitigate and adapt to climate change.

2.2 Policy and Management Context

The provincial planning policies that guide growth and development heavily influence the retention and enhancement of the forest. The following provincial legislation impacts the capacity for municipalities to protect and increase the forest.

Ontario *Planning Act*, 1990

- The province provides an overarching framework to guide land use planning and development through the *Planning Act*, passed in 1990. The legislation sets out rules for land use planning in Ontario, providing the basis for natural resource management, Provincial Policy Statements, the preparation of municipal Official Plans, and the control of land use through zoning by-laws.

Provincial Policy Statement, 2020

- Under Section 3 of the *Planning Act*, the province can issue directions for municipalities in the form of the Provincial Policy Statement. The current Provincial Policy Statement came into effect in 2020 and supports the provincial goals to increase housing, and protect the environment, while also reducing barriers and costs for development.

Municipal Act*, *2001

- The *Municipal Act*, *2001* empowers municipalities to be accountable for their own jurisdiction and provides the power to pass and adopt by-laws.

The subsequent list provides an overview of the municipal policies, programs, and plans that are currently applied in the governance or management of the forest in Markham.

Markham Official Plan 2014

- The City of Markham's Official Plan 2014 (Official Plan) provides a city-wide policy framework for the identification, protection, enhancement and restoration of the Greenway System and the Forest System. The Greenway System, consisting of key natural heritage features and other protected lands, is approximately 6,885 hectares or 32.4 percent of the City. Section 3.2.2 of the Official Plan provides direction to develop an Urban Forest Management Plan to address local tree canopy targets, tree species diversity, invasive species management, and soil conservation strategies.

Markham Greenprint Sustainability Plan (2011)

- Markham's Greenprint Sustainability Plan identifies ecosystem integrity as a sustainability priority and states it should be measured using indicators such as 'naturalness' and 'urban tree canopy'. Importantly, future-oriented objectives aligned with this Study include increasing biodiversity, increasing the city-wide tree canopy cover to 30 percent, and supporting wildlife habitat.

Markham Trees for Tomorrow Program

- The goals of the Trees for Tomorrow program are to 1) increase Markham's tree canopy to achieve a goal of 30 percent, 2) foster existing partnerships, and create new partnership opportunities to plant and care for trees, and 3) educate and engage the public to properly plant and care for trees on private property.

Markham Tree Protection and Preservation By-Laws

- Markham has tree protection and preservation by-laws to regulate the injury or removal of trees on private property and on municipal property. The municipality's tree preservation by-law protects trees with a trunk width of 20 cm or greater on any property, including private lands.

Markham Tree Maintenance Program

- Markham launched a tree maintenance program in 2020 to ensure that city-owned trees are pruned on a cyclical basis (every seven to ten years).

City of Markham Asset Management Plan (2021)

- The City of Markham Asset Management Plan (AMP) was revised in 2021, in compliance with *Ontario Regulation 588/17 Asset Management Planning for Municipal Infrastructure* (*O.Reg.588/17*). Certain green infrastructure assets (parks, stormwater management infrastructure) were incorporated into the plan, which allows City staff to form a business case to operate, maintain, and enhance green infrastructure alongside traditional capital assets.

York Region Official Plan (2022)

- The York Region Official Plan provides planning direction for all of York Region. This plan requires that all local municipalities develop an Urban Forest Management Plan (Section 2.2.50) and establishes a woodland cover target of at least 25 percent for the region. York Region has updated the Official Plan to provide direction for managing growth and development over the coming decades and to align with revised Provincial Plans. The Province issued a Notice of Decision on November 4, 2022 approving the 2022 York Region Official Plan, with amendments.

York Region Forest Management Plan (2016)

- The York Region Forest Management Plan was adopted by York Regional Council in 2016 and covers the time period from 2016 to 2026. The plan directs the municipality to undertake the forest studies and provides recommendations on the monitoring of canopy and woodland cover. Additionally, long-term canopy cover and woodland cover targets for the entire region and local municipalities, including Markham, are recommended in the plan. It also outlines strategic goals and actions for forest management in York Region.

York Region Green Infrastructure Asset Management Plan (2017)

- York Region developed the 2017 Green Infrastructure Asset Management Plan to ensure the management of regional green infrastructure assets in a way that effectively balances costs, risks, and benefits to ensure ongoing sustainable service delivery related to the Region’s green infrastructure. The assets within the plan include the forest (street trees, landscape planting, supporting infrastructure on roadways), York Regional Forest (forest tracts that include trails), and the Bill Fisch Forest Stewardship and Education Centre in Whitchurch-Stouffville.

York Region’s Greening Strategy (2022)

- Over the last 10 years, York Region’s Greening Strategy has helped to secure 1,500 hectares of land for conservation purposes and plant over 1.7 million trees. While the Greening Strategy has a focus on enhancing natural areas, private land stewardship is also promoted through planting programs for residents or best practices to support farmers on agricultural lands.

York Region’s Climate Change Action Plan

- Most of the alignment between this Study and the York Region Draft Climate Change Action Plan relates to community resilience actions such as conducting a vulnerability assessment on natural systems and integrate adaptive actions into watershed planning as well as assessing the role natural systems play in mitigating and adapting to climate change.

Currently, there are no federal policies or laws in place dedicated to Canada's urban forests. However, there are relevant national programs and plans which recognize the importance of urban forests, including:

A Healthy Environment and Healthy Economy, Canada's Strengthened Climate Plan

- A Healthy Environment and a Healthy Economy is the updated federal climate change plan that includes nature-based climate solutions as one of five pillars of action. Nature-based solutions include: the 2 billion trees program; enhancing carbon sequestration by enhancing wetlands, peatlands, and agricultural lands; and establishing a Natural Climate Solutions for Agriculture Fund.

Canadian Urban Forest Strategy (2019 – 2024)

- The Canadian Urban Forest Strategy was developed in partnership by the Canadian Urban Forest Network, Tree Canada, and municipal, provincial, and federal representatives. In recognition of increasing urbanization and resulting pressures on Canada's urban forest, the Strategy was developed to support the protection and enhancement of sustainable, biodiverse, and healthy urban forests across the country.

2.3 Study Background

The first analysis of Markham's forest was completed in 2012. TRCA and the United States Department of Agriculture (USDA) Forest Service completed an i-Tree Eco analysis (formerly known as UFORE) using land use mapping in conjunction with field data collected at sample plots across Markham to determine the species composition, condition, size class distribution, and measure ecological services and their value. This information informed the development of recommendations, many of which have been implemented by the City.

The 2022 Forest Study is intended to assess the change in the forest over the last decade by surveying a pool of the same plots assessed in 2012, following the i-Tree Eco protocol. Since 2012, additional assessments have been undertaken to supplement the i-Tree Eco protocol to better understand biotic factors that influence forest change including the evaluation of the invasive plants, pest and disease species, soil properties, and climate vulnerability. The analysis and recommendations presented in this report have been aligned with Markham's existing and new policies and frameworks.

3.0 METHODOLOGY

This study utilized several complementary approaches, datasets, and analysis tools:

1) Land cover/canopy cover mapping and spatial analysis
2) i-Tree Eco and Forecast
3) Statistical analysis of historical change in forest structure and composition
4) Statistical analysis of soil, tree condition, and invasive species data
5) Climate vulnerability assessment of dominant tree species

Each analysis tool is examined in more detail in the following sections. Taken together, these analyses provided a broad understanding of Markham's forest. While the i-Tree Eco and the canopy cover analyses each represent stand-alone assessments capable of supporting a forest management plan, experience from the 2012 Markham Urban Forest Study demonstrated the value of combining both approaches. By incorporating data collected in the field, the i-Tree Eco analysis allowed for the quantification of critical attributes such as tree species and tree height, as well as ecosystem services such as carbon storage and sequestration. In contrast, the canopy cover analysis relied on the mapping of land cover based on high-resolution satellite imagery and Light Detection and Ranging (LiDAR) data. This allowed a detailed and accurate assessment of the quantity and distribution of canopy cover and potential planting space across Markham. i-Tree Forecast offered an estimate of future canopy cover and ecosystem services given current planting plans, while additional data collected on soil, and invasive species, in combination with a climate vulnerability assessment, provided the basis for obtaining a more detailed understanding of the health and vulnerabilities of the forest in Markham.

3.1 Canopy Cover Analysis

In 2020, the Spatial Analysis Laboratory at the Rubenstein School of the Environment and Natural Resources at University of Vermont (UVM) completed land cover and canopy cover assessments for the whole of York Region. Detailed methods and results can be found in the 2021 York Region Canopy Cover Assessment Technical Report (Timmins & Sawka, 2022). Advanced automated processing techniques utilizing high-resolution, multi-spectral WorldView-2 imagery acquired in the summer of 2019, in combination with 2019 leaf-on LiDAR data, and ancillary datasets were used to map land cover for the entire City of Markham in such detail that single trees were detected. The following land cover classes were mapped: tree canopy, grass/shrub, bare soil, water, buildings, roads/railroads, and other paved/impervious surfaces. The overall accuracy of the land cover map was 97 percent and tree canopy mapped was 99 percent.

Using the land cover data, several canopy cover metrics were computed for Markham: existing canopy, potential vegetated tree canopy, potential impervious tree canopy, and not suitable (see Table 1 for a description of each metric). Canopy cover metrics were summarized as the total area in hectares, and as a percent of *land area* (i.e., water is excluded in the calculation of percentages).

Table 1: Existing and Potential Canopy Cover Categories

Category	Description
Existing Tree Canopy	The amount of tree canopy present when viewed from above using imagery
Potential Vegetated Canopy	Grass or shrub area that is theoretically available for establishing tree canopy
Potential Impervious Canopy	Asphalt, concrete, or bare soil surfaces, excluding roads and buildings, that are theoretically available for establishment of tree canopy.
Not Suitable	Areas where it is highly unlikely that new tree canopy could be established (buildings and roads, and water)

UVM calculated canopy cover change by calculating the difference between the canopy cover percent in the 2021 assessment and the 2012 assessment. Results were visually inspected to explore the causes of change.

For this report, existing and possible canopy cover were also summarized for ten land use categories derived from the Municipal Property Assessment Corporation (MPAC) codes assigned to each property in Markham.

MPAC is an independent body established by the *Ontario Property Assessment Corporation Act, 1997,* which administers a uniform, province-wide property assessment system based on current value assessment. MPAC data were obtained for the canopy cover assessment in 2019 and was last updated in 2016. Thousands of parcels were of an *unknown* land use (6.1% of York Region's land area) due to problems with joining the land use codes to the parcel boundaries via the roll or parcel ID number. TRCA filled in these "gaps" or unknown land uses and corrected some out-of-date land uses using a combination of the TRCA 2017 land use land cover layer, orthophoto inspection in combination with Google Maps, and various layers indicating municipal, provincial, and federal park and conservation authority lands. Errors may still exist within the land use layer.

Each original MPAC code or description was grouped into one of ten generalized categories based on similarities in ownership and management type (see Appendix A for the list of MPAC classes in each land use category). Road right-of-ways (ROWs) were added to the land use layer by UVM by filling in the gaps between the MPAC parcel boundaries and constitute an eleventh land use category.

3.2 i-Tree Eco

i-Tree Eco, a software application, model, and protocol, was chosen as the primary tool for the York Region Forest Studies. i-Tree Eco is an adaptation of the Urban Forest Effects (UFORE) model, which was developed by the U.S. Forest Service Northern Research Station (NRS), the USDA State and Private Forestry's Urban and Community Forestry Program and Northeastern Area, the Davey Tree Expert Company, and SUNY College of Environmental Science and Forestry. UFORE was used for the 2012 Markham Urban Forest Study. UFORE and i-Tree Eco have been used in many other municipalities in Greater Toronto Area in the past fifteen years. The built-in i-Tree Eco models are continually improved upon by their developers. Version 6.0.24 was used for this assessment.

3.2.1 Study Design

The study area boundary was defined by the municipal boundary of Markham. Two-hundred-and-thirteen randomly generated plot centres created for the 2012 Markham Urban Forest study were reused for the 2021 study[4] and two additional plots were added to increase the number of plots in the *Open Space – Natural Cover* land use stratum (more details on land use strata can be found in Section 3.2.2). Although increasing the number of plots would have led to lower variances and increased certainty in the results, it would have also 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 plots in a stratified random sample in a city will yield a standard error of approximately 12 percent (USDA, 2021). 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. In accordance with standard i-Tree Eco protocols, plots were circular and had an area of 0.0404 ha.

[4] Although it was attempted to collect data for every single plot it was not possible in all cases due to access restrictions.

i-Tree Eco was used to statistically extrapolate data upwards to estimate totals and standard errors for the entire study area for tree population, leaf area, species composition, size distribution, and condition, as well as carbon storage and sequestration, avoided runoff, air pollution removal, and building energy savings. i-Tree Eco uses a simplified CTLA Trunk Formula Method (Nowak, 2020) and a valuation for ecosystem services to provide a structural value for the forest.

3.2.2 Study Area Stratification

The study area was stratified into smaller units according to land use types (e.g., residential, commercial, industrial, etc.) to better understand variations in the structure of the forest. The randomly distributed plots were post-stratified according to the MPAC land use category in which they fell. The post-stratification approach was selected for the 2012 Markham Urban Forest Study to enable the monitoring and assessment of change over time at the same plots, as well as the ability to report on trends within land use categories. Using this approach, permanent sample plots are not dependent on a static land use distribution.

For this study, plots were stratified into six land use categories based on 2019 MPAC land use data acquired for the canopy cover assessment. The MPAC land use categories were last updated in 2016 and the next iteration was scheduled for completion in 2020 but delayed due to the COVID-19 pandemic. Given that land use changes are likely to occur within each four-year period, MPAC codes were screened visually by TRCA, and improvements and corrections were made, including the filling of “gaps” or parcels with an unspecified land use. It is likely that errors still exist in the dataset.

i-Tree Eco developers recommend that strata are set up to have a minimum of 15 to 20 plots within each strata to ensure a reasonable accuracy. Unfortunately, there were insufficient plots in the land use categories, *commercial, industrial, institutional, open space, other, residential medium / residential high,* and *utilities and transportation.* Consequently, the aforementioned categories were grouped into broader categories with other similar land use types based on similarities in vegetation cover and management needs to create a total of six land use categories or stratum as shown in Table 22. Appendix A contains a detailed description of the component land use types. Figure 1 shows the distribution of land use types and plots across Markham.

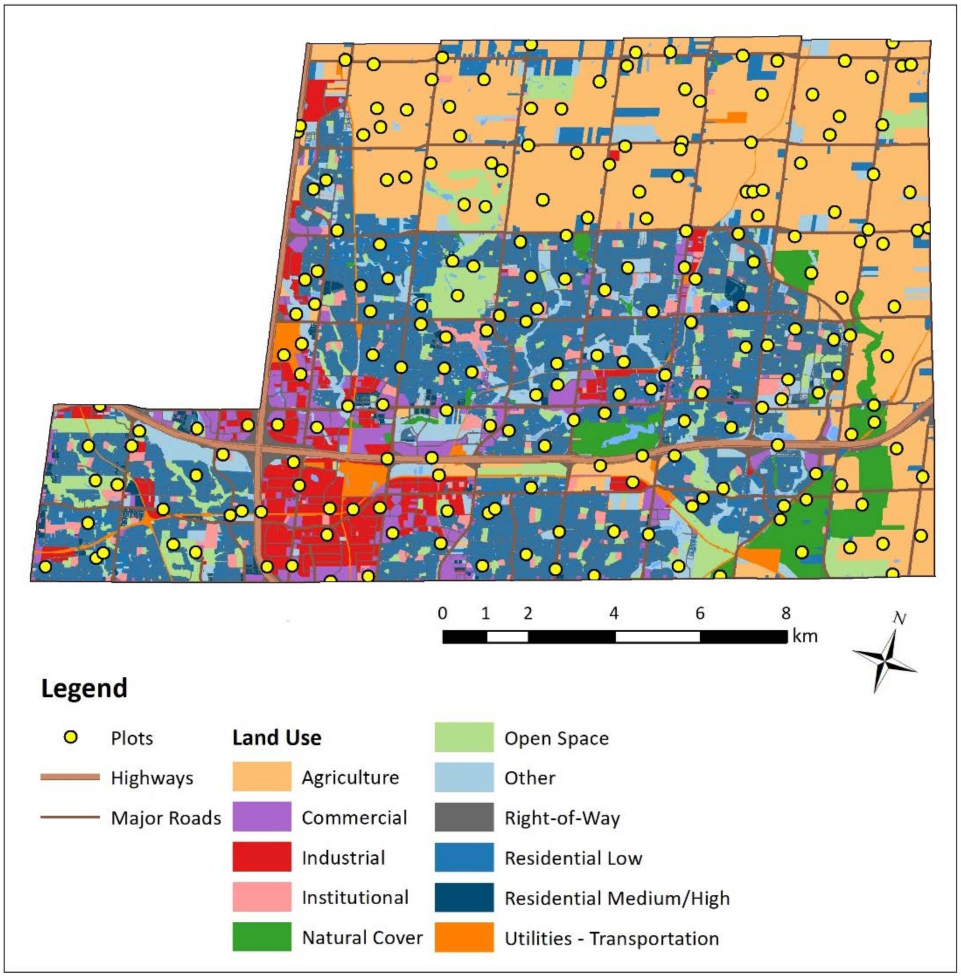

Figure 1: Distribution of MPAC land use types and plots across Markham in 2021

These are the same strata used in the 2012 Markham Forest Study, except *Utilities – Transportation* and *Other*. Previously, *Utilities – Transportation* included *Institutional*. For this study, *Institutional* has been grouped with *Other* to ensure a sufficient number of plots. In addition, *Right-of-Way* was not included in 2012, but was explicitly delineated and included within *Utilities – Transportation* for this study.

Some of the plots in the *Other* land use category fall in Markham's valley systems. For the next study, plots in the *Other* land use stratum should be examined closely and potentially recoded as *Natural Cover* or *Open Space* if they have not been updated in MPAC. The reclassification will ensure the natural woodlands and/or valleylands in the City are reflected, as well as their relative contribution (area and diversity of species) to the forest canopy.

Table 2: Land use categories used for i-Tree Eco stratification

Stratum	Area (ha)	Number of Plots[5]
Agriculture	6,590.41	70
Commercial – Industrial	1,942.86	19
Open Space – Natural Cover	2,252.84	22
Other[6] – Institutional	1,963.36	15
Residential	4,795.40	49
Utilities – Transportation – ROW	3,723.54	40
TOTAL	**21,268.41**	**215**

3.2.3 Landowner Contact

Permission to access plots located on private property was obtained primarily through written communication. Prior to entry, property owners received a request for access form in addition to a letter outlining the scope and duration of the study. In the case of businesses, telephone numbers and email addresses that could be found online were also used to contact owners. If it was not possible to contact an owner (for example, due to incorrect mailing address) or no response was given, field staff requested permission to access the property in person. In the event that permission was not granted, no person was on site to provide permission, access was restricted due to physical barriers, or the site was deemed unsafe, the plot was not assessed.

3.2.4 Field Data Collection

Field data collection was conducted by a two-member field crew during the summer leaf-on season of 2021. Plot centres were found by using a combination of handheld GNSS tablets and high-resolution aerial orthoimagery on a mobile device that illustrated the location of plot centre and plot boundaries for each plot. At each 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 the 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 in the i-Tree Eco web interface via a mobile device:

- percent tree cover
- percent shrub cover
- land use (as observed on the ground, which is different from the MPAC land use type)
- percent of plot within the land use

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[5] This is the total number of plots originally allocated per land use type. However, it was not possible to collect data for all of these plots due to access constraints.

[6] *Other* is comprised predominately of vacant land scheduled for development, but also includes non-commercial sports complexes, common lands (including some municipal land).

- 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 tree with the centre of its stem in the plot and a minimum diameter at breast height (DBH) of 2.5 cm, except in forested areas[7], where the DBH minimum was increased to 5 cm, the following information was recorded:

- species
- number of stems
- diameter at breast height
- tree height
- live tree height
- height to base of live crown
- crown width in east-west direction
- crown width in north-south direction
- percent canopy missing[8]
- percent dieback[9]
- distance and direction (measured from Magnetic North) from the tree to the building (for trees ≥ 6.1m in height and located within 18.3m of a residential building)

Given access constraints, data was collected at 202 out of the 215 planned plots. Prior to visiting plots in the field, plots were inspected using current orthoimagery and Google Street View. Eighty-eight plots did not require field visits since 98 to 100 percent of the plot was on impervious surfaces or agricultural lands and no trees were

[7] Forested areas were defined as areas surrounded by at least 10 percent canopy cover. Land was considered forested if it was not subject to use(s) preventing normal tree regeneration and succession, such as regular mowing, intensive grazing, or recreation activities. In some cases, areas with less than 10 percent canopy cover could qualify as a forest area if trees were harvested, died, or were otherwise removed but the land was expected to naturally regenerate to at least 10 percent cover.

[8] Percent canopy missing is the percent of the crown volume that is missing foliage. It is assessed within the measured live crown width and height and requires imagining a typical crown outline that is full of live foliage.

[9] Percent dieback is the percent of the crown that is composed of dead branches.

present. Field visits were completed for the remaining plots where access was possible. Field visits were not completed for 13 plots because no response was received from the landowner, the landowner could not be contacted, the plot could not be inventoried from the road and/or a neighbouring property where permission was obtained, or access was denied by the landowner/tenant. The landowners who denied access indicated a distrust or dislike of having staff representing TRCA or the municipality on their land. Others were wary to interact with staff due to COVID-19, and some had a general suspicion of strangers or how the survey might impact them, despite assurances that it would not. Table 3 and Table 4 summarize the number of plots that were visited in the field versus completed using digital resources, and the number of plots visited per stratum, respectively.

Table 3: Data collected for plots in 2022

Description	Plots Completed
Field visits	114
Orthophoto/Google Street View	88
Total plots	**202**

Table 4: Number of plots completed per stratum in 2022

Stratum	Number of Plots with Complete i-Tree Eco data	Total Number of Plots in Stratum
Agriculture	63	70
Commercial – Industrial	19	19
Open Space – Natural Cover	21	22
Other[10] – Institutional	14	15
Residential	46	49
Utilities – Transportation – ROW	39	40
Total	**202**	**215**

Research conducted by i-Tree Eco developers indicated that 200 plots (of 0.04 ha each) in a stratified random sample will have a standard error of approximately 12 percent for the municipality and around 13 percent for 180 plots (USDA, 2021). The relationship between the number of plots and standard error is non-linear, with the biggest gains in accuracy obtained in the first 80 to 90 plots. Therefore, the number of plots and plots per stratum that had complete data to run the i-Tree Eco model was deemed sufficient. In addition, we were able to collect enough plots per stratum although *Other – Institutional* will have the greatest uncertainty/variance in results given the smaller sample size.

[10] *Other* is comprised predominately of vacant land scheduled for development, but also includes non-commercial sports complexes, common lands (including some municipal land).

3.2.5 Data Analysis

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

1) Forest Structure: quantifies forest structure elements such as species composition, tree density, tree health (based on percentage dieback), leaf area, leaf, and tree biomass based on field data.

2) Biogenic Emissions: quantifies

1) hourly forest volatile organic compound (VOC) emissions (isoprene, monoterpenes, and other VOC emissions that contribute to ozone (O_3) formation) based on field and meteorological data, and
2) O_3 and carbon monoxide (CO) formation based on VOC emissions.

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

4) Air Pollution Removal: quantifies the hourly dry deposition of ozone (O_3), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), and particulate matter ($PM_{2.5}$) by the 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 the effects of trees on building energy use as a result of reduced heating and cooling.

3.2.6 Weather and Pollution Data, and i-Tree Eco Parameters

Weather and Pollution Data

Weather and pollution datasets are integrated into i-Tree Eco for use in modelling. It is not possible for the user to directly upload their own data into the application. Hourly precipitation data is utilized to calculate avoided runoff and improve the accuracy of estimating the removal of $PM_{2.5}$ by trees and shrubs. Weather data also impacts the calculation for emissions of volatile organic compounds. Toronto Pearson Airport meteorological station is the closest weather station to York Region and provides weather data from 2010 to 2020. It also provides hourly pollutant data for 2010, which was the most recent air pollution data available for the Region.

For use in York Region Forest Studies, hourly 2019 pollution concentrations of SO_2, and CO were obtained from the Ontario Ministry of Environment, Conservation and Parks' Toronto West station, and O_3, NO_2, and $PM_{2.5}$ data were obtained from their Newmarket station for the same year. This data was submitted to i-Tree Eco for inclusion into the i-Tree Eco platform in December 2021. More recent pollution data were not used as i-Tree Eco did not have the required radiosonde data. At the time of the third draft of this report, the updated weather data had not yet been included in the latest i-Tree Eco software update. If the update is made in time for the final report, the results will be updated accordingly.

i-Tree Eco parameters

The i-Tree Eco model requires the user to select a variety of parameters to support model runs. Parameters used for the 2022 Markham Forest Study are summarized in Table 5.

Table 5: i-Tree Eco parameters

Variable/Parameter/ Dataset	Value/Source	Comments
Weather	2019 Pearson International Airport	Closest station and corresponds to date of air pollution data.
Air pollution	2019 Newmarket and Toronto West data / Ministry of Environment, Conservation and Parks, Ontario	Most recent and closest station data
Census Subdivision and Population Size	Study area type = urban, Population (2021) = 338,503	i-Tree Eco Markham population source: Statistics Canada - 2021 Census
Electricity in Can$ (CAD)/kWh	$0.1216 / Ontario Energy Board	This is used to calculate the cooling benefit of trees due to less air conditioner use. While air-conditioners may be used most in the day during peak hours, many people continue to use air-conditioners at night[11]. In addition, many people turn their air-conditioners off when they are not at home, which is more likely during the day. Therefore, an average electricity price was used as shown below. Ontario (oeb.ca – 2021-11-30) rates for electricity: Time of Use Costs: • Off-peak: 8.2 c/kWh • Mid-peak: 11.3 c/kWh • On-peak: 17.0 c/kWh • Average: 12.16 c/kWh
Heating in Can$ (CAD)/therm[12]	$0.439 / Ontario Energy Board	Natural gas rates & prices in Ontario (oeb.ca – 2021-11-30) • Union Gas Ltd (South): 17.1480 c/m^3

[11] According to archived research from Statistics Canada, 48 percent of people with an air-conditioner in Ontario kept their air-conditioner on when away from home in 2009. Only 29 percent of Canadian households with an air-conditioner turned it off while sleeping.

[12] One therm is a non-SI unit of heat energy. It is the amount of energy in 100 cubic feet of gas.

		• Enbridge Gas Distribution: 13.2868 c/m^3 • EPCOR Natural Gas Ltd: 16.0543 c/m^3 o Average cost = 15.4964 c/m^3 • Convert to a cents per cubic foot by dividing by 35.3147: o Average: 0.439 c/ft^3 • Multiply the above by 100 to obtain a therm (100 cubic feet) o Average: 43.9 c/therm
Carbon in Can$/metric ton	$188.77 / From other local studies updated to 2021 values	Value used for York Region Ecosystem Services Quantification and Valuation project. It was based on the Credit Valley Business Case for Natural Assets[13] for the year 2020 inflated to 2021 using the Bank of Canada inflation rate.
Avoided Runoff in Can$ (CAD)/m^3	$2.324 / Default i-Tree Eco value	Default value from i-Tree Eco. It uses the U.S. national average dollar value to estimate value of avoided runoff. This value is based on 16 research studies on costs of stormwater control and treatment (Nowak, 2020)

Value of Air Pollution Removal

The default values of i-Tree Eco were used to estimate the value of air pollution removal services (there is no option to update these values). The associated economic value of the health benefits from the removal of pollutants NO_2, SO_2, O_3, and $PM_{2.5}$ is based on U.S. median externality values from the U.S. EPA's Environmental Benefits Mapping and Analysis Program (BenMAP) model (Nowak, 2020). Based on BenMAP, various standardized health impacts and dollar values (value/person/pollutant) were calculated in i-Tree Eco. The standardized values were calculated using local pollution and population data. These values are multiplied by the corresponding local population total and pollution concentration change as a result of trees and other vegetation in the study area to determine health impacts and associated dollar values. For international estimates, regression equations (Nowak et al. 2014) based on population density are employed to estimate a dollar value per ton of pollution removal.

[13] CVC's estimates were based on the Technical Update to Environment and Climate Change Canada's Social Cost of Greenhouse Gas Estimates, published by Environment and Climate Change Canada (2016), which in turn updates and slightly adjusts the Social Cost of Carbon developed by the U.S. Interagency Working Group on Social Cost of Carbon.

Table 6: Value per tonne of air pollutant removed

Pollutant	Unit value (CAD)
Carbon monoxide (CO)	$ 1,490 / tonne
Nitrogen dioxide (NO_2)	$ 1 ,330 / tonne
Sulphur dioxide (SO_2)	$ 480 / tonne
Ozone (O_3)	$ 8,890 / tonne
Particulate matter < 2.5 microns ($PM_{2.5}$)	$ 308,610 / tonne

3.3 i-Tree Eco Change Assessment

Where applicable, results from the 2012 report were compared to results from this study to understand changes in structure, composition, and health. The reported standard errors produced by i-Tree Eco were used to assess whether the changes were likely to be significant given the width of the standard error and the size of the change.

3.4 i-Tree Forecast

i-Tree Forecast is a separate model incorporated into the i-Tree Eco application. It was utilized in this study to estimate future canopy cover based on the current state of the forest and Markham's tree planting plans, which were provided by Markham. The objective of the i-Tree Eco Forecast analysis was to determine if, given the current planting plans, canopy cover would continue to stay within the current recommended canopy cover range by 2050 (20 to 35 percent), or would it increase or decline. If the canopy cover target range were not to be maintained, simulations would be run to determine how many more trees would need to be planted to ensure that the canopy cover range was maintained. The planting assumptions are identified in Appendix B.

i-Tree Forecast simulates future forest structure using current forest structure data from i-Tree Eco as the input. Forecast simulates each year within the simulation period using three components:

1) Tree growth: the projected growth of tree diameter, crown size, and leaf area for each tree recorded. Tree growth or annual increase in DBH is based on the number of frost-free days, crown light exposure, dieback, growth rate classification and median height at maturity.
2) Tree mortality: the projected annual mortality based on default or user-defined annual mortality rates for trees of various condition scores. Tree mortality rates are adjusted for tree size/maturity by i-Tree Eco.
3) Tree establishment: the projected number of trees added each year based on user inputs. Users must enter the stem diameter of newly established trees and annual planting rates.

i-Tree Forecast also allows the user to choose to simulate extreme events such as insect or disease outbreaks and storm events.

3.4.1 Simulation Scenarios

Simulations were run for a Thirty-year forecast period from 2021 to 2051. This corresponds to the time frame for meeting the canopy cover goals in the York Region Forest Management Plan. Simulations included diseases and pests that are currently impacting the forest. Storm events were excluded due to uncertainty in mortality rates following different types of storms, the geographical extent of damage, and the frequency of storms. The effects of climate change were incorporated by increasing the growing season length which would impact the annual growth rate of trees.

Currently, the length of the frost-free season is 163 days (climateatlas.ca). According to Historical and Future Climate Trends in York Region (Fausto et al. 2015), the length of the growing season is expected to increase by approximately 30 days by the 2050s. Since only one value can be entered in into i-Tree Eco, an average value of 178 was used.

At this time, the most commonly observed pests and diseases impacting Markham are emerald ash borer (EAB, *Agrilus planipennis*), spongy moth (*Lymantria dispar dispar*), and beech bark disease (*Neonectria faginata*). EAB is nearing the end of its worst impacts and spongy moth is collapsing. i-Tree Eco Forecast only applies mortality rates to tree species impacted by the pest.

Only pests that are known to occur in Markham were considered in the i-Tree Eco model. Oak wilt (*Bretziella fagacearum*) has yet to cross into Canada and Hemlock woolly adelgid (*Adelges tsugae*) was found in the Niagara Peninsula but eradicated. Asian long-horned beetle (*Anoplophora glabripennis*) was last found in Ontario in 2013 and eradicated. There is greater uncertainty as to when the other pests may arrive and establish themselves, for how long and what impact they will have, hence, they were excluded. These pests and diseases should be considered in future iterations of the Forest Study.

Appendix B summarizes the parameters used to set up i-Tree Forecast. All parameters remained the same for each simulation with the exception of the planting program input.

Three planting scenarios were run in i-Tree Forecast, as follows:

- No planting plan – Assumed no planting programs were implemented in the Thirty-year simulation period.
- Current planting plan – Assumed Markham proceeded with the current rate of planting across the Thirty-year simulation period (Development Services Commission plantings in the natural heritage system and the Trees for Tomorrow planting program).
- Doubled planting plan - Assumed Markham doubled the current rate of planting across the Thirty-year simulation period (Development Services Commission plantings in the natural heritage system and the Trees for Tomorrow planting program).

The potential changes to canopy cover and tree number over the thirty-year simulation period were output for each scenario and compared.

3.5 Soil

3.5.1 Background

Soil quality has been widely recognized in the literature and in strategic (urban) forest management guides and plans as a vital component and indicator of forest health. However, while regional forest management plans and assessments reference the need for high quality soil and sufficient soil quantity, they seldom provide guidelines beyond soil volume and the use of soil cells for street trees. To begin to address this gap, a baseline assessment of the physical and chemical soil properties across Markham was conducted as part of the Markham Forest Study. The results can be used to inform future management decisions targeting forest enhancement and planting and provide an additional facet that can contribute to our understanding of the overall health of the forest.

Three soil properties indicative of soil health were measured for this study: compaction, salinity, and pH.

Compaction

Research by the United States Department of Agriculture (USDA) has shown that almost no roots can penetrate soil with a penetration resistance (psi) of 300 psi or more (Duiker, 2002).

Psi values can be interpreted as follows:

- 0 – 200 psi: uncompacted / good growing conditions,
- 201 – 300 PSI: moderately compacted / fair growing conditions, and
- 300 PSI: highly compacted / poor growing conditions.

Salinity

Salts are chemical compounds which are made up of positively charged cations and negatively charged anions. Salts in moderation are good for plants as they provide key nutrients, and most fertilizers are salts. Salt concentrations in soil can vary greatly and are affected by several environmental factors including, climate, local biota (plants and animals), bedrock and surficial geology, as well as human impacts (such as irrigation) on the land (USDA, n.d.).

pH

Like salinity, soil pH is affected by several environmental factors including, climate, local biota (plants and animals), bedrock and surficial geology, as well as human impacts on the land. In general, pH readings between 1 and 6 are considered acidic, 7, neutral, and 8 to 14, basic/alkaline. Soil pH directly impacts the growing abilities of plants.

3.5.2 Field Data Collection

The collection of soil data was an auxiliary assessment outside of the i-Tree Eco data collection. A protocol specific to soil collection was developed and an overview of the methodology is included as follows. Measurements for compaction and salinity were taken *in situ* using a penetrometer and a probe, and pH measurements were attained by taking soil samples, which were submitted to ALS Environmental laboratory for analysis. Four *in situ* measurements were taken one meter around the centre of plots that had natural cover, were in parks, or undeveloped, and/or likely far away from human utilities, or around a tree or shrubs within plots near development to reduce the risk of striking utility lines. Four soil samples for pH were obtained within the circle delineated by the *in situ* measurements. Due to the necessity of taking actual samples from the ground for pH, it was not possible to obtain pH samples for most of the sites.

Compaction

Soil compaction was measured at four locations as described above using an analogue penetrometer. It was inserted into the soil to a depth of about 6 to 10 inches. The field crew would record uncompacted, moderately compacted, or highly compacted according to the range of psi values observed as follows:

- 0 – 200 PSI: uncompacted
- 201 – 300 PSI: moderately compacted, or
- 300 PSI: highly compacted.

Salinity

Salinity was assessed indirectly by measuring electrical conductivity (EC). Salt increases the ability of soil to conduct an electrical current, and therefore, electroconductivity can be used to infer salinity levels (Simons & Bennett 2020; Soil Science Division Staff 2017). EC is proportional to the total amount of salts present in a solution (it has been correlated to concentrations of nitrates, potassium, sodium, chloride, sulfate, and ammonia); however, it does not provide a direct measurement of specific ions or salt compounds. EC is usually measured in micro- or millisiemens per centimeter (uS/cm or mS/cm). It is possible to generalize and say that an EC of 1.0 mS/cm contains up to 1.0 gram of measured salts per 1 liter of water (Klaassen, n.d.).

FieldScout EC meters and probes were used to measure electroconductivity *in situ*, and results were recorded in Survey123. Conductivity measurements are directly affected by temperature, however, the EC meter compensated for temperature directly. Conductivity is also impacted by moisture levels. To produce a consistent moisture level, distilled water was poured into the measurement location to reach a saturation point, before inserting the EC probe approximately six inches into the ground. Trial experiments had found it was not possible to consistently obtain deeper depths than six inches in compacted soils.

pH

Originally, a FieldScout pH meter and probe was obtained to also measure pH *in situ.* However, after one week of use, the probe broke. After discussion with the supplier, it was decided to discontinue the use of the probe *in situ* which could not cope with the harsh real-world soil conditions, and an alternative approach was developed. Four samples were taken by auger within the first 6 inches of the surface. They were mixed together and sent for analysis at ALS Environmental. Due to the original methodology not requiring soil samples, this request was not made in the landowner letters. As such, pH soil samples were predominately limited to public lands, unless express permission was obtained from private property owners.

3.5.3 Data Analysis Methods

Compaction, salinity, and pH were each analyzed separately and then compared with percentage dieback.

Compaction

Compaction levels were transformed to ranked values, 1, 2, and 3 corresponding with uncompacted, moderately compacted, and highly compacted. These values were used to calculate an average compaction level per plot. Average compaction scores can be interpreted as follows:

- 1 – 1.5: Uncompacted
- 1.75 – 2.5: Moderately compacted
- >2.5: Highly compacted

The proportion of plots within each compaction category were calculated for the whole municipality, on public and private lands, and across land use strata. Public lands included municipal, provincial, federal, and conservation authority owned/managed lands. Land use strata were grouped into more general categories to ensure a sufficient sample size to lower uncertainty and perform statistical testing. Pearson's Chi-squared test was used to test if there were differences in the proportion of plots in each compaction category between groups, and the pairwise Wilcox test was used to identify which groups were different when there were more than two groups.

Salinity

Electroconductivity measurements per plot were screened for outliers. Outliers were removed before calculating an average electroconductivity score per plot. Plot-level electroconductivity measures were used to calculate the mean, median, minimum, and maximum electroconductivity scores for the municipality, for public (defined as described previously) and private lands, and per stratum. Land use strata were grouped together to increase sample size when necessary.

The Wilcoxon rank sum test for non-normal data were used to test for statistically significant differences in electroconductivity between private and public lands, while the Kruskal-Wallis rank sum test for non-normal data were used to test for differences among land use strata.

pH

A single pH value was obtained for each plot from ALS Environmental. Twenty-three pH samples were obtained across Markham and were used to calculate the average, median, minimum, and maximum pH for Markham. Due to a change in sampling procedure during the field season, following the use of ineffective pH probes, we had difficulty getting permission to take soil samples for lab analysis. A Wilcox rank sum test for non-normal data was used to test for a statistically significant difference in pH between public and privately owned plots and land use strata. Land use strata were grouped together to obtain a sufficient sample size to reduce uncertainty and allow for statistical testing.

Relationships between Soil Compaction, Salinity, pH, and Tree Condition

The relationship between soil compaction, electroconductivity, and pH and tree condition measured as percentage crown dieback were explored using correlation testing, scatter plots and linear regression. Where data were not bivariate normal, Spearman's rho and Kendall's tau testing was used.

3.6. Invasive Species

3.6.1 Background

Collected separate to the i-Tree Eco data, the objective of the invasive species analysis was to evaluate the degree and intensity of the spread of invasive plants, pests, and diseases of concern across the municipality and different land use strata. To have a better understanding of the distribution and impact of invasive plant species and priority pests and diseases across Markham, data about the presence or absence and extent of common invasive species was collected by the field crew as part of the Markham Forest Study. Species of concern were identified based on the 2018 Toronto Canopy Study, the 2016 York Region Forest Management Plan, and consultation with invasive species specialists at York Region, Markham and TRCA.

Potential future invasive insects and diseases such as oak wilt (*Bretziella fagacearum*), and spotted lanternfly (*Lycorma delicatula*) were not included in the priority list. As of 2021, oak wilt had not yet crossed into Canada from the United States. Spotted lanternfly was also not yet seen in Canada. Spotted lanternfly prefers invasive species, tree of heaven, and is a threat to wineries and fruit orchards. Table 7 below summarizes the list of invasive plant, pest, and diseases on which data were collected.

Table 7: List of invasive plants, pests, and diseases

Trees	Shrubs	Other Plants	Pests and Diseases
Norway maple *(Acer platanoides)*	Common buckthorn (*Rhamnus cathartica*)	Goutweed (*Aegopodium podagaria*)	Asian long-horned beetle (*Anoplophora glabripennis*)
Manitoba maple *(Acer negundo)*	Morrow's honeysuckle (*Lonicera morrowii*)	Oriental bittersweet (*Celastrus orbiculatus*)	Spongy moth (*Lymantria dispar dispari*)
Callery pear (*Pyrus calleryana)*	Tartarian honeysuckle *(Lonicera tatarica)*	Wintercreeper euonymus (*Euonymus fortunei*)	Hemlock woolly adelgid (*Adelges tsugae*)
Ivory silk lilac (*Syringa reticulata*)	Shrub honeysuckle (*Lonicera x bella*)	Dog-strangling vine (*Cynanchum rossicum*)	Emerald Ash Borer *(Agrilus planipennis)*
Tree of Heaven (*Ailanthus altissima*)	European fly honeysuckle (*Lonicera xylosteum*)	Lily of the valley (*Convallaria majalis*)	Beech bark disease (*Neonectria faginata*)
Black Locust (*Robinia pseudoacacia*)	Non-native honeysuckle spp. (*Lonicera spp.*)	Periwinkle (*Vinca minor)*	Beech leaf disease (caused by parasitic nematode *Litylenchus crenatae ssp. mccannii*.)
Black Alder (*Alnus glutinosa*)	European spindle-tree (*Euonymus europaeus*)	Himalayan Balsam (*Impatiens glandulifera*)	Dutch elm disease (*Ophiostoma ulmi*)
	Winged spindle-tree *(Euonymus alatus*)	Garlic mustard (*Alliaria petiolate*)	
	Japanese knotweed (*Reynoutoria japonica*)	Phragmites (*Phragmites australis*)	
		Wild parsnip (*Pastinaca sativa*)	

3.6.2 Field Data Collection

At each plot, crews were instructed to look out for the invasive species listed in Table 7. If the species was present, they assigned a score based on the degree of spread in Survey123. Degree of spread was measured differently for plants, pests, and diseases.

Scoring level of spread for plant species

The field crew recorded the degree of invasion for each plant system using an ordinal or ranked system where 1 was the least amount of spread and 4 the most. A definition for each is provided in Table 8. The scoring system was based on the one used for 2018 Toronto Canopy Study.

Table 8: Degree of spread scoring system for invasive plants

Score	Definition	Detailed Description
1	1 to 2 patches of the invasive plant	Trees: 1 or more trees that are adjacent to each other, or 1 or 2 patches of adjacent seedlings/saplings Shrubs: 1 or more shrubs that are adjacent to each other, or 1 or 2 patches of seedlings/saplings Ground cover/Vine: 1 to 2 patches of adjacent plants 1 to 2 patches have maximum size: 0 – 25 % of plot (or a circle with a max diameter of 11.35 m)
2	3 or more scattered pockets	There are 3 or more than patches and together they cover 0 – 49% of plot
3	a blanket effect	Pervasive spread: 50 – 100 % cover
4	an extensive blanket effect within the plot and the surrounding area	50% - 100% within plot and continues into surrounding area.

Note: The area of invasive cover pertains only to the pervious area; For example, a plot could be 60% impervious while 100% of the pervious area is filled with an invasive plant. In that case it would be assigned to a level 3.

Scoring pest and disease spread

The field crew recorded the distribution of symptoms/damage caused by each of the listed pests/diseases, using a numbered ranking system:

- 1: presence of a pest symptom/damage on 1-3 trees
- 2: presence of a pest symptom/damage on 4-6 trees
- 3: presence of a pest symptom/damage on 7 or more trees

The field crew recorded the distribution of each of the pests (insects), using a numbered ranking system:

- 1: presence of a pest/larvae/egg/caterpillar on 1-3 trees
- 2: presence of a pest/larvae/egg/caterpillar on 4-6 trees
- 3: the presence of a pest/larvae/egg/caterpillar on 7 or more trees

3.6.3 Data Analysis Methods

Invasive species, pests, and diseases were each analyzed separately by considering presence and degree of spread.

Presence

Presence was determined by calculating the percent of plots, on which data was collected, that have at least one invasive plant, pest or disease present across the municipality and each land use stratum. Each land use stratum had an attributed percentage for plots affected with an invasive plant species and percentage presence for each invasive species, by stratum, summarized in Table 8. The results were tabulated by land use and utilized to develop figures and tables statistics.

Degree of spread

Using the scores attributed to each category of spread, the average spread was calculated for each species, pest, and disease across the municipality and each land use stratum for plots invaded. A combined score, by land use stratum, was calculated for average number of species and average spread by multiplying the two scores.

3.7. Climate Vulnerability Assessment

The climate vulnerability of the top twenty most frequently occurring tree species was assessed. The approach for the climate vulnerability assessment follows the methods used to prepare the Peel Region Urban Forest Best Practice Guides, Guide 4: *Potential Street and Park Tree Species for Peel in a Climate Change Context* and is consistent with climate change adaptation frameworks developed by Gleeson et al. (2011), Glick et al. (2011), and Ordóñez & Duinker's (2015). The approach outlined in the Guide is appropriate for application in adjacent municipalities.

3.7.1. Background

One of the priority action's put forward to foster community resiliency as part of York Region's Draft Climate Change Action Plan, 2020, is to conduct a vulnerability assessment on natural systems. Therefore, conducting a vulnerability assessment of York Region's forest can contribute to this action and help better understand the expected impacts of climate change on the forest and inform adaptation.

3.7.2. Emissions Scenario and Timing Window

The emissions scenario used for the Markham climate vulnerability assessment was RCP 8.5 (AR5) – the "worst case" scenario based on "business as usual" – from the Intergovernmental Panel on Climate Change fifth assessment report (IPCC, 2013). York Region's *Historical and Future Climate Trends* (Fausto et al. 2015) and Peel Region Urban Forest Best Practice Guides, Guide 4: *Potential Street and Park Tree Species for Peel in a Climate Change Context* (Peel Guide 4) also use RCP 8.5 (AR5).

The time window for the assessment is 2041-2070, also known as the near future or 2050s. This time period is most suitable for forest planning in the next thirty years. It also aligns with the time frames used in York Region's *Draft Climate Change Action Plan* (2020) and *Historical and Future Climate Trends in York Region* (Fausto et al. 2015) and the Peel Region Urban Forest Best Practice Guide 4.

3.7.3. Near Future Climate and General Impacts on Markham's Forest

According to *Historical and Future Climate Trends in York Region* (Fausto et al. 2015), under RCP 8.5 conditions (business as usual scenario), the following climatic changes are anticipated in the years 2041 to 2070, all of which will impact the development of the Markham Forest:

- Minimum temperatures are expected to increase significantly across all seasons and annually. This will increase the range of tree species northwards. Species that are already at their southerly extent are likely to shift northwards and become rare or extirpated. Species typically present further south are likely to establish themselves. Additionally, warmer temperatures will impact the population, survival rate, and distribution of invasive pests and diseases.

- Precipitation is likely to increase annually and in every season except summer, when it is expected to remain the same or possibly decrease. Similar or decreasing rainfall in combination with hotter temperatures is expected to result in drier conditions in the growing season. This will cause stress for many species which are less drought tolerant.

- More frequent and intense extreme weather events are likely. In particular, it is anticipated that extreme precipitation events will become more frequent and severe, particularly in summer. Storm events will increase tree damage and mortality.

- The number of days of extreme heat will increase significantly, and the number of extreme cold temperatures will decrease. The increase in extreme hot days will increase stress on many species, particularly those on the southern end of their range.

- The length of the growing season will increase by over 30 days by the 2050s. The start date will arrive earlier, while the end date will be later. The growth of trees will accelerate, although this will be countered by less water availability.

3.7.4. Assigning a Vulnerability Score

A vulnerability score was assigned to the top twenty most abundant tree species in Markham based on their exposure and sensitivity to climate change using the method and values developed in the Peel Urban Forest Best Practice Guide 4 (henceforth noted as the Guide). Exposure refers to how much a species will be exposed to the impacts of climate change (such as high temperatures, extreme weather events, droughts), and sensitivity refers to the inherent characteristics or traits of species that make them more susceptible to climate change.

In the Guide, a combined vulnerability score was calculated for 88 tree species based on the likelihood of the species' exposure to climatic stress and the species' sensitivity to drought as follows:

Exposure to Climate Change

- Trees were considered to be exposed to climate change impacts if climate change would result in them occurring outside of their ideal range as determined by their climate envelope. Species which occur in areas with low climate suitability in the near future will experience climatic stress.

- The Guide classified tree species as likely to have high, moderate, or low exposure to climatic stress as follows:

  - High: species for which climatic suitability declines within Peel; area of suitable habitat in Peel is less than 20 percent.

  - Moderate: species with some loss in climatic suitability within Peel; area of suitable habitat in Peel does not fall below 20 percent.

  - Low: species with no future loss or with a gain in climatic suitability within Peel Region; area of suitable habitat is more than 20 percent.

Sensitivity to Drought

- The Guide classified species as having low, moderate, or high sensitivity to drought based on existing resources documenting drought tolerance.
- Niinemets and Valladares' (2006) five-level scale for assessing drought tolerance based on the geographical areas where species occur was used in Guide 4 to assign a drought sensitivity score. The Niiniments and Valladares numeric scale was converted to categorial values as follows:
  - High: 1 – 2.19
  - Moderate: 2.20 – 3.39
  - Low: >3.4.

Combined Vulnerability Score

- The Guide calculated a combined vulnerability score based on exposure and vulnerability as follows:
  - Extreme: high in climate exposure and drought sensitivity
  - High: high ranking of either climate exposure or drought sensitivity
  - Moderate vulnerability: two moderate rankings or one moderate and one low ranking of either climate exposure or drought sensitivity
  - Low vulnerability: low sensitivity to drought and low climatic exposure

The list of the top twenty most abundant species in Markham was cross-referenced with the calculated vulnerability scores for the species list from the Guide. Vulnerability ratings from the Guide were used to assign vulnerability scores to each of the top species across Markham (Table 26 in Section 4.8). Any tolerances, sensitivities, and risks identified for each species in the Guide were noted in Table 26. Two species were not listed within the Guide (green ash, *Fraxinus pennsylvanica*; and Amur maple, *Acer ginnala*). Green ash was assigned the same vulnerability score as white ash (*Fraxinus americana*), and Amur maple was assigned a vulnerability score using the method described above.

3.7.5. Development of Impact Statements

Impact statements identifying how climate stressors are expected to affect the entire municipal forest and the top five most abundant species growing across Markham were developed using the "If-Then-So" method – a qualitative approach used in traditional risk-based assessments. The method requires the following questions to be answered:

- **If** expected changes in the future climate were to occur, including acute shocks (e.g., more extreme weather events) and chronic stresses (e.g., hotter and drier summers),
- **Then** what outcomes/impacts on the forest as a whole and individual species would be expected?
- **So** what are the consequences of those outcomes/impacts (including strategic, financial, operational, environmental, public perception, and safety)?

4.0 RESULTS

4.1 Canopy Distribution

The 2022 canopy cover analysis found that approximately 4,346 ha or 21 percent of land area in Markham is covered by tree and tall shrubs[14] (termed existing canopy) while impervious surfaces—roads, buildings, and other paved surfaces—represent approximately 21 percent of the land area (Figure 2). The remaining 58 percent is comprised of grass, low shrubs, and bare ground. The high percentage of the latter is due to the large area of agricultural lands in Markham. At 21 percent canopy cover, Markham's current canopy falls within the recommended range of 20 to 35 percent canopy cover in the York Region Forest Management Plan.

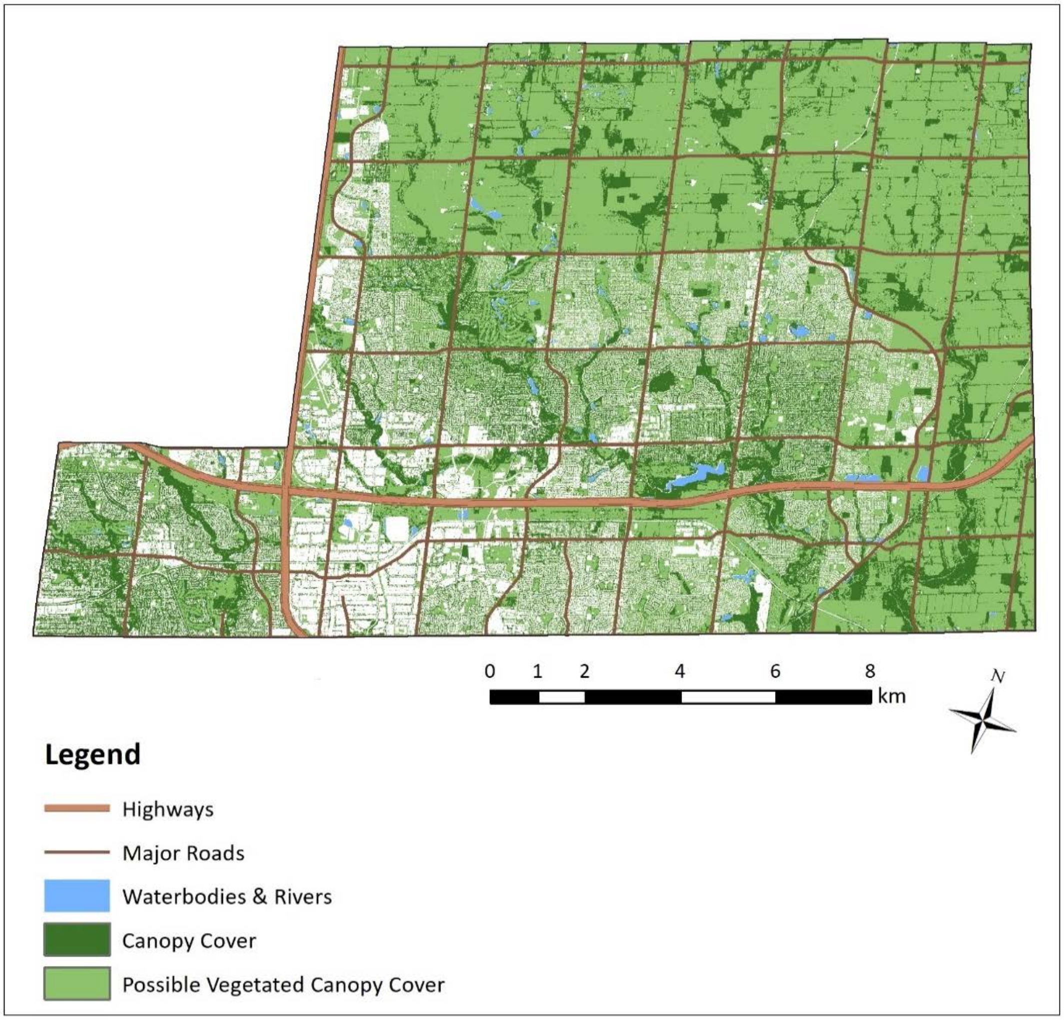

Figure 2: Distribution of existing and possible vegetated[15] canopy cover across Markham 2022.

[14] Shrubs that were at least 2 meters tall would be indistinguishable from trees.

[15] Possible Vegetated Canopy Cover are areas currently covered with low shrubs and herbaceous land cover.

Canopy cover has modestly increased by 3 percent in Markham since the previous assessment in 2012 of 18 percent. Based on UVM's visual inspection, while there are some losses of canopy due to construction, canopy gain occurred due to natural growth of trees, particularly in residential areas, which outpaced losses from construction and development.

A total of 66 percent (13,826 ha) of the municipality's land area could *theoretically* support additional canopy (Figure 3). However, much of this area is contained within active agricultural lands which in practice cannot be planted. Within the possible canopy category, 88 percent (12,226 ha) is identified as possible vegetated canopy and the remaining 12 percent is possible impervious canopy (1,600 ha). Detailed canopy cover and land cover metrics (areas and percentages) for Markham can be found in Appendix C.

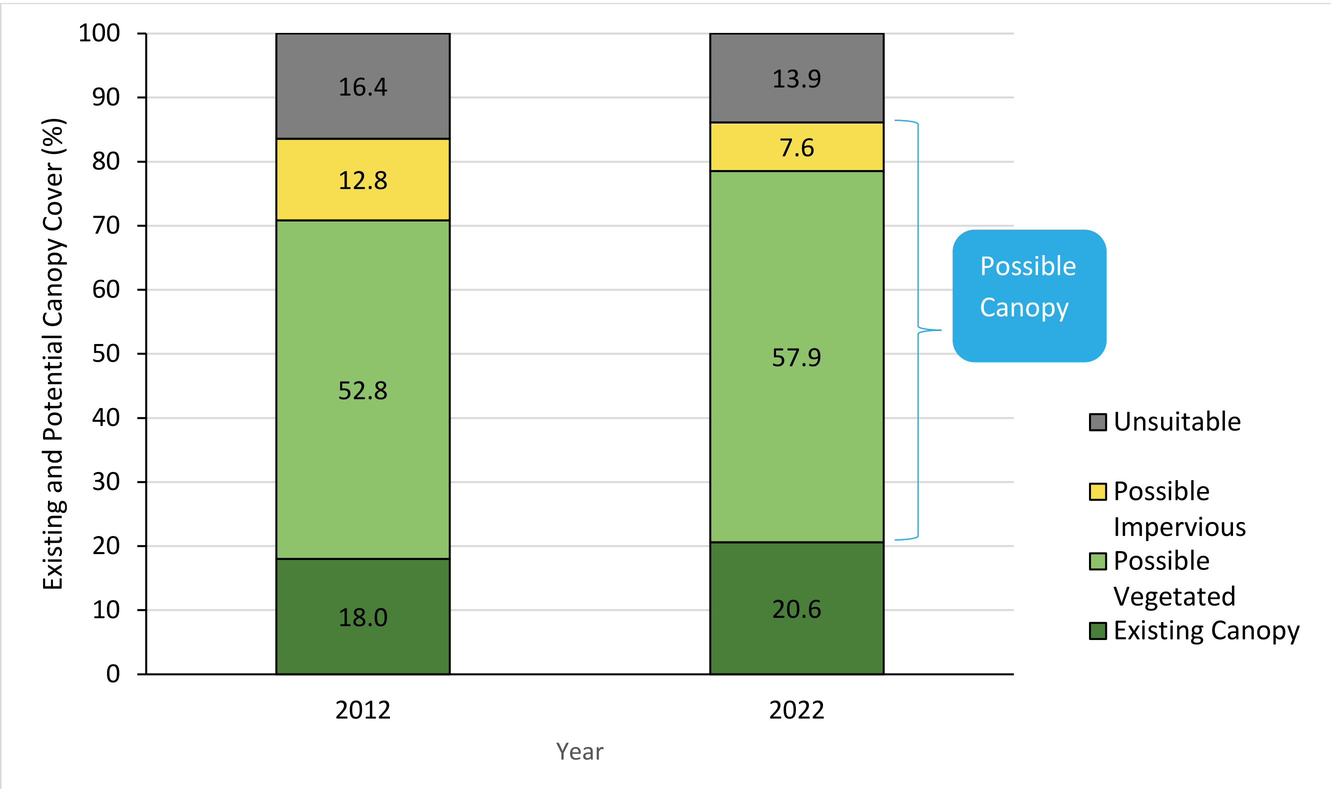

Figure 3: Canopy cover metrics for Markham in 2012 and 2022

4.1.1 Canopy Cover and Plantable Space by MPAC Land Use Type

Canopy cover metrics were also calculated by MPAC land use types. As noted in Section 3.1, land use changes have occurred since 2016 (the date of land use designation by MPAC); while efforts were made to improve upon the land use results, results summarized by land use should be viewed as approximate totals for each land use. Figure 4 summarizes the proportion of each land use type within Markham, while Figure 5 illustrates the land use distribution, and Figure 6, the area of existing and possible canopy cover. *Agricultural* areas occupy the greatest proportion of area in Markham at 31 percent, followed by *Residential Low Density* at 22 percent.

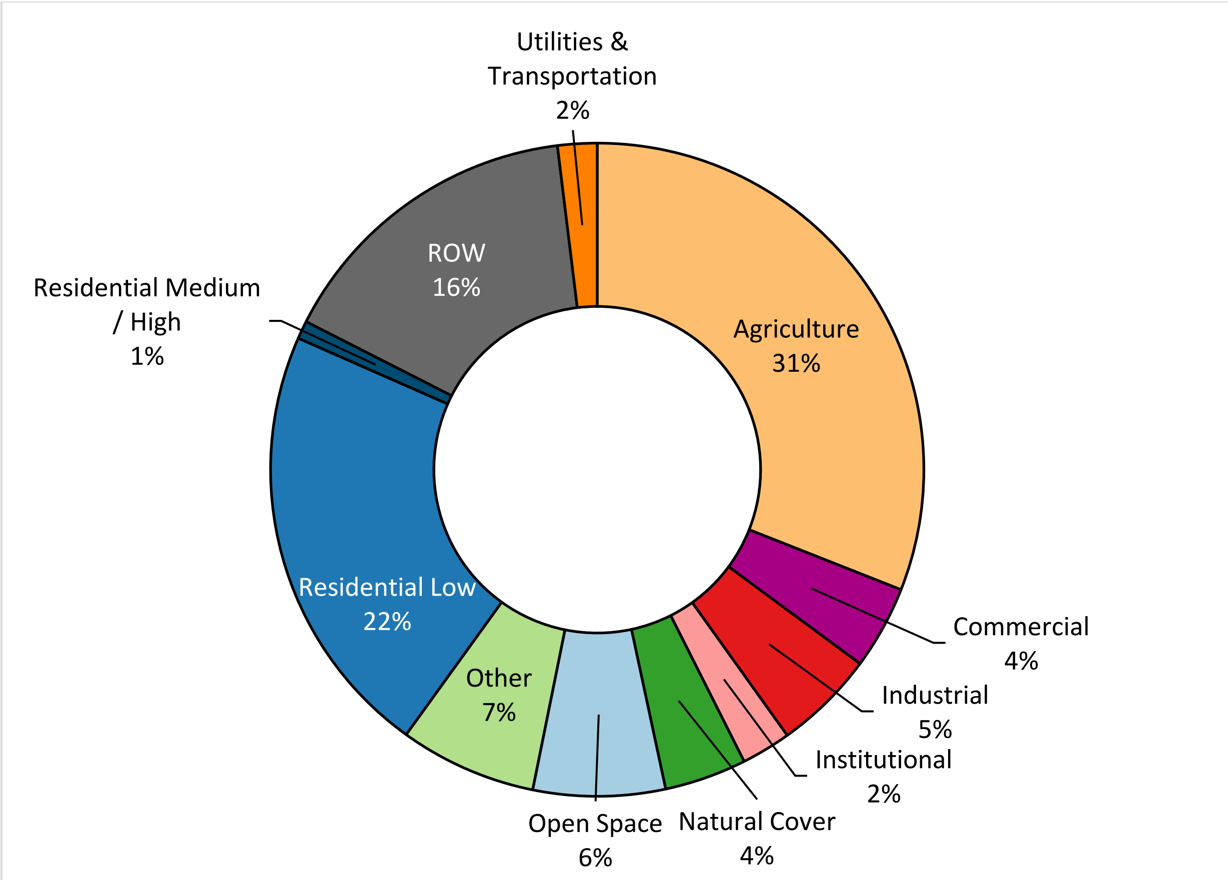

Figure 4: Current approximate land use distribution in Markham 2022

The distribution of canopy cover varies across the MPAC land uses in Markham (Table 9: Contribution of each land use type to total canopy cover and canopy cover percent in each land use in 2022Table 9). The *Residential Low* land use type, which occupies 22 percent of municipal land area, contributes the greatest proportion of the total existing canopy containing 1,171 hectares of tree canopy or 27.0 percent of the municipality's total canopy area. 48 percent of Markham's total canopy cover is found on properties designated as *Residential Low* and *Agriculture* by MPAC. A small portion of the canopy cover is found in *Institutional*, *Industrial*, *Commercial*, *Utilities & Transportation*, *Residential Medium/High*, and *ROW* land uses.

Table 9: Contribution of each land use type to total canopy cover and canopy cover percent in each land use in 2022

MPAC Land Use	Contribution to Total Canopy Cover (% of Total Canopy Cover)	Canopy Cover Area (ha)	Canopy Cover with Land Use (% of Land Area within Land Use)
Residential Low	26.9	1,171.0	25.5
Agriculture	21.1	915.0	13.9
ROW	12.6	548.3	16.6
Other	10.8	468.7	34.1
Open Space	9.9	432.1	31.7
Natural Cover	9.5	410.5	49.0
Commercial	2.5	109.8	12.5
Institutional	2.3	100.3	19.4
Industrial	1.8	77.6	7.3
Utilities & Transportation	1.6	69.1	16.8
Residential Medium / High	1.0	43.4	22.8
Markham	100.0	4,345.8	21.0

The largest area of possible canopy is theoretically found within the *Agriculture* land use, which occupies 31 percent of the municipal area; however, possible canopy considers only the physical requirements of tree planting and not the social or economic expectations for each land use. In reality, it is unlikely that most of this area can be planted with trees, although there are opportunities to plant windbreaks around fields.

Understanding the distribution of canopy cover is important, but another key component is understanding the distribution within land uses to guide management decisions. In the *Residential Low* category, 25.5 percent of the land area has canopy cover, whereas in the *Natural Cover* category, 49 percent of the land use has canopy cover (Figure 55). However, due to the relatively small size of this land use (4% of municipal area), tree canopy within the *Natural Cover* category only contributes 9 percent to the municipality's total canopy cover area (411 ha). Existing canopy cover percent is lowest within the *Industrial* land use categories (less than 10%).

Excluding agricultural lands, the greatest opportunity to increase total municipal canopy area is found in the *Residential Low* land use category (See Figure 6). Approximately 1,847 ha (40%) of the *Residential Low* category is classified as possible additional vegetated canopy cover, and an additional 259 ha (6%) of the *Residential Low* category is classified as possible additional impervious canopy. Detailed canopy cover and land cover metrics (areas and percentages) for Markham can be found in Appendix E.

Following *Agriculture* and *Residential Low* categories, the *Right-of-Way* land use category, has the greatest land opportunity for tree establishment at 1,898 hectares, comprised primarily of land currently vegetated with grass/herbaceous and low shrub cover. It will be important to ensure that development guidelines support tree planting and maintenance of pervious surfaces so that future opportunities are not curtailed. Although these represent the greatest potential to increase the municipal canopy cover, opportunities for expanding the municipal forest exist on all land use types and should be pursued to increase both local and municipal wide benefits.

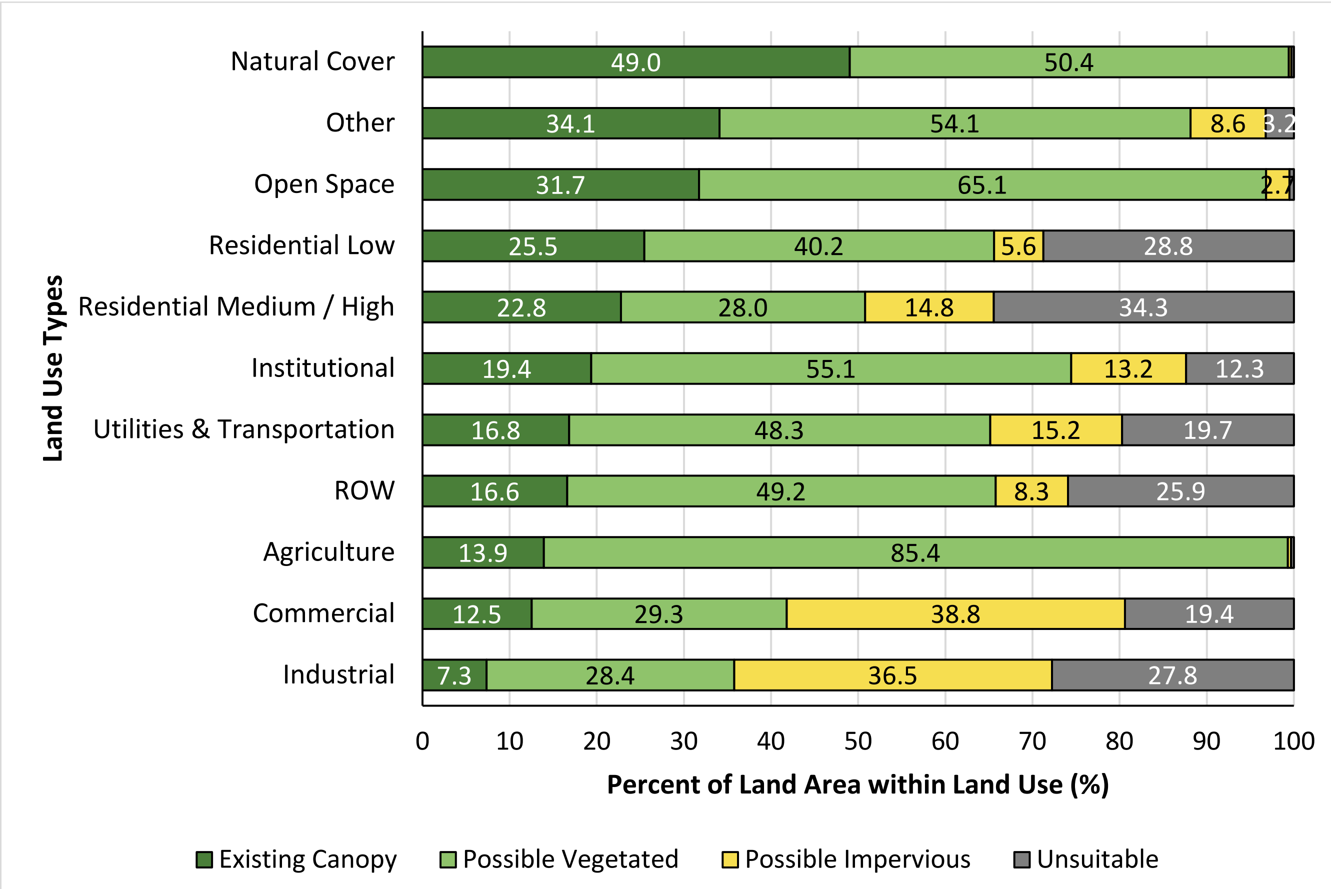

Figure 5: The distribution of existing canopy cover, possible vegetated cover, and possible impervious canopy cover as a percent of land use land area in Markham 2022

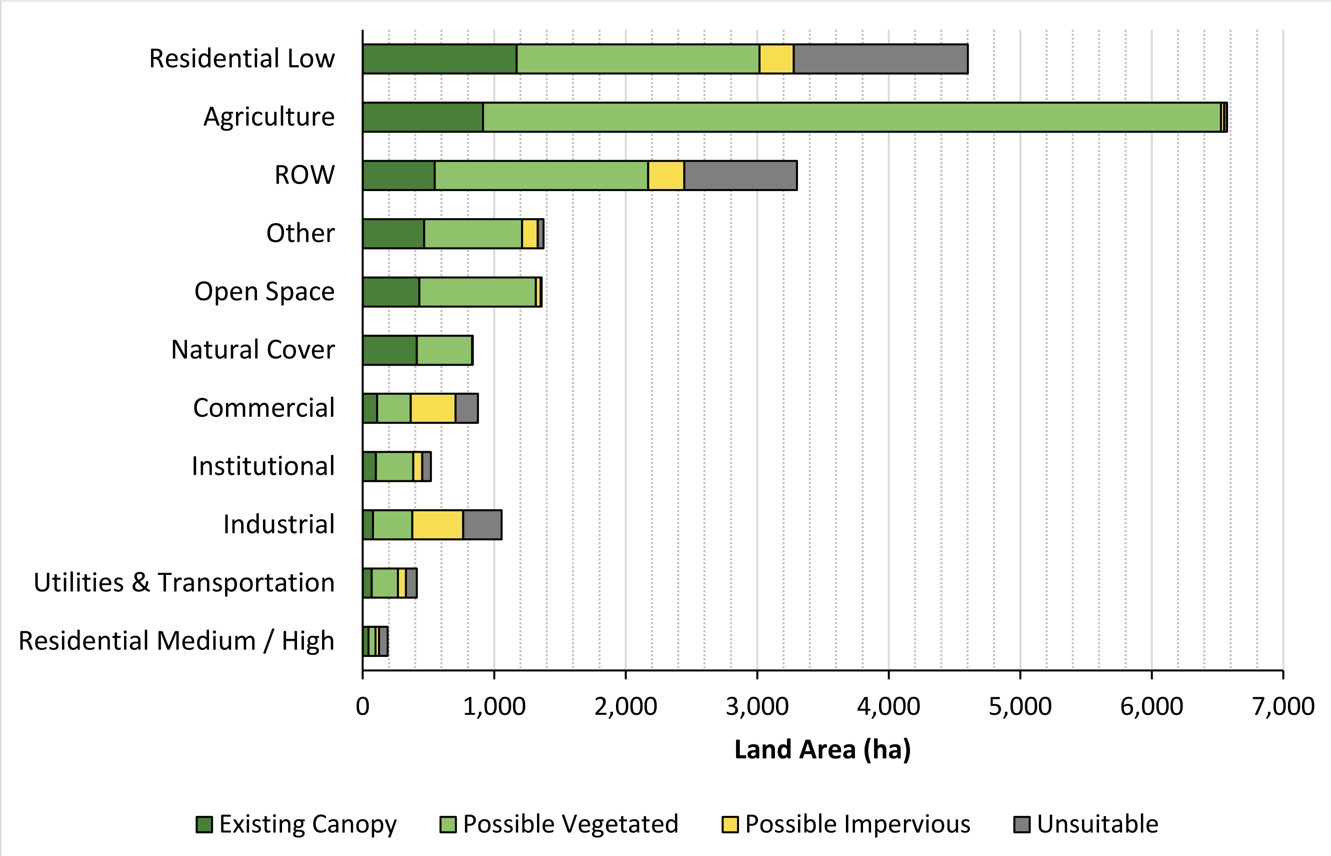

Figure 6: The distribution of existing canopy cover, possible vegetated cover, and possible impervious canopy cover measured in hectares in Markham 2022

4.2 Forest Structure

4.2.1 Structure

The i-Tree Eco model determined that there are approximately 3,295,310 (±469,829) trees in Markham compared to 3,155,000 (±542,000) trees in 2012. The results suggest that the population size has remained the same, or slightly increased; however, the standard errors are large enough that the change cannot be concluded with certainty. The average tree density in Markham is 155 trees/ha (compared to 148 trees/ha in 2012). The *Other-Institutional* land use stratum has the highest tree density at 355 trees/ha, followed by *Open Space – Natural Cover* (305 trees/ha) and *Residential* (286 trees/ha) (Figure 7); the *Other* land use is comprised of a mix of land uses, but particularly vacant residential land and vacant residential development land, as well as storm water ponds, non-commercial/recreational sports complexes, and communal land. The high proportion of trees can be attributed to the vacant residential land not on water within the ravine and valley network of Markham, which also includes undeveloped woodlots.

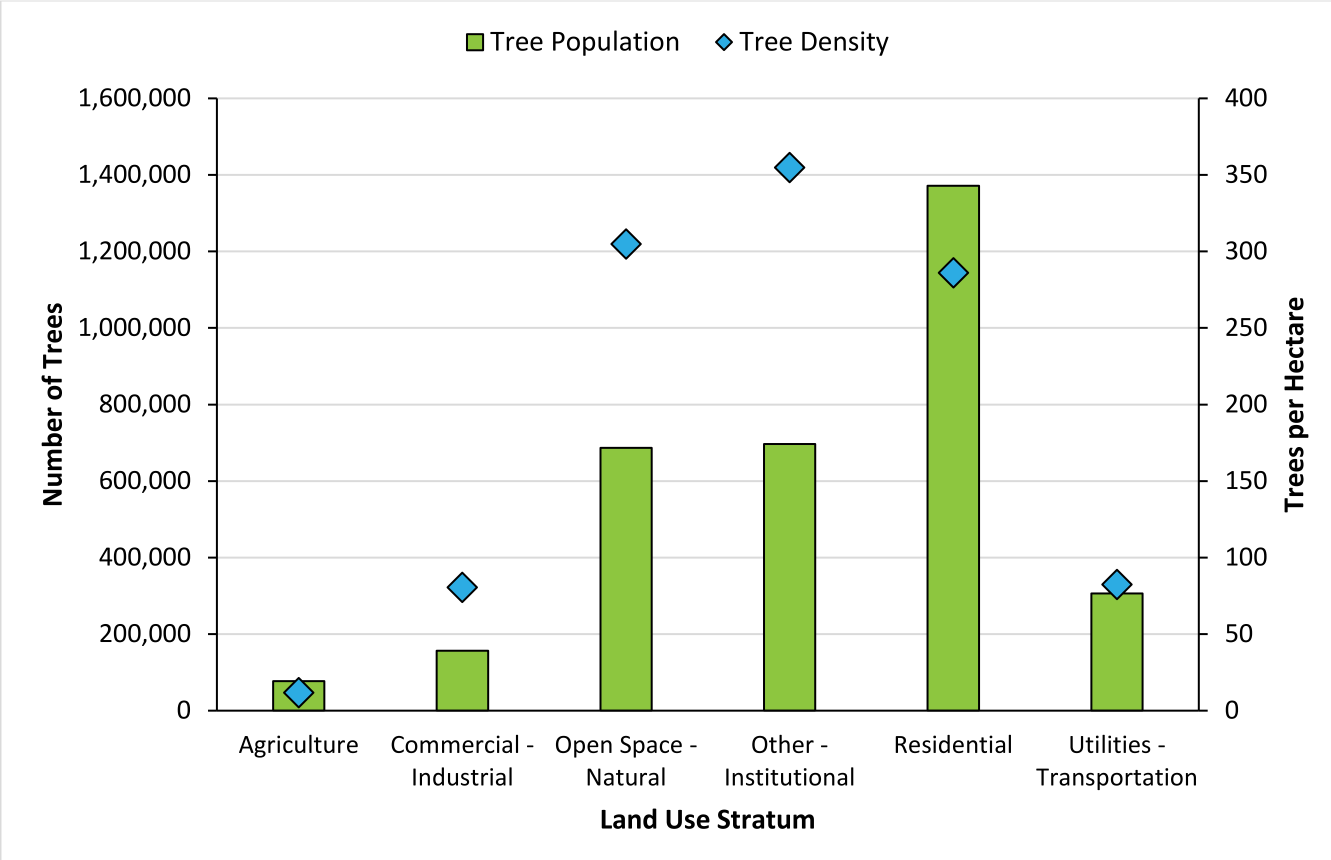

Figure 7: Total number of trees and tree density (trees per hectare) summarized by land use stratum in Markham 2022

Leaf area in Markham is approximately 23,912 hectares (±4,072 ha) across a municipal area of 21,268.4 hectares compared to 21,600 hectares (standard error unreported) in 2012. Thus, the mean leaf area density (of trees) in Markham is approximately 1.12 hectares per hectare of land (in comparison to 1.01 ha/ha in 2012). This can also be expressed as 1.12 m^2 of leaf area for every 1.0 m^2 of land area. Leaf area density varies widely between land uses and is highest in the *Open Space – Natural* and *Other – Institutional* strata (Figure 88); these land use strata represent 10 percent and 9 percent of the total area in Markham, respectively. Leaf area density is lowest in the *Agricultural* land use stratum. Table 10 summarizes tree population and density and leaf area and leaf density statistics per stratum.

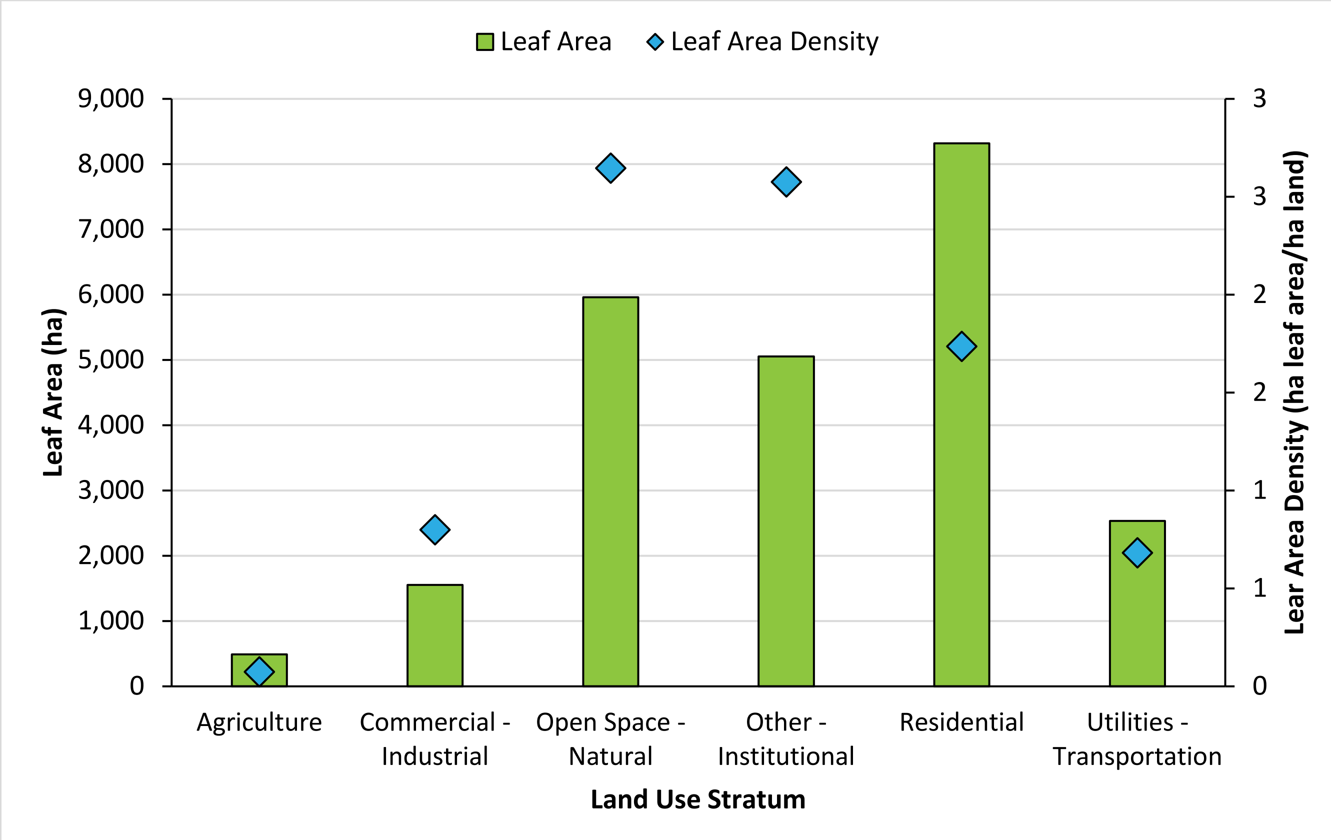

Figure 8: Leaf area (ha) and leaf area density (hectare of leaf area per hectare of land) by land use stratum in Markham 2022

Table 10: Tree structure statistics by land use stratum in 2022

Stratum	Number of Trees	Percent of Population	Tree Density (Trees / ha)	Leaf Area (ha)	Leaf Area Percent (% of Total Leaf Area)	Leaf Area Density (ha leaf area/ha of land)
Agriculture	77,549	2.4%	11.8	488.6	2.0%	0.07
Commercial – Industrial	156,661	4.8%	80.6	1,552.6	6.5%	0.80
Open Space – Natural	686,582	20.8%	304.8	5,959.2	24.9%	2.65
Other – Institutional	696,546	21.1%	354.8	5,055.8	21.1%	2.58
Residential	1,371,270	41.6%	286.0	8,321.1	34.8%	1.74
Utilities – Transportation	306,702	9.3%	82.4	2,535.2	10.6%	0.68
Markham	**3,295,310**	**100.0%**	**154.9**	**23,912.3**	**100.0%**	**1.12**

Public and Private Trees

Forty-five percent (±10.7%) of Markham's trees occur on public lands, such as municipal parks, ROWs, protected areas, and conservation authority lands, and fifty-five percent (±10.9%) of trees are privately owned. The *Open Space – Natural Cover* land use stratum has the greatest proportion of public trees at 45 percent of trees in that stratum, and 20 percent of all public trees. However, the *Open Space – Natural Cover* land use stratum is very closely followed by *Other – Institutional* with the second most proportion of public trees at 43 percent of trees in the stratum, and 19.7 percent of all public trees.

4.2.2 Composition

Species composition can be expressed either as a percent of total leaf area[16] or as a percent of the total number of trees. Leaf area indicates the *total* area of leaves within the canopy layer. It is much larger than canopy cover area, which is simply a vertical projection of the canopy layer onto the ground. When species composition is measured by the number of trees, species that maintain a smaller growth form and that grow in high densities (such as European buckthorn (*Rhamnus cathartica*)) 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 volume as well as to the provision of ecosystem services (as ecosystem services are generally a function of leaf area). Using these two different measures will highlight a different set of species as being most abundant or dominant. Figure 9 depicts the top ten species by percent of total population and Figure 10, the top ten species as a percent of leaf area.

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[16] Leaf area is defined as the total surface area (one-sided) of tree leaves. It is not equivalent to canopy cover which is the area of ground covered by canopy as viewed from directly above.

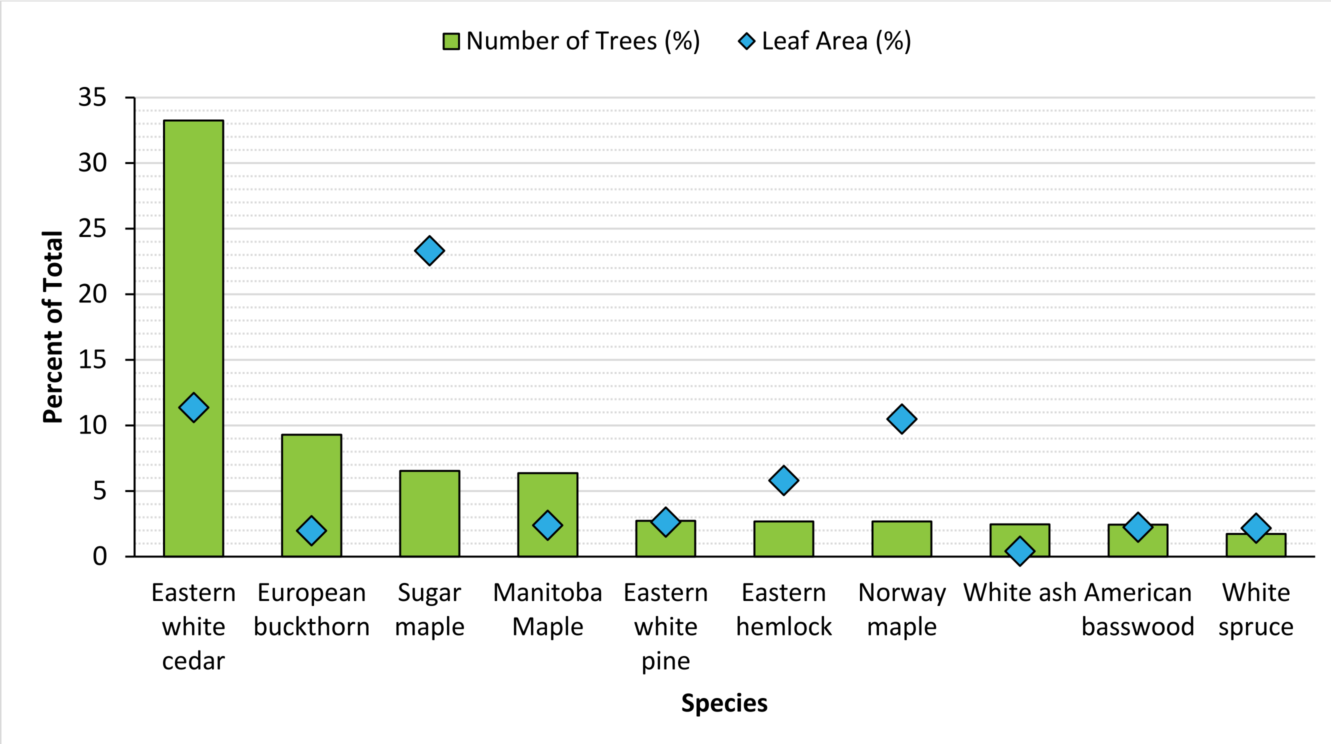

Figure 9: Top ten most abundant tree species by percent of trees in 2022

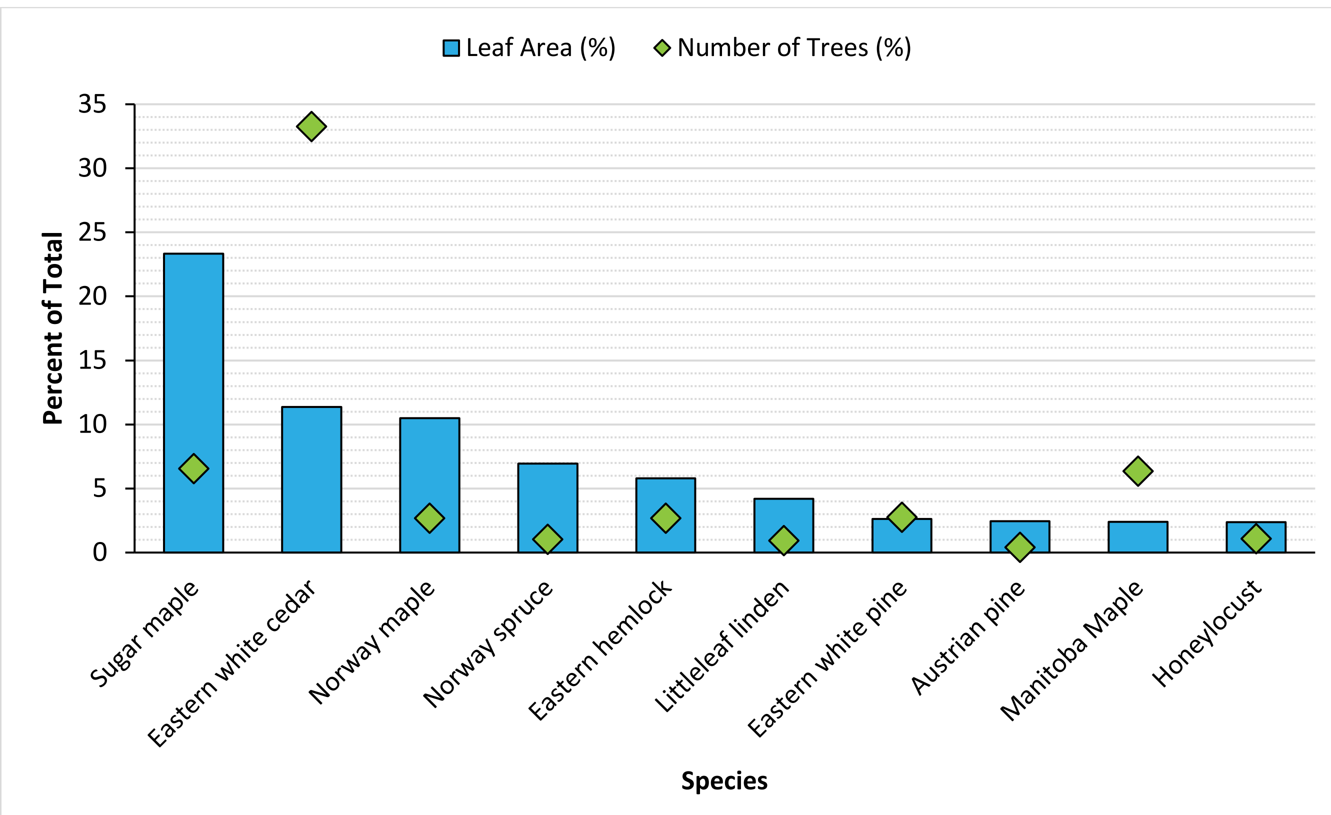

Figure 10: Top ten species in terms of leaf area in 2022

In Markham, the cedar/juniper (*Cupressoideae* sub-family, 33.7%) and maple (*Acer spp.,* 17.8%), sub-family/genus are the most dominant in terms of percent of the tree population. These are followed by buckthorn (*Rhamnus spp., 9.7%*), ash (*Fraxinus spp.,* 4.8%), pine (*Pinus spp.*, 4.2%), spruce (*Picea spp*., 3.9%), and basswood/linden (*Tilia spp.*, 3.4%).

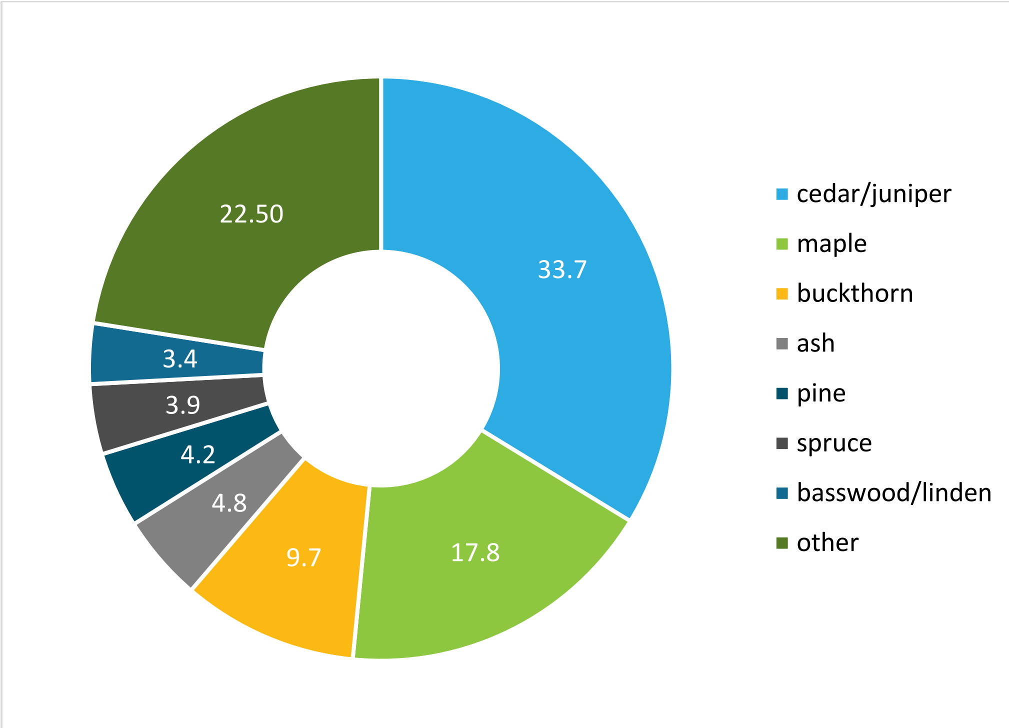

Figure 11: Dominant sub-families/genera in terms of percent (%) of tree population in Markham 2022

The overall species diversity in Markham is low across each land use type, with the same species dominating most land uses. A breakdown of the top three most abundant species is provided in Table 11. In terms of population, eastern white cedar (*Thuja occidentalis*) and European buckthorn highly dominate most land uses. Another important species is sugar maple (*Acer saccharum*). Sugar maple has the highest percentage leaf area of any species in Markham and is a top species in four of the six land use categories: *Commercial – Industrial*, *Open Space – Natural Cover*, *Other – Institutional*, and *Utilities – Transportation.*

Table 11: Dominant tree species by percent of tree population and percent of leaf area within land use stratum in Markham 2022

	Percent of Tree Population per Land Use		Percent of Leaf Area per Land Use	
Land use	**Common Name**	**Percent**	**Common Name**	**Percent**
Agriculture*	European buckthorn	40	Scots pine	35
	Hawthorn spp.	27	Eastern white cedar	22
	Eastern white cedar	13	European buckthorn	22
Commercial – Industrial*	European buckthorn	40	Sugar maple	50
	Sugar maple	15	Norway maple	10
	Red pine	11	Honey locust	9
Open Space – Natural Cover	European buckthorn	12	Sugar maple	27
	Eastern white pine	12	Eastern white cedar	12
	Sugar maple	9	Eastern hemlock	10
Other – Institutional	Manitoba maple	22	Sugar maple	46
	Sugar maple	12	Eastern hemlock	16
	Eastern white cedar	11	Eastern white cedar	12
Residential	Eastern white cedar	65	Norway maple	21
	Norway maple	4	Norway spruce	20
	European buckthorn	3	Eastern white cedar	15
Utilities – Transportation (incl. ROW)	Eastern white cedar	19	Sugar maple	33
	Sugar maple	14	Norway maple	15
	White ash	8	Littleleaf linden	12

* Estimates for *Agriculture* and *Commercial – Industrial* have a very high standard error relative to the stratum population size due to the small number of trees sampled in these categories.

A total of 81 tree species were identified across all plots in Markham. Species richness is highest in the *Residential* land use stratum (45 species); this comparatively large number of species found can likely be attributed to the number of exotic horticultural species commonly planted in residential gardens. It follows that in the context of forest studies that include urban areas, high species richness should not necessarily be viewed as an indication of ecosystem health. Rather, it may simply indicate an abundance of exotic species. Thus, urban forests often have a species richness that is higher than surrounding rural landscapes. In Markham, 57 percent of the tree species identified were native to Ontario. The proportion of native species was approximately 38 percent in 2012.

Composition Change

Since 2012, there have been some changes in the dominant species and/or their relative abundance. Figure 12 shows the top five most abundant species in terms of number of trees and percent of leaf area in 2012 and 2022.

In terms of population, the top five most abundant species are largely the same, however, eastern white cedar has increased significantly since 2012. This is likely due to the increase in residential neighbourhoods where planting cedar hedge rows is popular. White (*Fraxinus americana*) and green ash (*Fraxinus pennsylvanica*) declined as a proportion of the population, most likely due to the impacts of emerald ash borer (EAB). Manitoba maple (*Acer negundo*) also appeared in the top five in 2022, displacing eastern hemlock (*Tsuga canadensis*). This may be a result of its ability to spread and establish more easily than other species.

In terms of leaf area, again there is mostly overlap in the top five species. However, between 2012 and 2022, white and green ash dropped off the list and Norway spruce (*Picea abies*) appeared. The top five species have increased in terms of their dominance as a proportion of the total leaf area from 45 to 57 percent.

The sugar maple population decreased from 11 percent in 2012 to 7 percent in 2022, a decline in the estimated number of trees of 334,465 (standard error unspecified) to 215,623 (±79,783) respectively. However, sugar maple leaf area increased between 2012 and 2022 from 13 to 23 percent. The size distribution of the sugar maple population is primarily small, with 49.6 percent of trees found in the two smallest diameter classes (under 15.2 cm). However, 28.1 percent of the sugar maple population are in the top three diameter classes, measuring over 30.5 cm diameter, which likely explains the higher leaf area. The large population of smaller sugar maple trees will eventually grow to replace the larger ones into the future with appropriate maintenance.

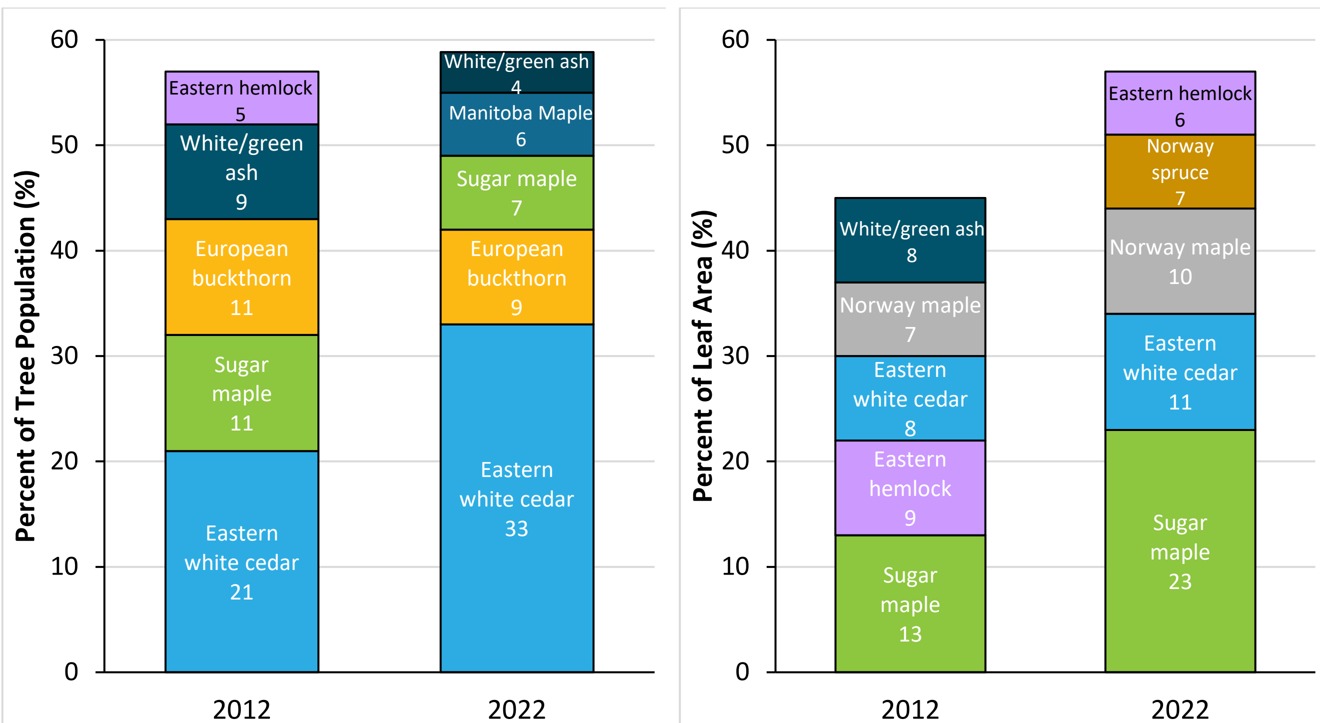

Figure 12: Top five dominant species by population size and leaf area in 2012 and 2022

Since 2012, ash trees (white; green; and black, *Fraxinus nigra*) have decreased in the population from 320,020 (standard error unspecified) to 157,647 (±61,266) and as a percent of the population from 10 percent to 5 percent. Given the large standard error in population estimates for 2022, it cannot be ruled out that this apparent decline is from chance. However, their reduction could also reflect the impact of EAB over the past eleven years as the average condition of ash trees in 2022 was poor. Green and white ash had an average condition of 29 percent and 39 percent, respectively, where condition is the inverse of percent dieback (100 percent minus percent dieback). All specimens of black ash observed were dead. Section 4.7 reviews the presence and spread of EAB and other pests in more detail.

4.2.3 Size Distribution

All trees measured were grouped into size classes based on diameter at breast height (DBH) and diameter class increased in 7.6 cm increments. Approximately 72 percent of all trees in Markham are less than 15.2 cm DBH (Figure 13). The proportion of large trees is low; just more than nine percent of the tree population has a DBH of 30.6 cm or greater. Since 2012, there has been an increase in the number of trees in the second smallest size class, and a decrease in the smallest size class. However, the average tree diameter across the forest is relatively unchanged, being 14.2 cm in 2022 and 14.3 cm in 2012. The slight increase in the proportion of trees in the second smallest size class could reflect a change in protocol, in which the minimum DBH of forested areas was increased from 2.5 cm in 2012 to 5 cm in 2022.

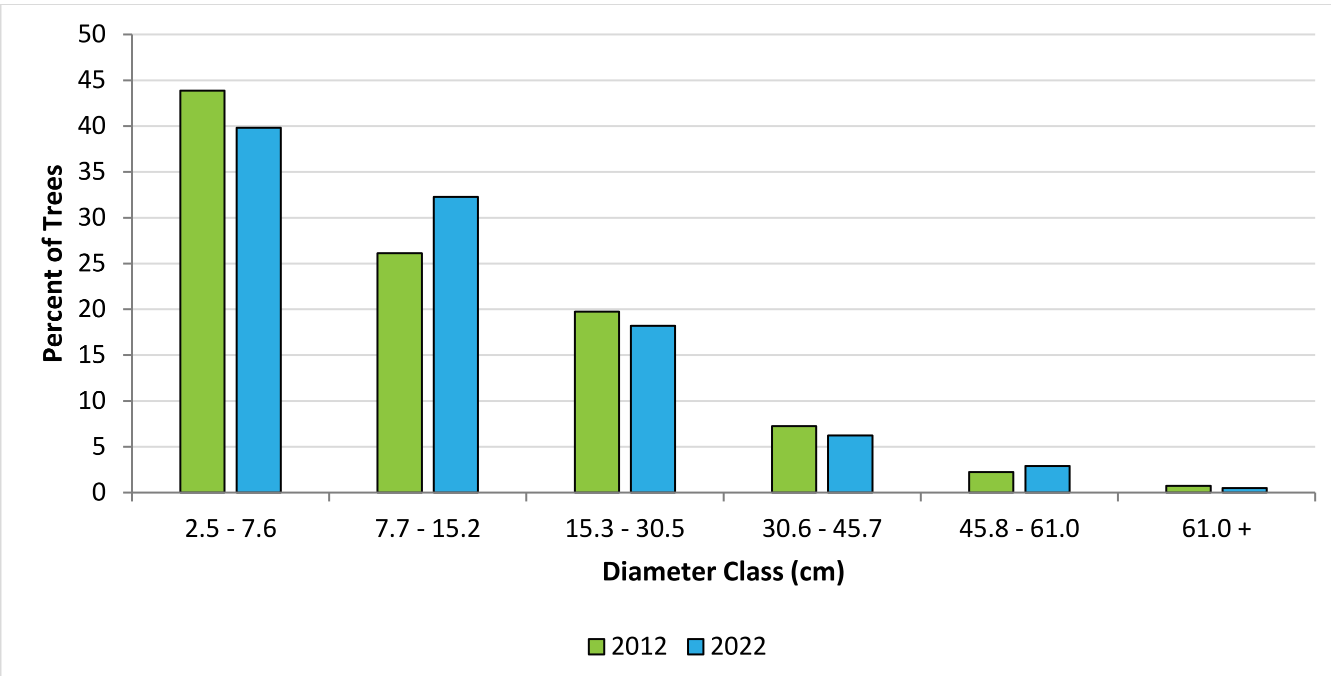

Figure 13: Diameter class distribution of trees in Markham in 2012 and 2022

Figure 14 presents the diameter class distribution by land use stratum for 2022 and 2012. The trend is similar across all land uses, with the smallest diameter classes containing the large majority of trees and very few trees (3.4%) found in the larger (>45.7 cm) diameter classes (Figure 14 – top). *Open Space – Natural Cover* has the smallest proportion of small trees (<15.2 cm) and *Residential* has the greatest proportion of small trees indicating the younger age of many residential suburbs. Surprisingly, *Commercial – Industrial* has the largest proportion of very large trees (>45.7), followed by the *Utilities – Transportation and ROW* land use categories.

When comparing the size distribution to 2012, it is important to note that land use strata were grouped slightly differently for the previous assessment. The *Institutional* land use was grouped with *Utilities* and *Transportation*.Therefore, the *Other – Institutional* stratum in 2022 is not exactly comparable to 2012's *Other*, as the latter does not include institutional land uses. Additionally, the size distribution for the *Utilities – Transportation – Institutional* category was omitted from the size class analysis by land use for 2012. However, it is still possible to observe general patterns over time. Since 2012, there has been an increase in the number of trees in the second smallest size class (7.7 cm to 15.2 cm), and a decrease in the population within the smallest size class, with the exception of the *Residential* stratum (likely due to new development plantings). The increase in the population found in the second smallest size class is particularly positive and is likely driven by the growth of young trees planted across strata over the past decade and prior. Additionally, this may indicate increased survivorship of new trees across the municipality however there is insufficient information to determine whether this is the case. There has been a decline in the population within larger size classes, particularly the third largest (30.5 cm to 45.7 cm) across all land use strata. This is potentially due to the impacts of EAB and/or extreme weather events that have occurred between 2012 and 2022.

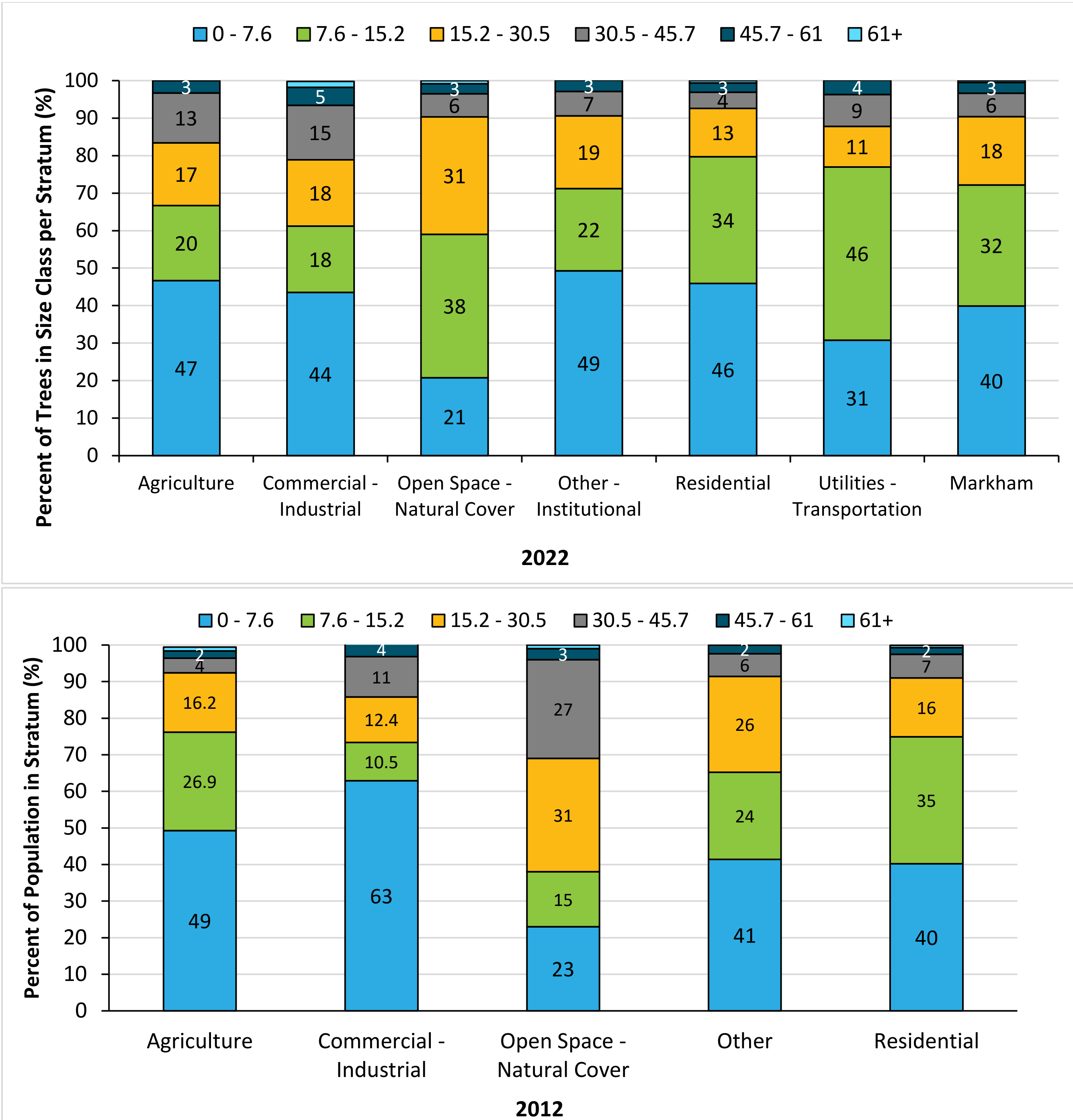

Figure 14: Diameter class (cm) distribution of trees by land use stratum in Markham in 2022 (top) and 2012[17] (bottom)

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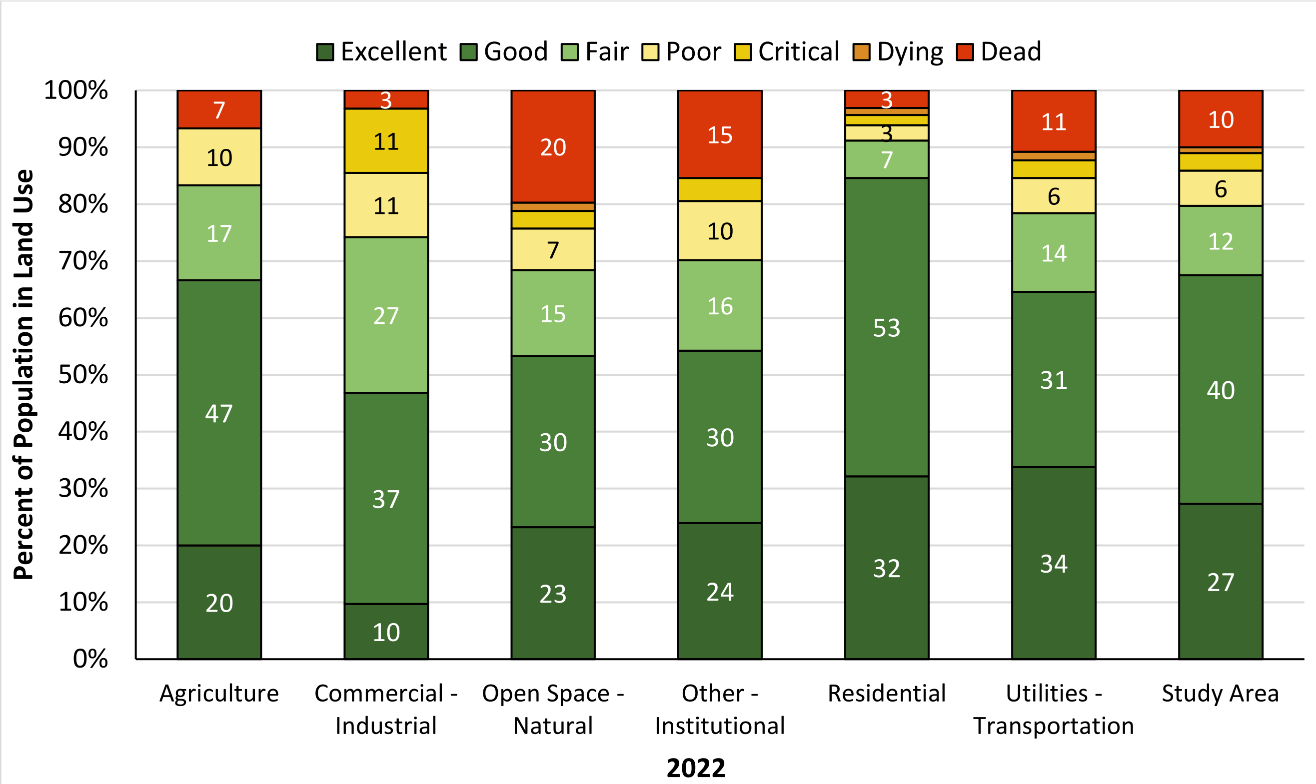
[17] Land use strata were grouped slightly differently for the 2012 report. The *Institutional* land use was grouped with *Utilities* and *Transportation*. Additionally, the size distribution for the *Utilities-Transportation-Institutional* category was omitted from the size class analysis by land use for 2012.

4.2.4 Condition

All trees measured were 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):

- excellent (<1% dieback)
- good (1-10% dieback)
- fair (11-25% dieback)
- poor (26-50% dieback)
- critical (51-75% dieback)
- dying (76-99% dieback)
- dead (100% dieback - no leaves)

Basic condition ratings do not incorporate stem defects and root damage. Approximately 79 percent of trees in Markham were estimated to be in either excellent, good, or fair condition (Figure 15 – top), and 87 percent in 2012 (Figure 15 – bottom). This moderate decline in the proportion of healthy trees, in addition to an increase in the proportion of trees in poor, critical, dying, or dead condition from 12 percent to 20 percent indicates that tree condition has worsened over the past twelve years.



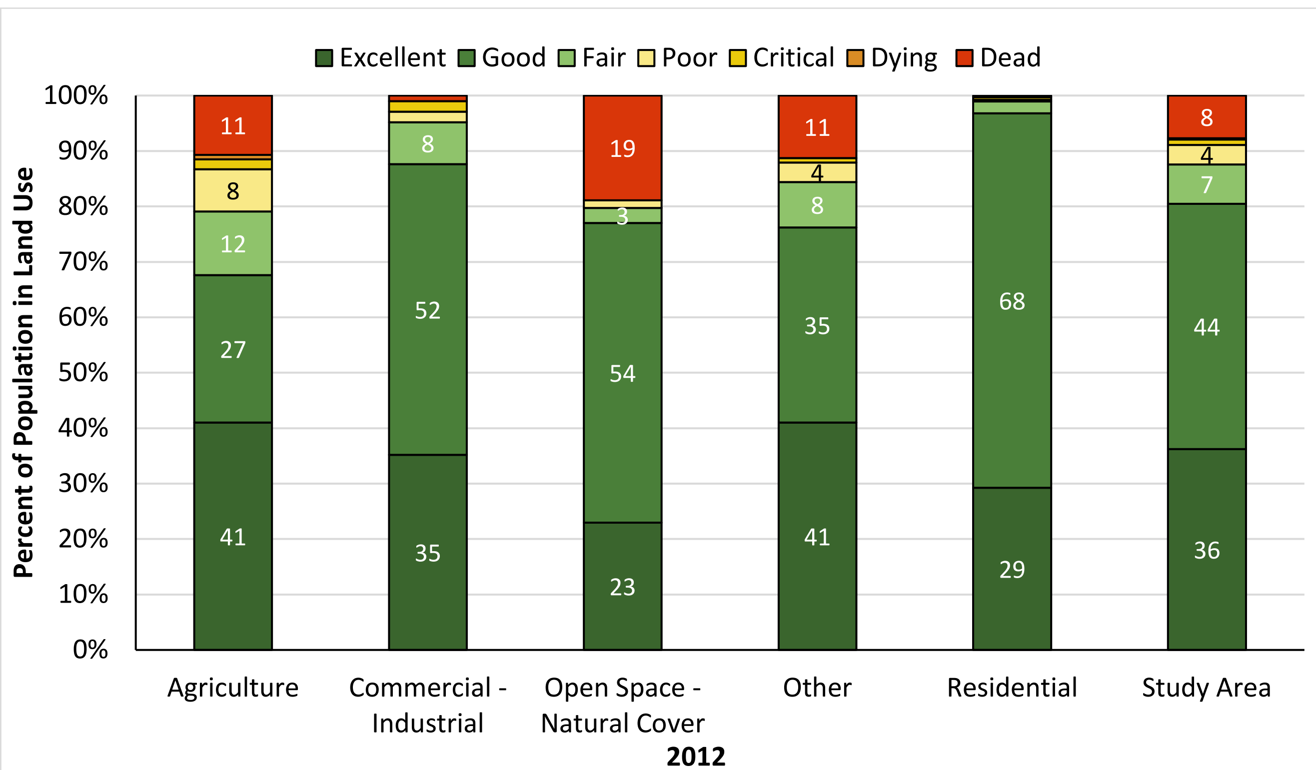


Figure 15: Condition of trees by land use stratum in Markham in 2022 (top) and 2012[18] (bottom)

The worst decline in tree health is observed in the *Commercial – Industrial* and *Other – Institutional* strata where the percent of trees in poor to dying condition or dead, increased by 21 and 14 percent, respectively[19]. While the *Other – Institutional* stratum in 2022 is not exactly comparable to 2012's *Other* category, which did not include institutional lands, the *Institutional* land use only occupies a small proportion of the *Other – Institutional* category, thus making this comparison over time still valid. Land categorized as *Other* is a mix of land uses such as non-commercial sports complexes and vacant residential or development land. It includes much of the ravine network in Markham and undeveloped woodlots. Like *Open Space – Natural Cover*, dying and dead trees are not actively removed if they do not pose a risk to infrastructure or public safety. However, the large increase in dead trees from 11 percent to 15 percent is concerning.

In the *Commercial – Industrial* stratum, 40 percent of American elm (*Ulmnus americana*) are dead, and European buckthorn, and English oak (*Quercus robur)* account for the majority of trees in poor to very poor health in 2022. In the *Other – Institutional* stratum, a large proportion of white and black ash are dead, at 67 and 100 percent, respectively, and their average condition score is 32 and 0 percent, respectively. Together these species account for 5.5 percent of the tree population in this stratum. Conversely, green ash is in quite good condition with an overall average condition score of 75 percent. The biggest contributor to poor health in this stratum is eastern white cedar which comprises 11 percent of the population and has an average condition score of 62 percent. Fifty-six percent of cedar trees are in poor, critically, dying, or dead condition. Other species with a high percentage of low average scores that make up at least 1 percent of the tree population in the *Other – Institutional* stratum include yellow birch (*Betula alleghaniensis*) – 100 percent dead, black walnut (*Juglans nigra*) – 57 percent dead, Scots pine (*Pinus sylvestris*) – 100 percent dead, and American elm – 50 percent dead.

In the *Open Space – Natural Cover* stratum, 47 percent of white ash and 100 percent of green ash were dead, corresponding with an average condition score of 53 and 0, respectively. Other species with a high percent of low average scores are Hawthorn spp. (*Crataegus spp*.) – 100 dead, balsam poplar (*Populus balsamifera*) – 100 percent poor, and quaking aspen (*Populus tremuloides*) – 50 percent dead.

4.2.5 Structural Value

The estimated structural value of all trees in Markham in 2022 is approximately $1.12 billion. This value does not include the ecological or societal value of the forest, but rather it represents an estimate of tree replacement costs or compensation that would be owed if the trees were destroyed. i-Tree Eco assesses structural value using a modified version of the Council of Tree and Landscape Appraisers (CTLA) Trunk Formula Method (Nowak, 2020). This value is based on species, DBH, condition, and location. A base value of a tree is determined by its replacement cost, which in turn is informed by the maximum DBH trees available for replacement and average

[18] Land use strata were grouped slightly differently for the 2012 report. The *Institutional* land use was grouped with *Utilities* and *Transportation.* The 2012 report did not include condition results for the *Utilities-Transportation-Institutional* land use stratum.

[19] It should be noted that we do expect to see more trees in poor health and dead trees in natural areas as these are not generally a risk to the public or homeowners and may be left to stand. In fact, dead trees provide important habitat and resources to wildlife and other organisms.

cost per square cm of trunk area. The base value is adjusted by a species factor (species specific factors are available for Canada as a whole), condition (the inverse of percent dieback), and land use (as an indicator of location). For non-U.S. countries, the average replacement cost assumes a maximum replacement size of 10 cm and cost per unit area based on the average value of all species within hardwood (dicotyledon) and softwood (conifer) categories. There is a positive relationship between the structural value of a forest and the number and size of healthy trees. Trees in locations that provide more amenities to humans, such as golf courses, are also provided a higher score.

4.3 FOREST FUNCTION

4.3.1 Carbon Storage and Sequestration

Gross carbon sequestration by trees in Markham is approximately 8,693 tonnes of carbon per year (31,879 tonnes of carbon dioxide per year) with an associated annual value of $1.6 million, and net carbon sequestration[20] is approximately 5,424 tonnes per year (19,891 tonnes CO_2 per year) with a value of $1.0 million. Trees in Markham are estimated to store 265,348 tonnes of carbon (972,943 tonnes of CO_2-equivalents), with the value of this service being $50.1 million.

Since 2012, gross annual carbon sequestration has remained roughly equivalent (9,200 tC/year in 2012), but net sequestration has decreased from 7,400 tonnes carbon per year. The decline in net sequestration can likely be attributed to the increase of trees in critical, dying, or dead condition from 9 to 14 percent and an increase in dead trees from 8 to 10 percent. In particular, dying and dead ash trees (*Fraxinus* spp.) are expected to emit carbon as they decompose (1,325 tC/year). The total carbon storage increased from 230,000 tonnes carbon, this is in line with the increase observed in canopy cover, population size, and leaf area (correlated with biomass).

Sugar maple (*Acer saccharum*) stores the greatest mass of carbon (approximately 24% of total carbon stored) and is also responsible for the most annual net sequestration (23% of total net sequestered carbon and 16.0% of gross sequestration). Norway maple (*Acer platanoides*) and Manitoba maple (*Acer negundo*) are two invasive tree species which also sequester a significant amount of carbon each year (Table 12).

[20] Net sequestration is an estimate of the carbon lost due to more rapid carbon release (e.g., mulching of tree components and burning) and delayed release (e.g., decomposition) is calculated and subtracted from the gross sequestration to estimate net sequestration. To estimate carbon release, various assumptions are made related to probability of mortality, probability of recording a dead tree, and decomposition rates.

Table 12: Top five species for carbon storage and net sequestration 2022

Carbon Stored			Net Carbon Sequestration		
Species	**Tonnes C**	**Percent**	**Species**	**Tonnes C/year**	**Percent**
Sugar maple (Acer saccharum)	63,307.90	23.9	Sugar maple (Acer saccharum)	1247.38	23.0
Eastern white cedar (*Thuja occidentalis)*	47,537.20	17.9	Eastern white cedar (*Thuja occidentalis)*	1035.47	19.1
Norway maple (*Acer platanoides)*	31,593.50	11.9	Norway maple (*Acer platanoides)*	947.79	17.5
Norway spruce (*Picea abies)*	10,492.90	4.0	Manitoba maple (*Acer negundo)*	348.76	6.4
Eastern hemlock (*Tsuga canadensis*)	9,675.00	3.6	Little-leaf linden (*Tilia cordata)*	313.61	4.4

4.3.2 Annual Air Pollution Removal

The i-Tree Eco model quantified pollution removal by trees and shrubs in Markham based on air pollution data from stations in Newmarket and north Toronto in 2019. Pollution removal is greatest for ozone (O_3), followed distantly by nitrogen dioxide (NO_2) and particulate matter less than 2.5 microns ($PM_{2.5}$) (Figure 16). Trees and shrubs remove a total of 147.1 tonnes of air pollution (CO, NO_2, O_3, $PM_{2.5}$, SO_2) per year with an associated removal value of $2.7 million (based on estimated externality costs). The removal of $PM_{2.5}$ has the greatest value in terms of health benefits, followed by ozone.

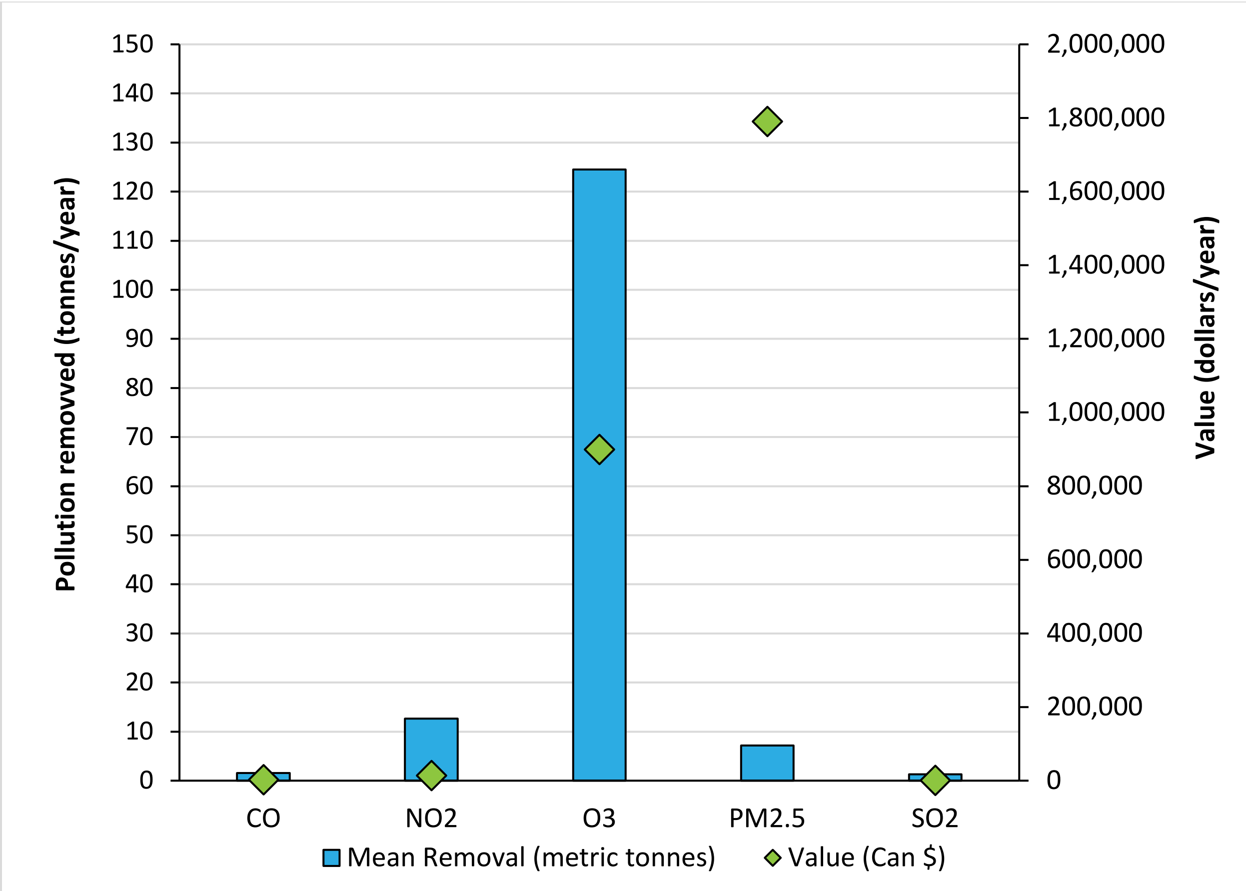


Figure 16: Annual pollution removal by trees and shrubs and associated removal value in 2022

4.3.3 Residential Energy Effects

The i-Tree Eco model estimated the effects of trees (≥ 6.1 m in height and within 18.3 m of a residential building, excluding high rises) on building energy use due to shading, windbreak effects, and local micro-climate amelioration. Estimates were based on field measurements of tree distance and direction to space-conditioned residential buildings[21]. Annually, trees adjacent to residential buildings in Markham are estimated to reduce

[21] Because this model component is designed specifically for the U.S., its utility is limited in international applications. International users will receive energy results that are based on the characteristics of the user-defined U.S. climate region, typical construction practices and building characteristics, and energy composition (i.e., type of and amount used). Therefore, results should be used with caution as they assume that the building types and energy use of the U.S. are the same as those internationally (Nowak, 2020)).

The only local values used in the estimates outside the United States are electricity and fuel costs. The remainder of the estimation is based U.S. conditions from the assigned climate zone. Details on local energy values and the comparisons between international areas and U.S. climate zones is given in Nowak, 2020, Appendix 9).

energy consumption by 416,089 million British thermal units (MBTU) for natural gas use and 11,245 megawatt-hours (MWH) for electricity use (Table 13).

Based on average energy costs in 2022, trees in Markham are estimated to reduce energy costs for residential buildings by $3,180,590 annually (Table 14)[22].

Table 13: Energy savings due to trees near residential buildings in Markham in 2022

Energy Units	Heating	Cooling	Total
Natural Gas (Million British Thermal Units)	416,089	n/a	416,089
Electricity (Megawatt-hour)	3,538	7,707	11,245

Table 14: Financial savings (CAD) in residential energy expenditures during heating and cooling seasons in 2022

Energy Units	Heating	Cooling	Total
Natural Gas (Million British Thermal Units)	$ 1,831,230	n/a	$ 1,831,230
Electricity (Megawatt-hour)	$ 424,596	$ 924,764	$ 1,349,360
Total	$ 2,255,826	$ 924,764	$ 3,180,590

4.3.4 Hydrological Effects

i-Tree Eco was used to calculate the hydrological benefits provided by trees in Markham based on 2019 rainfall data from Pearson International Airport[23]. The i-Tree Eco model estimates the amount of rainfall intercepted, stored, evaporated, and transpired by trees as well as the volume of runoff avoided because of the urban tree canopy (Nowak 2020). Results are shown in Figure 17 and summarized in Table 15. Trees in the *Residential* and *Open Space – Natural Cover* land use strata provide the greatest hydrological services to the municipality. Rainfall that is prevented from entering the stormwater system reduces the costs of building stormwater infrastructure and the risk of flooding. The overall value of the stormwater benefit (measured as avoided runoff) is $1.7 million per year based on 2019 precipitation levels[24].

[22] See Section 3.2.6 for the source of electricity and gas costs. Energy saving value is based on the price of $120.00 per MWH and $4.40 per MBTU.

[23] A total of 94 centimeters of annual precipitation (excluding snow) was recorded in 2019.

[24] The overall value is based on a rate of $2.324 / m^3 - the default value from i-Tree Eco converted into CAD. This rate is based on sixteen research studies on costs of stormwater control and treatment (Nowak, 2020).

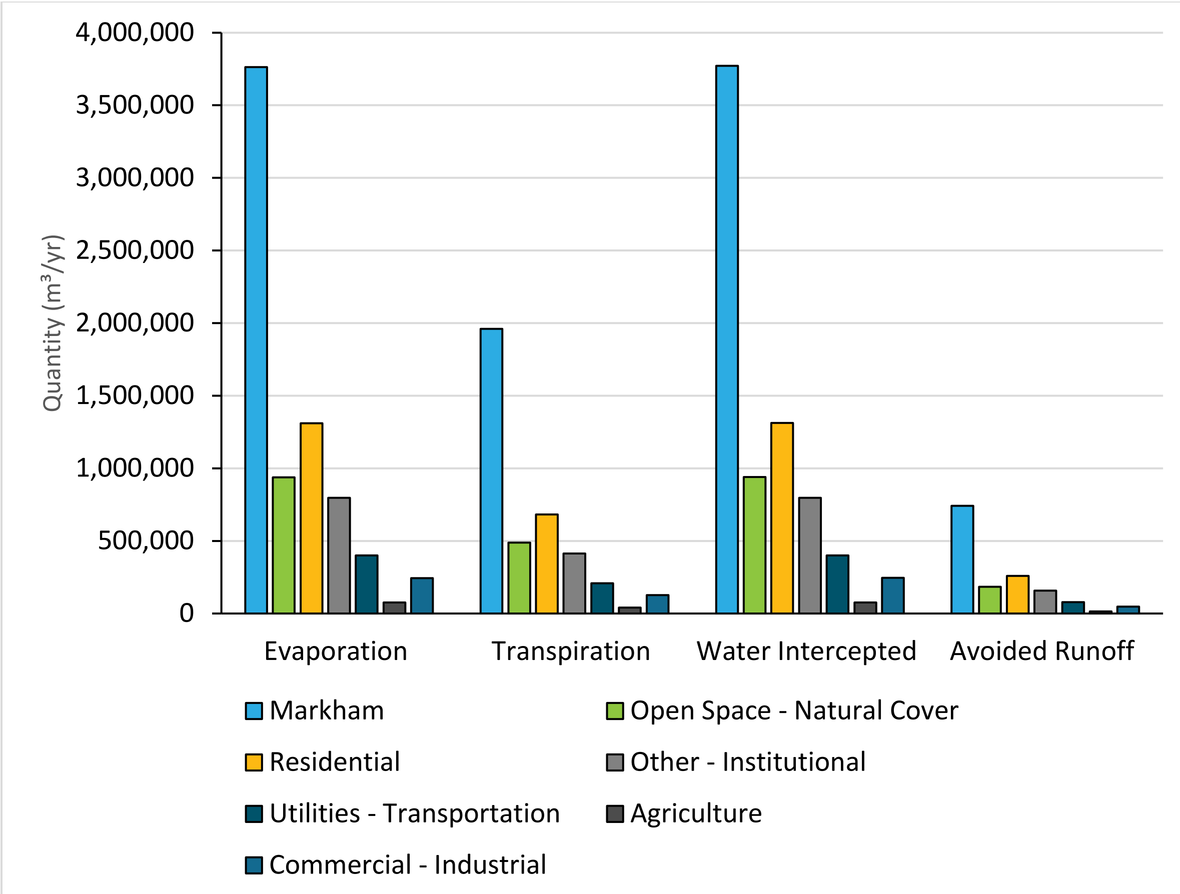


Figure 17: Hydrological services provided by trees in Markham in 2022

Table 15. Avoided stormwater runoff and value

Land Use Stratum	Avoided Runoff (m^3/yr)	Value ($/yr)
Open Space – Natural Cover	185,026	$ 430,131
Residential	258,359	$ 600,611
Other – Institutional	156,976	$ 364,925
Utilities – Transportation	78,712	$ 182,982
Agriculture	15,171	$ 35,269
Commercial – Industrial	48,205	$112,064
Markham	**742,449**	**$1,725,981**

4.3.5 Other Benefits and Services

Markham's forest provides numerous other services, many of which are difficult to quantify. Some additional services that were quantified include oxygen production and UV index reduction in residential areas. The Markham forest produces 14,447 tonnes of oxygen per year. Under the shade in residential areas reduces the UV index by 52 percent and by 29 percent overall in residential areas, thereby reducing exposure to harmful UV rays and the risk of developing skin cancer. However, it should be noted that the most recent UV data available for the model is from 2013.

Unfortunately, trees also have some disservices. In addition to being a source of allergens, trees emit volatile organic compounds (VOCs) such as monoterpene and isoprene. A total of 78,205 kg of VOCs is emitted by the forest per year, with the greatest mass being emitted from *Residential* and *Open Space – Natural Cover* areas which have the most trees. Norway spruce (*Picea abies*) emits the most VOCs at 20,949 kg/year followed by sugar maple at 7,377 kg/year, and blue spruce (*Picea pungens*) emitting 6986 kg/year.

4.4 i-Tree Forecast

Based on the current municipal planting programs, the expected canopy growth, and the anticipated impacts of spongy moth (*Lymantria dispar dispar*), emerald ash borer (*Agrilus planipennis*), and beech bark disease (*Neonectria faginata*) in the next ten years, Markham will stay within the recommended canopy cover range, (i.e., 20 to 35 percent) over the next thirty years. At the current rate of planting and natural growth, the i-Tree Forecast model estimates that canopy cover will increase by 11.4 percent to reach 32.4 percent by 2051. Under a doubled planting scenario, the model estimates that canopy cover will increase by 12.3 percent to reach 33.3 percent by 2051. Lastly, assuming no planting programs are undertaken, the forecast projects canopy cover will increase by 10.4 percent to reach 31.4 percent by 2051 (Figure 18). It is important to note that the annual number of frost-free days in Markham was increased during the Thirty-year simulation period to an average value to account for climactic changes. The longer growing season is more likely to benefit tree growth in the latter half of the simulation period than the earlier half. Thus, canopy growth over the next six years is likely to be less than 5 percent.

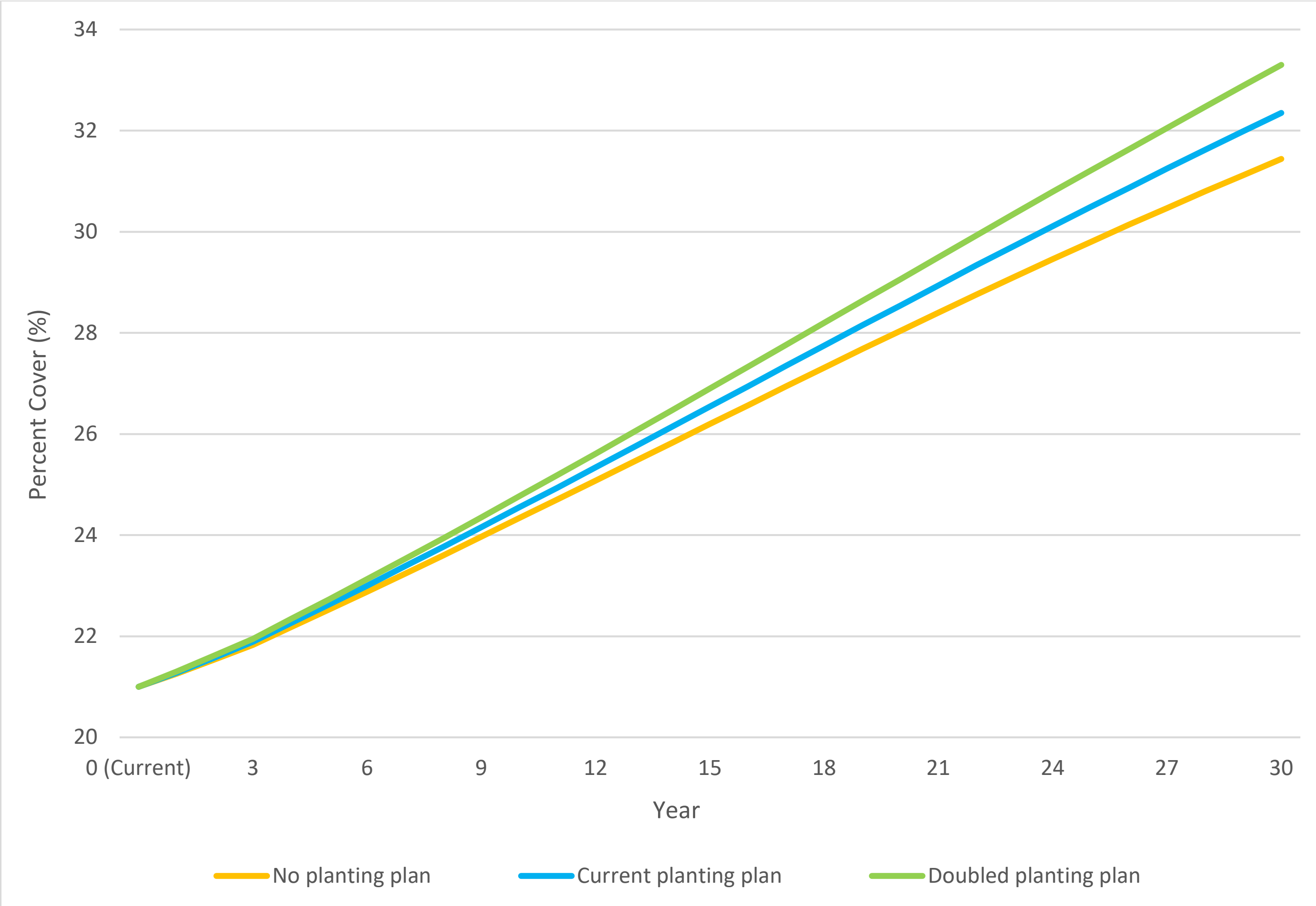


Figure 18: i-Tree forecast projections on canopy cover across planting scenarios

It should be noted that while canopy cover is expected to increase, the number of trees, as determined by the i-Tree forecast model, across the municipality is expected to decline in each forecast scenario. By 2051, the tree number is expected to decrease from 2.96 million to 2.05 million under the current planting scenario, to 2.3 million under the doubled planting scenario and to 1.8 million under the no planting scenario (Figure 19). While canopy cover will largely consist of existing public and private tree populations having grown and shifted into larger size classes, further emphasizing the importance of maintaining these populations, ultimately the tree population and planting rates will not keep up with projected tree mortality rates. Continued tree planting remains necessary to maintain trees across all size classes, especially across urbanized private and public land uses, and to replace older trees as they die.[25]

[25] i-Tree Eco does not include natural regeneration or ingrowth of trees. In other words, it assumes that the only new trees established in the simulation period are those that are deliberately planted.

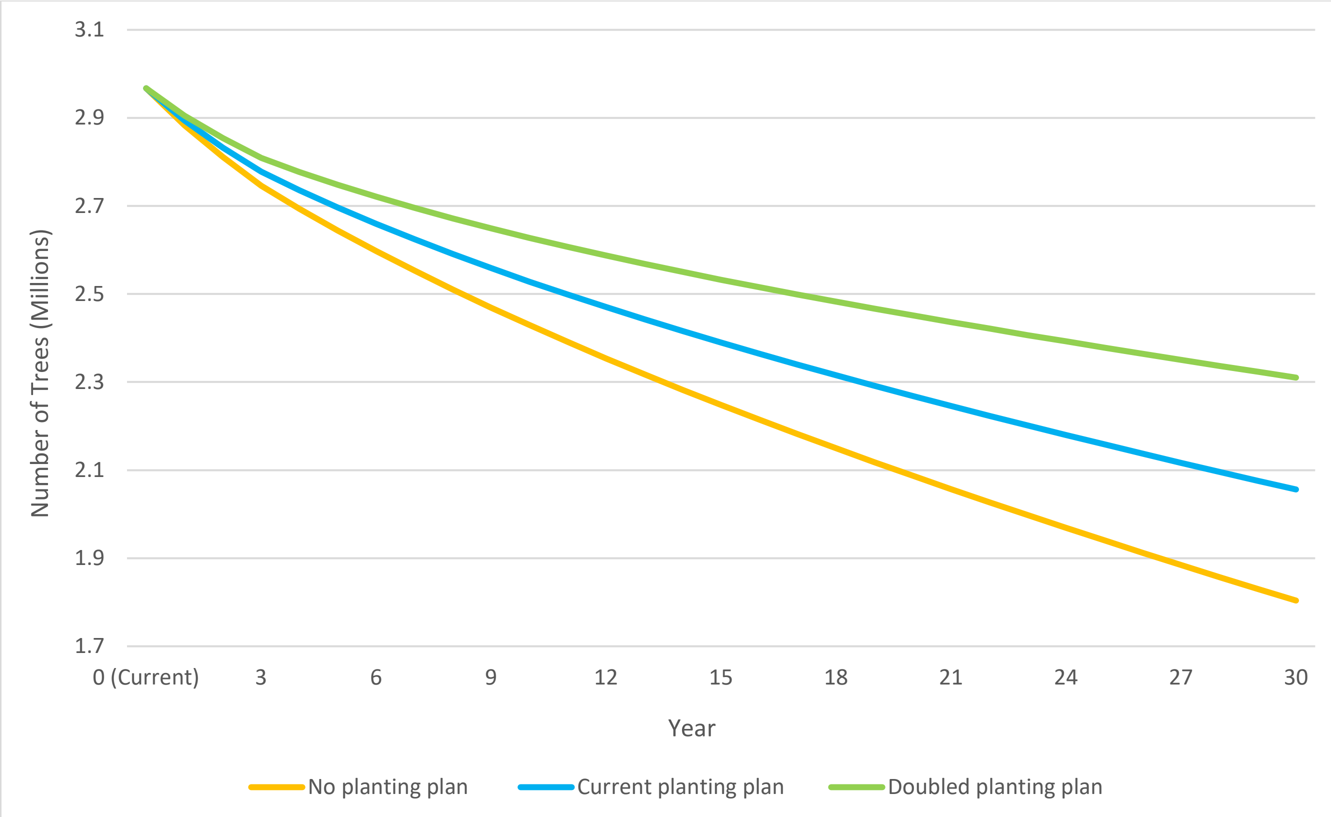


Figure 19: i-Tree forecast projections on number of trees across planting scenarios

Figure 18 appears to suggest incremental improvements to the canopy cover from ongoing investments in the urban forest. However, as tree number decreases and assuming little to no changes in species diversity, the urban forest will become more susceptible to various impacts ranging from climate change to pests and diseases. It should be noted, there is also a great deal of uncertainty regarding current tree mortality rates, the impacts of climate change, and future pests and diseases. Also, human policies around the protection of natural areas and development that cannot be quantified and made tractable are not included in the i-Tree Forecast model.

4.5 Soil

4.5.1 Compaction

Compaction level was measured at 99 plots. Across the study area, approximately 19.2 percent of the sampled plots are uncompacted, 40.4 percent are moderately compacted, and 40.4 percent are highly compacted. Across plots on public and private lands, public plots have a slightly lower mean compaction score (2.24 vs 2.36, respectively) and a greater proportion of plots that are uncompacted (29 versus 15 percent, respectively) Table 16). However, the differences between mean compaction scores and the proportion of uncompacted plots are not statistically different across public and private lands. The sample size may have been insufficient to detect a difference, although a small effect was observed.

Table 16: Compaction across private and public lands in Markham in 2022. Public lands include municipal, provincial, federal, and conservation authority properties

Ownership type	Plots sampled (#)	Mean compaction score	Uncompacted plots (%)	Moderately compacted plots (%)	Highly compacted plots (%)
Private	68	2.36 (±0.58)	14.7	47.1	38.2
Public	31	2.24 (±0.80)	29.0	25.8	45.2

Differences across land use strata were also investigated. To increase sample size, land use types were combined as shown in Table 17.

Table 17: Combined land use stratum for compaction analysis in 2022

Stratum	Plots sampled (#)	Mean compaction score	Constituent land use stratum	Number of Plots
Built – Other	38	2.60 (±0.51)	Commercial – Industrial Utilities – Transportation[26]	10 28
Residential	40	2.13 (±0.58)	Residential	40
Open Space – Natural – Other	21	1.83 (±0.73)	Agriculture Open Space – Natural cover Other – Institutional	1 11 9

The mean compaction score is significantly different across all land use strata. The Wilcoxon rank sum test for non-normal data found that the most significant difference is between *Open Space – Natural Cover* and the *Built – Other* category ($p < 0.001$). Similarly, there is a significant difference between the proportion of compacted plots across all land use strata (χ^2 = 23.651, df = 4, p < 0.0001) (Figure 20).

[26] This class also includes rights-of-way.

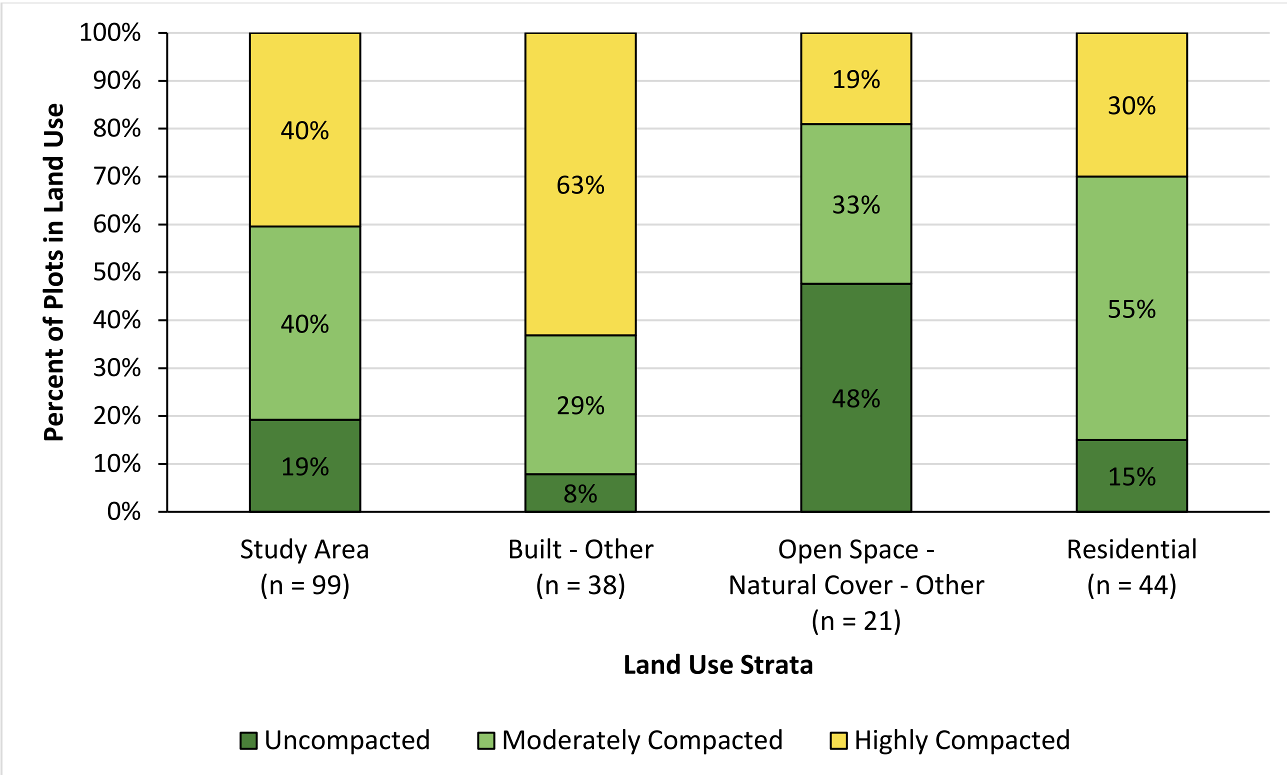


Figure 20: Compaction across combined land use strata[27].

4.5.2 Salinity

Salinity across Markham was inferred from *in situ* electroconductivity (EC) measures, quantified in micro-siemens (µS/cm). In total, 84 plots were assessed and found to have a mean of 300.8 µS/cm (±145.4), median of 273.9 µS/cm, and a minimum and maximum value of 46.7 µS/cm and 1,070.5 µS/cm, respectively. The maximum value is an outlier, with the next highest salinity being 608.5 µS/cm. The outlier value belongs to plot 107, which is a forested patch surrounded by residential land and owned by the municipality. Field staff noted that the site was a swamp; swamps are known to have higher salinity values. The presence of water also increases electroconductivity. This value was not removed because it is not believed to be erroneous.

Using the Wilcoxon rank sum test for non-normal data, it was found that there is a significant difference in electroconductivity between private and public lands (W = 976.5, $p < 0.05$), with private lands having higher EC values than public lands (Table 18).

[27] *Built – Other* is comprised of plots occurring on *Commercial – Industrial* and *Utility – Transportation*; *Open Space – Natural Cover – Other* is made up of *Open Space – Natural Cover, Other – Institutional,* and *Agriculture*.

Table 18: Electroconductivity across private and public lands in Markham 2022 (p<0.05)

	Number of Plots	Mean (µS/cm)	Median (µS/cm)
Private	58	311.0 (±109.7)	291.3
Public*	26	278.0 (±177.3)	227.63

Note: * Public lands include municipal, provincial, federal, and conservation authority properties.

Differences across land use stratum, *Residential, Built – Other*, and *Open Space – Natural Cover – Other*, were also tested using the Kruskal-Wallis rank sum test for non-normal data. Although results show that differences between land use stratum are not significantly different (χ^2 = 2.0433, df = 2, p = 0.36), the *Residential* land use has an overall higher salinity than the other classes as shown in Table 19 and Figure 21. If a larger sample size had been obtained this difference may have been significant. Further, the significant outlier of plot 107, will have skewed the mean higher. The median salinity for *Open Space – Natural Cover – Residential* is 34 values lower than *Built – Other.*

Table 19: Electroconductivity across land use strata 2022 (p>0.05).

	Number of Plots	Mean (µS/cm)	Median (µS/cm)
Built – Other*	29	296.1 (±116.3)	284.3
Residential	34	309.7 (±117.3)	291.3
Open Space – Natural Cover – Other	21	292.8 (±214.1)	230.8

Note: * Built – Other is comprised of plots occurring on Commercial – Industrial and Utilities – Transportation (includes ROW) and Open Space – Natural Cover – Other is comprised of Agriculture, Open Space – Other and Other – Institutional.

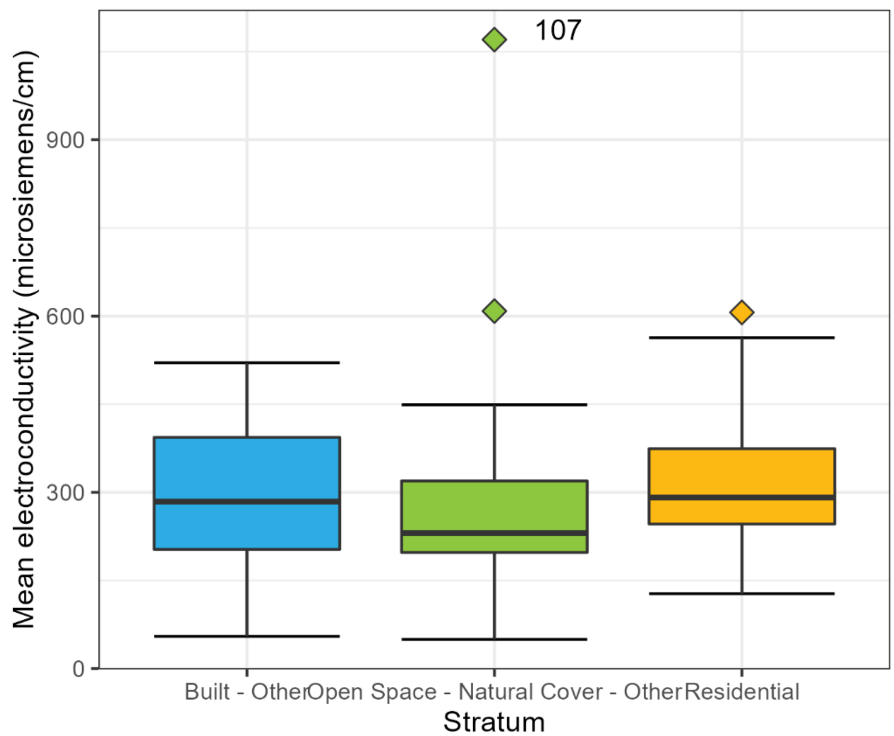


Figure 21: Electroconductivity across land use stratum in Markham 2022. Labels indicate plot IDs for outliers.

As shown in Figure 21, plot 107 is an outlier for the *Open Space – Natural Cover – Other* class and is an overall outlier for the combined dataset. An orthoimage of the plot is depicted in Figure 22. This area is Raymerville Woodlot, owned by Markham, which field staff indicated was swampy. It is dominated by eastern white cedar (*Thuja occidentalis)* and American basswood (*Tilia americana)*. It also includes two bitternut hickory (*Carya cordiformis*). The site used to have eight black ash (*Fraxinus nigra*) trees and one white ash (*Fraxinus americana*), all of which are dead. Many of the trees have crown dieback, with sugar maple (*Acer saccharum*) and bitternut hickory fairing the best at this site in terms of condition. The results of the analysis of the relationship between salinity and tree health are presented in more detail in Section 4.5.4.

Figure 22: Plot 107 – an outlier for salinity in Markham. Photo source: Google Earth, 2021, © 2022 Maxar Technologies

4.5.3 pH

pH is a measure of the concentration of hydrogen ions in liquids. Values range from 1 (acidic) to 14 (alkaline); seven is neutral. Twenty-three pH samples were obtained across Markham. The average pH is 7.12 (±0.50), the median value is 7.21, and the minimum and maximum are 5.15 and 7.54, respectively. This puts pH within the optimal pH range for most plants in southern Ontario (5.5-7.5) (Ontario Ministry of Natural Resources and Forestry, 2000). This is the range where nutrients are most available, however, optimal ranges vary from species to species (Ontario Ministry of Natural Resources and Forestry, 2000).

The relationship between pH and ownership type—private and public (municipal, provincial, federal, and conservation authority lands)—was investigated. Soils on private lands have a more basic/alkaline pH than public lands (Table 20), however, a Wilcox rank sum test for non-normal data found that the difference in pH between public and privately owned plots is not statistically significant (W =71.5, $p > 0.5$).

Table 20: pH across private and public lands in Markham in 2022

	Number of Plots	Mean	Median
Private	9	7.25 (±0.17)	7.21
Public	14	7.03 (±0.61)	7.20

pH was also examined by land use strata. Because there were so few plots per stratum, land use strata were aggregated into two categories:

1) Built: Plots falling on built or developed classes, including residential
2) Unbuilt: Plots falling on undeveloped land such as natural and protected areas, undeveloped vacant land, and agricultural lands.

Table 21: pH across built and unbuilt land use types in Markham in 2022

	Number of Plots	Mean	Median
Built	12	7.28 (±0.23)	7.32
Unbuilt	11	6.61 (±0.83)	7.05

A Wilcoxon rank sum test found that there is a moderately significant difference in pH of plots in Built and Unbuilt land use types, with Built plots having a higher pH (W = 545.5, $p < 0.05$). Figure 23 shows the distribution of pH values across classes. It was anticipated that Built classes would have a higher pH due to the presence of building materials in the soil.

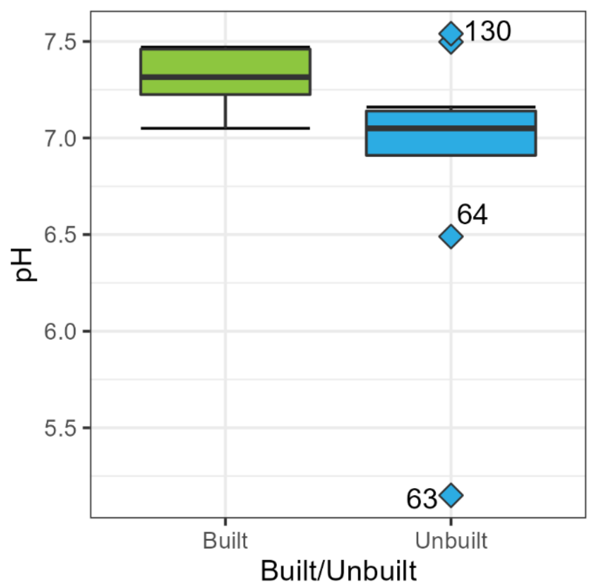


Figure 23: pH across Built and Unbuilt[28] classes in Markham 2022

Of interest are the three outliers, plots 130, 64 and 63. Plot 130 occurs in Rouge National Park, just east of Little Rouge Creek and south of Highway 7 on what appears to be an old road/previously cleared area that has subsequently become forested, thus explaining the higher pH. Plot 63 is an outlier for the Unbuilt category and across all samples. It is a forested plot that occurs in Rouge National Park, east of Donald Cousens Parkway and south of Highway 71 (Figure 24). This plot is dominated by ironwood/eastern hophornbeam (*Ostrya virginiana*), followed by sugar maple. Ironwood are known to be a hardy species that can tolerate a wide variety of conditions. Plot 64 also occurs in Rouge National Park southeast of plot 63. Both plots 64 and 63 are in drainage areas that appear to be swampy. Swamps tend to have a higher acidity. It should be noted that with more samples, these plots may not have been identified as outliers.

[28] Built includes plots on developed land uses, while Unbuilt includes plots on undeveloped lands such as forests, meadows, protected areas, and undeveloped and vacant land, and ravines.

Figure 24: *pH outlier plot for the Unbuilt class and all plots in Markham*

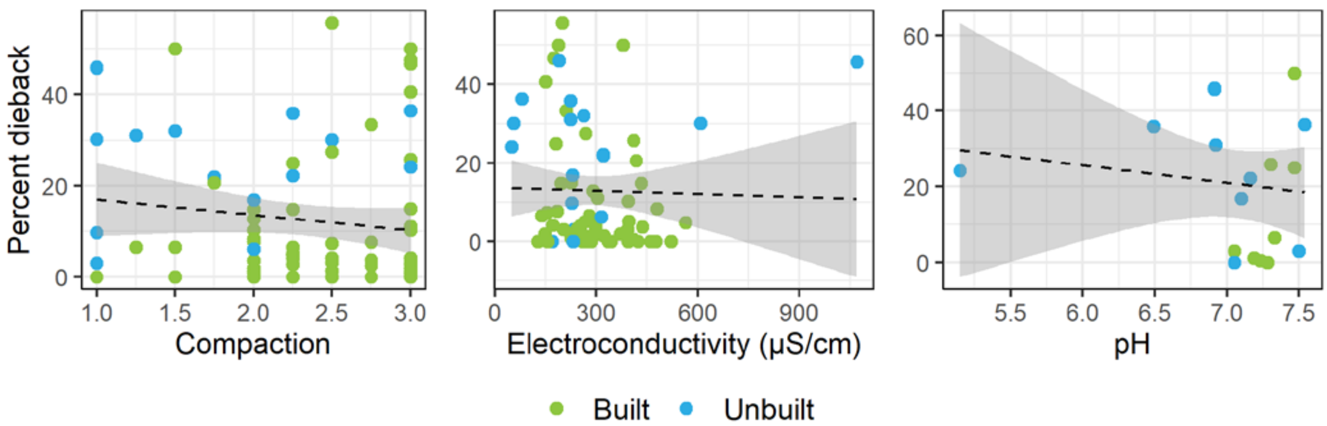
4.5.4 Relationships between Soil Compaction, Salinity, pH, and Tree Condition

The relationship between soil compaction, salinity (indicated by electroconductivity), pH, and tree condition measured as percentage crown dieback, was explored using correlation testing. See Table 22 and Figure 25. All findings here are shown to be non-significant and do not have a major impact on crown dieback.

Surprisingly, percent dieback decreases as soil compaction increases. However, this is likely to be explained by the fact that natural areas which were the least compacted had high proportions of dead trees, particularly ash trees. Crown dieback also decreases with increasing pH. Again, this can be likely attributed to the fact that more natural areas tended to have lower pH values, but more dead or dying trees. Finally, the relationship between salinity and crown dieback had a similar relationship, where dieback decreases as salinity increases.

Table 22: Correlation (Pearson not used in cases where not bi-variate normal)

Dieback vs	Summary	Degrees of Freedom	Pearson's Correlation Test	Spearman's Correlation Test	Kendall's Correlation Test
Compaction	A non-significant negative correlation with dieback	*80 (not bivariate normal)*	*cor = -0.14* *$p > 0.1$*	*rho = -0.16* $p > 0.1$	*tau* = -0.13 $p > 0.1$
Salinity (electro-conductivity)	A non-significant negative relationship with dieback	71	*cor* = -0.026 $p > 0.1$	*rho = -0.2* *$p > 0.05$*	*tau* = -0.14 $p > 0.05$
pH	A non-significant negative correlation with dieback	16	*cor* = -0.14 $p > 0.1$	*rho* = -0.12 $p > 0.1$	*tau* = -0.09 *$p > 0.1$*



Note: Line indicates a linear regression and grey shaded area is the standard error.

Figure 25: Scatterplots of crown dieback versus soil compaction, electroconductivity an indicator of salinity, and pH

4.6 Invasive Plants

Out of the 202 plots surveyed, 87 plots or 43 percent of all plots had at least one invasive plant species present. Invasive plant species were most prevalent in the *Residential* land use stratum (80% of plots), followed by *Other – Institutional* (64% of plots).

Table 23: Invasive plant species statistics for Markham by land use stratum in 2022

Land Use Stratum	Number of Plots	Percent Plots with at Least One Invasive Plant Species	Avg. Number of Invasive Plant Species on Invaded Plots	Avg. Spread of Invasive Plants on Invaded Plots	Avg. Num. Species x Avg. Spread
Open Space – Natural Cover	21	42.9	3.4	1.7	5.8
Residential	46	80.4	3.7	1.1	4.1
Utilities – Transportation (including ROWs)	39	56.4	1.9	1.2	2.2
Other – Institutional	14	64.3	3.7	1.3	4.8
Commercial – Industrial	19	42.1	1.9	1.3	2.5
Agriculture	63	3.2	2.0	1.2	2.4
Markham	**202**	**43.0**	**3.0**	**1.2**	**3.6**

Residential and *Other – Institutional* have by far the greatest proportion of plots that are invaded at 80 percent and 64 percent, respectively. This is followed by *Utilities – Transportation* (56%), *Open Space – Natural Cover* (43%) and *Commercial – Industrial* (42%). While it might seem surprising that *Agriculture* has such a low percent of plots with invasive plants (< 5%), most plots surveyed in this category occurred in agricultural fields. Agricultural lands do contain some forest patches; however, the field team wasn't able to access many forested areas that fell on agricultural lands.

The results showed that when plots are invaded, they typically have more than one invasive plant species present, with an average of 3 species per plot, although the level of spread[29] was quite low (1.2). *Residential* and *Other – Institutional* areas have the highest number of invasive plants (average of 3.7), while *Open Space – Natural Cover* has the greatest average level of spread (1.7). By multiplying the average number of invasive plants with the average spread, *Open Space – Natural Cover* is shown to have the worst invasion levels, followed by *Other – Institutional* and *Residential.*

Appendix F provides a table showing all results by invasive species and land use.

The most common invasive species in terms of the proportion of plots affected are European buckthorn (*Rhamnus cathartica)* (22%), Norway maple (*Acer platanoides*) (16%), dog strangling vine (*Cynanchum rossicum*) (14%), Manitoba maple (*Acer negundo)* (13%), wintercreeper euonymus (*Euonymus fortunei)* (12%), and garlic mustard (*Alliaria petiolata*) (10%). European buckthorn and dog strangling vine have the highest spread out of the top invasives. Manitoba maple and garlic mustard also have higher degrees of spread on average per invaded plot. Norway maple and wintercreeper euonymus are not particularly high (average score of 1.1). Wild parsnip (*Pastinaca sativa*) has the highest degree of spread (3) on those plots in which it did occur. Figure 26 details the proportion of plots impacted and the average spread of invaded plots for all those species detected in this study. Tartarian honeysuckle (*Lonicera tatarica*), European fly honeysuckle (*Lonicera xylosteum*) and tree of heaven (*Ailanthus altissima)* were not found on any plots.

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[29] Field crews recorded the degree of invasion for each priority invasive plant using an ordinal or ranked system where 1 was the least amount of spread and 4 was the most. The rankings were defined as follows: 1 (one to two patches of the invasive plant), to 2 (three or more scattered pockets), 2 (a blanket effect), up to 4 (an extensive blanket effect within the plot and the surrounding area).

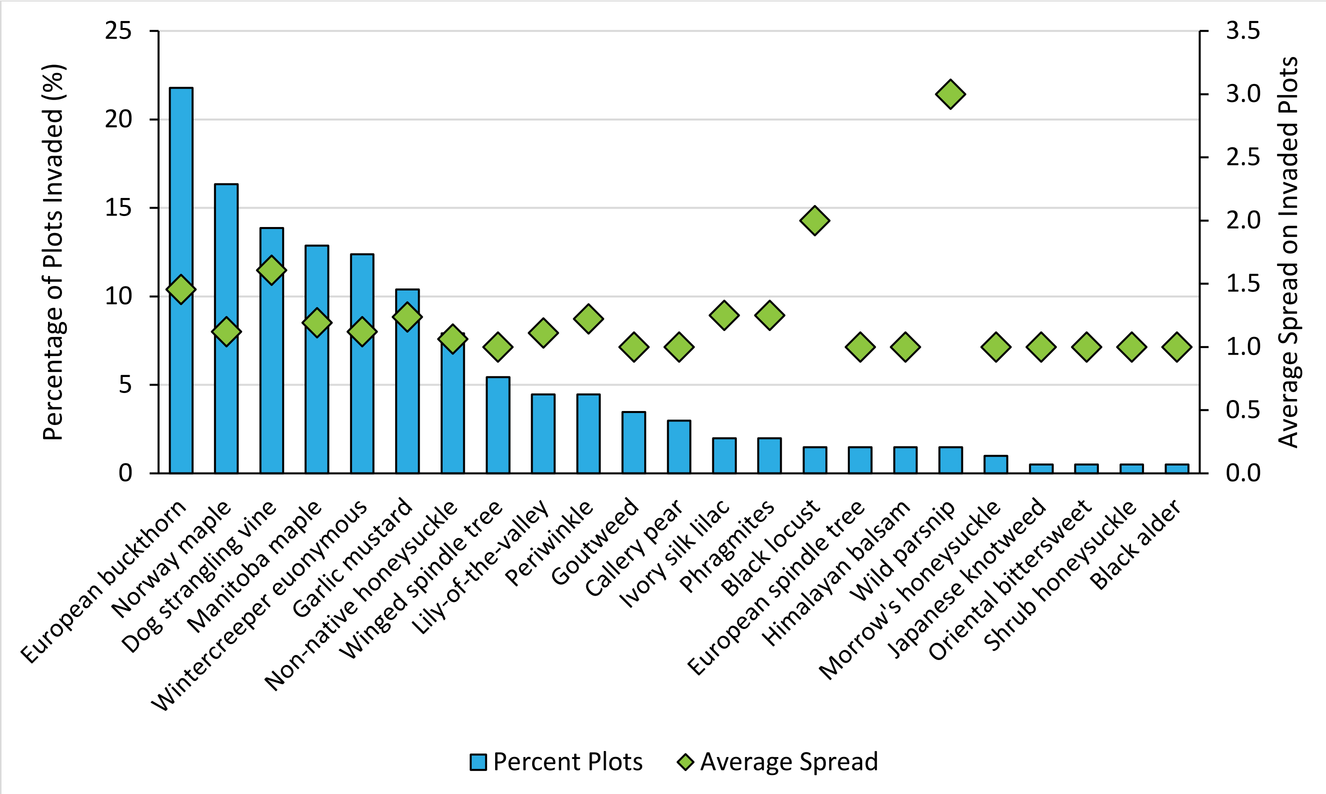

Figure 26: Percent and spread of invasive plant species in Markham 2022

European buckthorn, dog strangling vine, and Norway maple are the most prevalent species across most land uses as shown in Table 24.

Table 25 lists the land uses on which the most common invasive species were most frequently found.

Table 24: Top three most prevalent invasive species by land use 2022

Land Use Stratum	Top three most Frequent Invasive Plant Species (% of Plots)	Percent Plots with at Least One Invasive Plant Species	Avg. Spread of Invasive Plant on Invaded Plots
Open Space – Natural Cover	European buckthorn	33.3	2.0
	Manitoba maple	28.6	1.3
	Dog Strangling Vine	23.8	2.2
Residential	Norway maple	41.3	1.2
	European buckthorn	37.0	1.2
	Wintercreeper euonymus	37.0	1.1
Utilities – Transportation (including ROWs)	European buckthorn	17.9	1.1
	Norway maple	17.9	1.1
	Dog strangling vine	15.4	1.8
Other – Institutional	European buckthorn	57.1	1.5
	Dog Strangling Vine	28.6	1.5
	Norway Maple	28.6	1.0
Commercial – Industrial	European Buckthorn	15.8	2.0
	Non-native honeysuckle	15.8	1.3
	Dog strangling vine	10.5	1.5
	Garlic Mustard	10.5	1.0
Agriculture*	European buckthorn	3.2	1.5
Markham	European buckthorn	21.8	1.5
	Norway maple	16.3	1.1
	Dog strangling vine	13.9	1.6

* Insufficient number of field plots to identify other common invasive species

Table 25: Land uses on which most common invasive plant species were most frequently found across Markham 2022

Species	Top Three Land Use Stratum on which Species was Most Frequently Found	Percent Plots with Species Present (%)	Avg. Spread of Species on Invaded Plots
European buckthorn	Other – Institutional	57.1	1.5
	Residential	37.0	1.2
	Open Space – Natural Cover	33.3	2.0
Norway maple	Residential	41.3	1.2
	Other – Institutional	28.6	1
	Utilities – Transportation	17.9	1.1
Dog strangling vine	Other – Institutional	28.6	1.5
	Open Space – Natural Cover	23.8	2.2
	Utilities – Transportation	15.4	1.8
Manitoba maple	Open Space – Natural Cover	28.6	1.3
	Residential	28.3	1.0
	Other – Institutional	21.4	1.7
Winter creeper euonymus	Residential	37.0	1.1
	Other – Institutional	14.3	1.0
	Utilities – Transportation	12.8	1.2

4.7 Invasive Pests and Diseases

4.7.1 Invasive Pests

While visiting plots to collect i-Tree Eco and other data, field crews also recorded the presence and degree of spread of emerald ash borer beetle (EAB; *Agrilus planipennis*), spongy moth (*Lymantria dispar dispari*), hemlock woolly adelgid (*Adelges tsugae*), and Asian long-horned beetle (*Anoplophora glabripennis*). Signs of hemlock woolly adelgid and Asian long-horned beetle were not observed at any sites. However, signs of spongy moth were present at 30 percent of plots, and EAB was observed at 12 percent of plots. Figure 27 shows the percentage of plots where the insect itself (in some stage of lifecycle development) or insect damage was observed per land use type, while the average spread, ranging from the least (1) to the most (3), is shown on the second axis. A score of one indicates that the insect/damage was observed on 1 to 3 trees, two, 4 to 6 trees, and three, more than 6 trees.

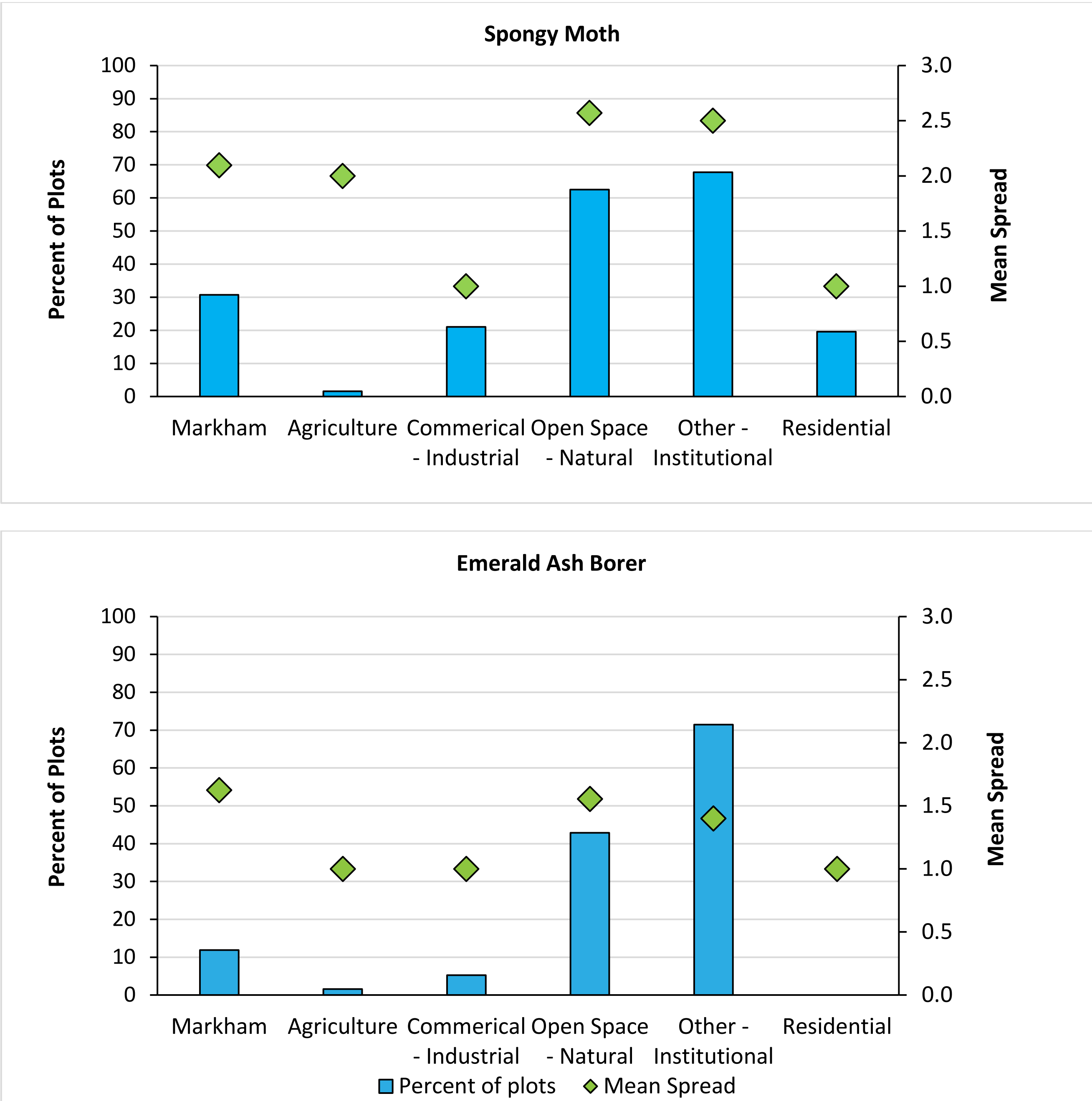

Figure 27: Percent of plots affected and average spread of spongy moth (top) and emerald ash borer (bottom) 2022

Both spongy moth and EAB are most frequently found in *Other – Institutional.* Sixty-seven percent of plots in *Other – Institutional* have spongy moth, with an average spread of 2.5 indicating that at least 4 to 6 trees are infected. Spongy moth also has a high degree of invasion in *Open Space – Natural Cover* and was found in 62 percent of plots with an average spread score of 2.57. Impacts of EAB are most prevalent in the *Other – Institutional* stratum, being present in just over 70 percent of plots with an average spread score of 1.4. The

Open Space – Natural Cover land is also highly invaded by EAB, with impacts found in 42 percent of plots and a mean spread of 1.56.

4.7.2 Invasive Diseases

While collecting field data at plots, crews also checked trees for the presence of beech bark disease (*Neonectria faginata*), beech leaf disease (caused by *Litylenchus crenatae ssp. mccannii*.), and Dutch elm disease (*Ophiostoma ulmi*). Dutch elm disease and beech leaf disease were not found on any trees, and beech bark disease was only found in 3 plots with an average spread of 1.6 (1-3 trees infected).

4.8 Climate Vulnerability

4.8.1 Vulnerability Scores for the Top Twenty Most Abundant Species

The top twenty most abundant tree species in Markham were given a climate vulnerability score based on their exposure (occurrence outside of their ideal temperature range) and sensitivity to drought between 2040 to 2070 assuming the RCP8.5 scenario. The results are shown in Table 26**Error! Reference source not found.**.

Some notable results to highlight about the top twenty abundant tree species are that:

- The forest is very homogeneous
    - The most abundant species found in Markham is the eastern white cedar (*Thuja occidentalis*), making up a third of the tree population across the municipality. The second most abundant species is the invasive European buckthorn (*Rhamnus cathartica*). The dominance of the population by a few species makes the forest more vulnerable to the impacts of climate change.
- Average condition:
    - Trees that are already in poor condition are more vulnerable to the stressors of climate change. While the average condition score of the Markham Forest is 81 (considered good to fair, and equivalent to a percent dieback of <19%), there are several species that have a much lower average condition. Of the top twenty species, white and green ash (eighth and thirteenth most abundant, respectively) have the worst average condition ratings (39.3% and 28.8% respectively) due to the impacts of emerald ash borer.

Of the top twenty tree species growing in the municipality, only six species were assigned a low vulnerability score, two of which are not recommended for planting because they are invasive (Manitoba maple, *Acer negundo;* and black locust, *Robinia pseudoacacia*). Only three species were given a moderate vulnerability score. Eleven of the species were rated as highly or extremely vulnerable to climate change including the most abundant species, eastern white cedar, which makes up 34 percent of the tree population across Markham.

Table 26: Climate vulnerability scores the top twenty most abundant species in Markham

Vulnerability Score	Vulnerability classifications based on climate projections between 2040 to 2070 assuming the RCP8.5 scenario (PCCP 2021)
Low	Species having low sensitivity to drought and low climatic exposure
Moderate	Species with two moderate rankings or with one moderate and one low ranking of either climate exposure or drought sensitivity
High	Species that had a "high" ranking of either climate exposure or drought sensitivity
Extremely High	Species that were both "high" in climate exposure and drought sensitivity rankings

Common Name	Percent of Population (%)	Population with DBH <15.2 cm (%)	Vulnerability Score	Tolerances	Sensitivities	Risks
Eastern white cedar	34	86.4	High	• High resistance to ice damage	• At the southern end of their current range	
European buckthorn	9	94.5	High			Not recommended – invasive
Sugar maple	7	49.6	Moderate		• Sensitive to drought	
Manitoba maple	6	94.9	Low		• Low resistance to ice damage	Not recommended – potentially invasive
Eastern white pine	3	88	High	• Drought tolerant	• Flood intolerant	
Norway maple	3	25.2	High			Not recommended - invasive
Eastern hemlock	3	26.9	Extreme	• High resistance to ice damage	• Vulnerable to pest/disease	
White ash	2	92.5	High		• Flood intolerant	Not recommended

					• Vulnerable to pest/disease	
American basswood	2	76.1	Moderate		• Low resistance to ice damage	
White spruce	2	57.2	High	• High resistance to ice damage	• Flood intolerant • At the southern end of their current range	
Black locust	2	57.8	Low	• Drought tolerant	• Flood intolerant • Low resistance to ice damage	Not recommended - invasive
Eastern hophornbeam	2	46.6	Low	• High resistance to ice damage • Drought tolerant		
Green ash[30]	1	36.4	High		• Flood intolerant • Vulnerable to pest/disease	Not recommended
American elm	1	65.9	Low		• Low resistance to ice damage • Vulnerable to pest/disease	
Amur maple[31]	1	100	Low	• Moderately drought Tolerant		

[30] Green ash was not assessed as part of the Peel Region Urban Forest Best Practice Guides, Guide 4: *Potential Street and Park Tree Species for Peel in a Climate Change Context* (Peel Guide 4). Due to similarities to white ash, it was given the same score.

[31] Amur maple was not assessed as part of the Peel BMP Vulnerability Assessment. It was given a low vulnerability score because it can tolerate a wide range of temperature conditions and currently is distributed as from far south in the United States to as far north as Manitoba and Calgary. It is also moderately tolerant of drought.

Quaking aspen	1	43.6	High		• Low resistance to ice damage
Black walnut	1	53.3	Moderate	• High resistance to ice damage • Drought tolerant • At the northern end of their current range	
Honey locust	1	56.1	Low	• Drought tolerant • At the northern end of their current range • Tolerant of poor soils	
Norway spruce	1	16.6	Extreme	• High resistance to ice damage	• Flood intolerant
Colorado blue spruce	1	8.5	High	• High resistance to ice damage • Drought tolerant • Planted successfully in other southern Ontario urban areas	• Flood intolerant

4.8.2 Impact of Climate Change on the Markham Forest and Top Five most Abundant Species

Trees in urban areas are exposed to a variety of environmental stressors that are expected to be exacerbated by climate change. Based on the projected climatic conditions under the RCP 8.5 scenario, it is anticipated that the Markham Forest will be vulnerable to increased average temperatures, heat events, drought, and changes in precipitation patterns. Additionally, pests and diseases are likely to become more pervasive because of increased average temperatures and shorter, warmer winters. These impacts will directly affect the ability of urban trees to become established and survive. Table 27 and Table 28 present summary impact statements identifying how stressors brought on by climate change are expected to affect the entire municipal forest and the top five most abundant species growing across Markham.

Table 27: Impacts of climate change on Markham Forest

Climate Stressor	Outcome	Consequence
Increase in the frequency, intensity, and severity of extreme heat and other extreme weather events (e.g. wind storms)	• Greater damage to urban trees (and reduced urban tree canopy cover) • Higher tree mortality	• Loss of ecosystem goods and services provided by trees • Decreased shade from loss of canopy cover • Increased heat island effect in urban areas • Increased maintenance and tree replacement costs
Increase in average temperature, including warmer winters and drier summers	• Increased stress responses, such as loss of leaves and reduced tree growth • Shifting eco-regions for plants and animals • Change in species composition and the establishment of certain species (some species fare well with higher temperatures and drier conditions, while others do not) • Increased risk of pests and diseases • Disruptions in seed production	• Loss of ecosystem goods and services provided by trees • Loss of biodiversity among tree species • Increased maintenance and tree replacement costs • Increased survival and spread of invasive pest species such as emerald ash borer and diseases
Increase in extreme precipitation	• Greater damage to urban trees • Higher tree mortality • Increased risk of pests and diseases • Increased soil erosion • Increased stress and decline in tree growth	• Loss of ecosystem goods and services provided by trees • Increased maintenance and tree replacement costs • Increased survival and spread of invasive pest species such as emerald ash borer and diseases

Table 28: Impact statements for top five most abundant species

Species	Vulnerability	Outcome	Consequence
Eastern white cedar	High	Shifting eco-region for species	Risk of species extirpation from Markham because currently at southern end of current range
European buckthorn	High	Increased temperatures can result in enhanced growth; however, increased droughts can cause stress and negatively impact growth and condition.	Climate change impacts could potentially help efforts to control this species
Sugar maple	Moderate	Decrease in health and increased mortality due to dry conditions and drought	Risk of population decline in Markham; Increased maintenance and monitoring required
Manitoba maple	Low	Population will continue to do well in Markham	One of the few species with low vulnerability. Increased survival relative to other species, may increase its dominance.
Eastern white pine	High	Decline in condition and/or increased mortality due to higher precipitation and flood events	Risk of population decline in Markham; Increased maintenance and monitoring required

5.0 DISCUSSION

This section offers a discussion of the results and presents recommendations for strategic management; these recommendations are listed at the end of each relevant section and summarized again in Section 6.0. Several recommendations are relevant in different sections and appear more than once. The recommendations have been developed in alignment with Markham's existing planning and management documents, including the York Region Forest Management Plan, Markham Official Plan, Markham's Greenprint Sustainability Plan and Markham's Trees for Tomorrow Program.

5.1 State of the Forest

The discussion and recommendations presented in this Section pertain to three aspects of forest structure: distribution (sub-section 5.1.1), species composition (sub-section 5.1.2), and age (or size) (sub-section 5.1.3). Many benefits attributed to the forest are largely influenced by these structural elements.

5.1.1 Existing and Possible Forest Distribution

Markham's forest covers approximately 21 percent of the total land area. This is an increase of 3 percent since 2012. Factors that contributed to the increase include growth of residential trees and improved mapping methods since 2012 which are better able to detect smaller, isolated trees. Total leaf area in the study area is 239.1 km^2, with a leaf area density of 1.12 m^2/m^2 (leaf area to land area). Leaf area has increased slightly from the previous forest assessment, although changes are not significant.

In Markham's Strategic Plan and the Greenprint Sustainability Plan, a canopy cover target of 30 percent was set, while, for Markham, the York Region Forest Management Plan recommended canopy cover within 20-35 percent and woodland cover within 8-10 percent. It is recommended that a time commitment should also be set by which to achieve the canopy target (e.g., 30% canopy cover by 2040). This will allow for estimates of the numbers of trees to plant on a yearly basis or the number of hectares to restore on a yearly basis to be made. A timeline to reach the canopy target makes it more tractable and easier to incorporate into the City's strategic plan, asset management plan, and budgeting process.

Approximately 66 percent of the municipality (13,826 ha) has been identified as possible tree canopy (area theoretically available for additional tree establishment); the majority of this is identified as possible vegetated land cover (8,005 ha). However, it is not practical to plant in all pervious vegetated areas due to site considerations. For example, a significant portion of this pervious area is comprised of agricultural lands that are unlikely to be available for planting. Additionally, some potential impervious land (i.e., asphalt, concrete, or bare soil surfaces) may already be approved for development.

Markham has opportunities for planting on both public and private properties across the municipality, but the greatest opportunity to feasibly increase total leaf area and canopy cover is on Markham's public lands, largely found within the *Institutional, Other*, right-of-way (*ROW*) and *Residential Low* land uses (Figure 6). The canopy cover analysis determined that 55, 54, 49 and 40 percent of the *Institutional, Other*, *ROW* and *Residential Low* categories, respectively, are currently available as possible vegetated cover for the establishment of tree cover, representing 21 percent of the entire land area across Markham. From a municipal perspective, there is significant opportunity to increase canopy cover within the ROWs. It is important to note that the opportunities for canopy enhancement identified in ROWs may be a function of tree size. All available planting locations (based on tree spacing standards) could be occupied, but canopy cover could still be low, given many of the trees are young. In this case funding would be better spent on maintenance to ensure tree health and survival. Additionally, although establishing tree canopy in impervious surfaces is more challenging than in pervious cover, it would reduce the heat transfer from such surfaces and the volume of stormwater runoff.

Additionally, Markham has opportunities for planting on private lands. It is necessary to use a variety of tools to engage private property owners including education, incentives, and mechanisms to make it easier to plant and maintain trees. The enforcement of by-laws is also essential to protecting the existing trees on private lands and ensuring that developers protect and plant trees. Development guidelines should ensure that developers include tree planting that follows industry best practices

It can be useful to set targets for specific land use types and use a prioritization method or tool to identify priority planting areas within particular land uses and neighbourhoods. York Region has developed a tree planting prioritization tool that could be adapted and customized for the City of Markham. The tool allows the user to adjust the weighting of nine criteria (canopy cover, potential canopy, air quality, urban heat island, water quality, stormwater reduction, critical places, vulnerable population, and economic vitality) and identify priority areas for planting at the dissemination block scale.

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 forest should also 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. Many areas have been impacted by emerald ash borer (EAB, *Agrilus planipennis*) and the resulting decline in ash tree (*Fraxinus* spp.) populations. These areas can be targeted for the planting of diverse tree and shrub species to ensure succession. Additionally, many areas have been recently impacted by spongy moth (*Lymantria dispar dispar*), particularly natural areas. While spongy moth has and will be problematic for a few years, it does not often cause widespread mortality, however impacted areas should be monitored and restored as needed.

Increasing native shrub cover under canopied areas also represents an opportunity to increase total leaf area. Shrub cover that is established around mature trees can discourage human traffic and compaction of root zones. Many of the benefits provided by the 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.

Beyond planting strategies, existing valley systems, woodlots and wetlands, as well as restoration areas, need to be prioritized. The *Other – Institutional* stratum is of particular interest given that it represents a number of vacant lands, woodlots and valleylands. These may represent fragmented systems similar to those found in the *Natural Cover* land use which should be considered for protection. Protection of fragmented networks can improve species migration efforts while limiting edge effects from future development and provide corridors for species range shifts as climate change impacts continue to increase.

The distribution of the forest is also an important social justice consideration. Ultimately, the protection of trees equates to the protection of ecosystem services that are essential to the health of both humans and wildlife (e.g., clean air, cooler summer temperatures). The services provided by the forest are an asset that belong to the entire community and must be managed in a manner that ensures equitable access by all residents.

Recommendation 1: The City's Urban Forest Management Plan is a study to be undertaken starting in 2023 and should address: local canopy targets; species diversity; forest health, maintenance, and monitoring; invasive species management; soil conservation strategies; and climate change mitigation and adaptation.

Recommendation 2: The next Official Plan update should include a commitment to at least 30 percent canopy cover target to align with the Markham Greenprint Sustainability Plan. However, it is recommended to aim for a more ambitious target of 35 percent. Additionally, the development of a woodland cover target should be further explored as a component of an overall canopy target by assessing the feasible restoration potential in the Greenway System.

Recommendation 3: Develop canopy cover targets for all land use types within the Official Plan.

Recommendation 4: Work with York Region to customize and utilize the Region's tree planting prioritization tool for Markham to improve equitable canopy cover distribution, the maximization of ecological benefits and ecosystem services, and target areas impacted by invasive pests.

Recommendation 5: Develop mechanisms to encourage and support private landowners (particularly commercial and industrial landowners, and property developers) to protect and enhance canopy and educate those landowners about maintenance best practices.

Mechanisms, campaigns and courses could be facilitated through the Trees for Tomorrow program that the City has already implemented.

Recommendation 6: Continue to plant, prune and replace trees on municipal roads, parks and other municipal properties. Evaluate planting and maintenance budgets regularly as the City grows and assumes responsibility for new roads, parks and facilities.

Recommendation 7: Continue to carry out restoration plantings in the natural heritage system and other naturalized areas.

5.1.2 Tree Species Effects

Leaf morphology is influenced by species characteristics and varies across the forest, influencing growth patterns, canopy cover, and benefits provision. For example, a dominant tree species in the study area, sugar maple (*Acer saccharum*), is a broad-leaved species and despite only representing seven percent of the tree population it is the largest contributor to leaf area (23%) across Markham. Alternatively, the most common species, eastern white cedar (*Thuja occidentalis*), a narrow-leaved species, comprises 33 percent of all trees across the municipality but only contributes 11 percent of the leaf area across the forest.

Species composition in Markham is influenced by the pattern of vegetation distribution between land uses. As such, species common in the *Residential* land use stratum strongly influence municipal-scale species composition. For example, eastern white cedar represents 65 percent of all trees in this land use and is the most common species in Markham when expressed as a percent of total trees. This is due to extensive use of the species in hedgerows on residential properties.

The most dominant species in Markham in terms of tree leaf area are sugar maple (23%), eastern white cedar (11%) and Norway maple (*Acer platanoides,* 10%). Together, these three species represent 44 percent of the total tree leaf area across Markham. In the previous assessment, white and green ash (*Fraxinus americana, Fraxinus pennsylvanica*) together were the fifth most dominant species (8% of leaf area), however, due to EAB they now only contribute a negligible percentage of the total leaf area. In terms of percent of population, eastern white cedar (33%), European buckthorn (*Rhamnus cathartica*, 9%), and sugar maple (7%) are most abundant comprising 49 percent of the total trees.

These genera are distributed across land use categories as they thrive in natural areas as well as high traffic urban zones. A high relative abundance of maple is typical in the forests of this ecoregion; however, the lack of diversity among genera is a threat to the sustainability of the forest. This is of particular concern in Markham since 59 percent of the tree population and 57 percent of the leaf area are represented by 5 species. It is also of concern, that European buckthorn, a non-native invasive species that displaces native vegetation, is so abundant across land uses. Additionally, dominant species like eastern white cedar and European buckthorn are not large and at full growth they will not offer the same benefits and canopy as other species.

It is important for forests, in an urban context, to establish and maintain a diverse tree population (Leff, 2016). This increases the resilience of the forest to stressors such as species-specific insects or diseases and climate change. Thus, a forest that is not sufficiently diverse is at risk of widespread canopy loss. A greater diversity of tree species also supports more biodiversity and a wider range and quantity of ecosystem services (Gamfeldt et al., 2013). While native and introduced tree species have a place in forests, some introduced species can pose a risk to native plants if they spread easily and out-compete or displace native species.

In general, it is important to establish native species that support greater levels of biodiversity and ecosystem resilience. In addition, the Sustainable Forest Guide (Leff, 2016) recommends that no single species (native or not) represent more than 5 percent of the total tree population, no genus more than 10 percent and no family more than 15 percent. By these standards, Markham is unfortunately overly dominated at the species, genera, and family levels. Monitoring species composition provides an indicator of the diversity of forest and how vulnerable it might be to threats such as climate change and introduced pests. Changes over time indicate which species might be struggling with environmental shifts and which might be thriving or perhaps becoming invasive and therefore requiring management intervention or changing planting strategies. It is important to note that these rules apply well to intensively managed urban trees, but not natural areas. Climatic and soil conditions, and natural disturbance patterns generally establish the diversity of species in natural forests.

Recommendation 5 from 2012 Forest Study:

- no species represents more than 5% of total population
- no genus represents more than 10% of total population
- no family represents more than 20% of the intensively managed tree population both municipal-wide and at the neighbourhood level

The impact of the EAB infestation highlights the risk associated with a lack of species diversity. Ash species were distributed across all land uses in Markham, reflecting the ability of these species to thrive in both natural areas and high traffic urban environments where soil quality is low. Unfortunately, while Markham still has a green and white ash population, their overall condition is very poor (29% and 39%, respectively). Additionally, the forest is now currently experiencing a widespread spongy moth outbreak which feeds on a greater variety of species (discussed further in section 5.3.3).

The frequency and severity of pest outbreaks is increasing, creating an even greater need for diversity and resilience. Markham is located in an ecoregion capable of supporting a high level of diversity (ecodistrict 7E-4, which corresponds to the Carolinian Forest Region), relative to other ecoregions in Canada. Therefore, more aggressive diversity targets may be feasible. In addition, by utilizing a diverse mix of species from the Carolinian zone, Markham's forest will be more adaptable to both the predicted and unknown impacts of climate change. Markham is advised to establish a species composition for intensively managed urban trees 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.

When developing species diversification programs consideration must be given to the potential damage of multi-host pests. The Pest Vulnerability Matrix (PVM) is a model developed to visualize and assess the susceptibility of the forest to outbreaks of insects and diseases based on species composition and diversity (Laçan & McBride, 2008). The model predicts how the introduction of certain tree species, or a new pest species, will affect the overall vulnerability of the forest. The model has been applied for Toronto, in research by Vander Vecht, & Conway (2015), which explored the vulnerability of Toronto's forest to pests using the PVM. Using a model such as the PVM during tree species selection will help account for potential damage by future pest outbreaks, particularly by multi-host pests.

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. Such diversity is not likely feasible within the street tree population as a smaller range of species can survive the harsh growing conditions found along high traffic boulevards and streetscapes. Efforts must be made to encourage and support nurseries, private landowners, and developers to sell or plant a greater diversity of native and suitable non-native non-invasive species. There is a need to decrease the planting of eastern white cedars on private properties, increase diversity in existing sugar maple dominated forests, and control European buckthorn to decrease species population. Markham should consider adding an educational campaign focused on species diversity for private landowners that ties in with any existing programming.

The use of high-quality native planting stock grown from locally adapted or suitable 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. Genetic variability 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 (discussed further in section 5.4.4). A reliance on clones in the 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. Species ranges should be considered when planting in the future as well to accommodate for a shifting climate (i.e., planting species at the northern half of their range as opposed to southern).

Recommendation 1: The City's Urban Forest Management Plan is a study to be undertaken starting in 2023 and should address: local canopy targets; species diversity; forest health, maintenance, and monitoring; invasive species management; soil conservation strategies; and climate change mitigation and adaptation.

Recommendation 8: In line with current practices, continue to establish a diverse tree population in intensively managed urban areas, 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 intensively managed tree population both municipal-wide and at the neighbourhood level.

This recommendation is consistent with Markham's Greenprint Sustainability Plan and Trees for Tomorrow program which has a subgoal of investigating and implementing best practices to increase species diversity through tree establishment planning.

Recommendation 9: Investigate the utility and potential application of pest vulnerability tools, such as the Pest Vulnerability Matrix (PVM) during species selection for municipal tree and shrub planting.

This recommendation was made in the 2012 report and has been updated for the 2022 report. Given the anticipated increase in invasive pest outbreaks as a consequence of climate change, it is essential to enhance the diversity of the forest to ensure it is resilient to insect and disease outbreaks. Using a model such as the PVM during tree species selection will help account for potential damage by future pest outbreaks, particularly by multi-host pests.

Recommendation 10: Consider the development of an education campaign focused on educating private landowners about the importance of species diversity for a resilient forest, particularly in the context of climate change.

Recommendation 11: Utilize native and appropriate non-native, non-invasive planting stock in both intensively and extensively managed areas. Increase genetic diversity of tree populations by using the guidance provided by the Ontario Tree Seed Transfer Policy. This policy is intended to help managers source seed based on the projected changes in climate to increase the likelihood of producing trees well-adapted to current and future conditions.

The Markham Greenprint Sustainability Plan also has a goal to investigate and plant species adapted to current and future climates suitable for Markham. The Forest Gene Conservation Association is a useful resource.

5.1.3 Tree Size Effects

The proportion of large trees in Markham is low; approximately 9.6 percent of the tree population has a DBH of 30.6 cm or greater. This is a small decrease from 10.25 percent in 2012. Diameter class distribution of the tree population is influenced by a variety of factors. Most notably, the natural growth patterns and forms of the dominant species will strongly influence average tree size. For example, European buckthorn is the second most dominant species with respect to the total number of trees. This species typically maintains a comparatively small, shrubby form even at maturity and are likely to never be in the larger size classes.

Tree age will also impact diameter class distribution. Much of the urban development in Markham has occurred quite recently. Consequently, the trees planted at these new development sites have not yet reached maturity. However, there has been an increase in the number of trees in the second smallest size class (7.6 cm to 15.2 cm) which has positive benefits. Young urban trees show an exponential increase in ecosystem service contribution within their early growth windows. Given the increase in light availability and lack of competition in most urban environments, young urban trees have been shown to have accelerated carbon cycling by up to four times compared to their natural counterparts (Smith et al., 2019). As trees continue to age, their resources shift from focusing on primary growth to secondary growth and the once rapid increases in carbon cycling and associated ecosystem services slows down, albeit increasing over time.

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. Large trees also provide greater infrastructure repair savings. For example, in Modesto, California, the shade from large-stature trees over city streets was projected to reduce costs for repaving by 58 percent (financial savings of \$7.13/m^2) over a 30-year period when compared to unshaded streets (McPherson & Muchnick 2005). In comparison, shade from small-stature trees was projected to save only 17 percent in repaving costs (financial savings of \$2.04/m^2). However, it is important to note that in the winter climate of Markham, shaded streets require more salt to address snow and ice. Large trees are clearly underrepresented in the existing population of Markham's forest, therefore it is vital that trees are maintained and protected to ensure these services are delivered into the future.

Due to the highly modified and intensively managed nature of the forest, there is no appropriate historic/pre-settlement age-class distribution for which to strive. In other words, the intensively managed areas of the forest will necessarily maintain a very different diameter or age-class distribution than that observed in conventionally managed woodlands. Typically, woodlands maintain an inverse j-shaped curve that reflects the abundance of small trees in the understory as a result of natural regeneration (Oliver & Larson 1996). Natural regeneration occurs infrequently in intensively managed woodlands. Consequently, active management is needed in order to facilitate regeneration. In areas of the municipality where mature trees are dominant, managers should plan for future succession by planting replacement trees well in advance of mature tree decline and removal.

The Sustainable Urban Forest Guide recommends an ideal age distribution for a forest of 40 percent juvenile trees (average DBH of 0 to 20.3 cm), 30 percent semi-mature trees (average DBH of more than 20.3 cm and less than or equal to 40.6 cm), 20 percent mature (more than 40.6cm and less than or equal to 61.0 cm), and 10 percent senescent (more than 61.0 cm) (Leff, 2016).

The results of the i-Tree Eco analysis revealed the following diameter class distribution in Markham: 72.1 percent of municipal trees were less than 15.2 cm DBH, 18.2 percent were between 15.3 and 30.5 cm, 9.1 percent were between 30.6 and 61 cm, and less than one percent were greater than 61 cm. According to these guidelines, the proportion of small trees in Markham is significantly higher than recommended and the proportion of large trees is significantly lower. It is important to maintain the population of small and medium trees and ensure that they can grow into larger trees and provide more benefits into the future.

Recommendation 1: The City's Urban Forest Management Plan is a study to be undertaken starting in 2023 and should address: local canopy targets; species diversity; forest health, maintenance, and monitoring; invasive species management; soil conservation strategies; and climate change mitigation and adaptation.

Recommendation 12: Evaluate and develop the strategic steps required to increase the number and proportion of large, mature trees across Markham's forest including the City's Greenway System, street and park trees and trees on private lands.

This can be achieved using a range of tools including Official Plan planning policy, by-law enforcement, and public education. Maintenance and monitoring of new plantings is critical to ensure that juvenile trees are healthy and able to grow to maturity. Where tree preservation cannot be achieved, an Official Plan policy could be considered that would require compensation for the loss of mature trees and associated ecosystem services.

Recommendation 13: Review and enhance tree preservation requirements in municipal guidelines (Trees for Tomorrow Streetscape Manual) and regulations for sustainable streetscape and subdivision design standards (and particularly soil volume) to support tree establishment and eliminate conflict between natural and grey infrastructure.

5.2 Forest Function

The following is a discussion of the services (benefits) that have been quantified by the i-Tree Eco model for effects on air quality, stormwater runoff, residential energy effects, and climate change mitigation and adaptation. All forest benefits should increase in Markham as a result of the implementation of the recommendations shared in this report. In addition, recommendations are provided here to address additional needs and opportunities.

It should be noted that changes have been made to the i-Tree Eco suite of software[32] since the 2012 study, therefore the quantified benefits cannot be directly compared between the study years.

5.2.1 Effect on Air Quality

Trees and shrubs in Markham removed a total of 147 tonnes of air pollution (CO, NO_2, O_3, $PM_{2.5}$, SO_2) annually with an associated removal value of $2.7 million annually. Pollution removal is greatest for ozone (O_3), followed distantly by nitrogen dioxide (NO_2) and particulate matter less than 2.5 microns ($PM_{2.5}$). 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). Exposure to ambient nitrogen dioxide is shown to have an interaction with the immune system which could increase the risk of respiratory tract infections (Chen et al., 2007). $PM_{2.5}$ is shown to cause similar effects with acute exposure leading to irritation of the eyes, nose, throat, and lungs with potential for effects related to toxicity and inflammatory responses (Feng et al., 2016). Environmental pollution is now a concern as well, with the increasing presence of air pollution following the rapid urbanization of many municipalities, the compounded effects of air pollution on temperature regimes can have consequences on the frequency or presence of many infectious diseases and natural disasters (Manisalidis et al., 2020).

A study by Pollution Probe suggests that climate change (coupled with the urban heat island effect) could further exacerbate the degree of health effects associated with air pollution (Chiotti et al., 2002). For example, the occurrence of oppressive air masses that bring hot, humid and/or smoggy conditions is projected to increase from 5 percent of summer days to 23-39 percent by 2080. This means that the Greater Golden Horseshoe Region will likely experience more frequent, severe, and possibly longer smog episodes in the future. Thus, by mitigating the human health risks associated with air pollution, as well as mitigating both the causes and effects

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[32]Refer to i-Tree Suite Change Log here for additional information on changes to the model: https://www.itreetools.org/documents/186/iTree_suite_change_log.pdf

of climate change, Markham's forest plays an important role in community wellness, particularly for those more vulnerable members of the population.

The i-Tree Eco results show that larger diameter trees remove more pollution on average, per tree, than smaller trees. Similarly, trees were found to remove greater volumes of pollution than shrubs. In both cases, pollution removal capacity was a direct function of leaf area. Selecting species that are well adapted to local conditions and require little to no maintenance is recommended as they will typically have longer life spans providing long term filtration of air pollutants. Additionally, studies have shown that areas with high levels of ground emissions, such as vehicular traffic along a highway, should be targeted for plantings. As pollutants are released upwards from areas of high emission, the adjacent planted areas can increase immediate removal while limiting trapping pollutants beneath the canopy (Nowak et al., 2002).

However, it is important to note that trees and shrubs emit volatile organic compounds (VOCs) such as monoterpene and isoprene. These compounds are natural chemicals that make up essential oils, resins, other plant products, and are the precursor chemicals to ozone and carbon monoxide formation (Kramer and Kozlowski, 1979). An estimated total of 78,205 kg/yr of VOCs (64,212 kg/yr of monoterpenes and 13,993 kg/yr of isoprene, respectively) are emitted annually with the largest portion of the emissions coming from the *Residential* and *Open Space – Natural Cover* areas which have the most trees. However, this process is temperature dependent and given that trees typically contribute to lowering air temperature, the net results are still often positive in terms of the impact of trees on air quality.

Recommendation 1: The City's Urban Forest Management Plan is a study to be undertaken starting in 2023 and should address: local canopy targets; species diversity; forest health, maintenance, and monitoring; invasive species management; soil conservation strategies; and climate change mitigation and adaptation.

Recommendation 14: Where appropriate, select and plant long lived, low maintenance, and low volatile organic compound (VOC) emitting tree species.[33]

Since larger, long-lived individuals provide the greatest per-tree effects they should be selected to provide long-term benefits. Similarly, having low maintenance trees will reduce the associated emissions from arborist maintenance by use of gas-powered equipment.

Recommendation 15: Bolster evergreen tree population across the municipality to improve year-round pollution removal services.[33]

By planting evergreen species, with foliage all year round, such species can provide air pollution removal benefits during the leaf-off seasons (late fall to early spring) where deciduous trees don't provide air pollution associated benefits.

[33] Some evergreen species emit high levels of VOCs, however this should not preclude them from planting programs. When possible and appropriate, consider planting low VOC emitting species.

Recommendation 16: Engage in strategic tree planting in high emissions zones.

Areas with dense pollution emissions should be targeted as high priority planting sites. For example, planting adjacent to highways or high emission industrial sites would be beneficial to offsetting immediate emissions. The York Region Priority Planting Tool considers air quality as one of the criteria for determining priority planting locations and should be leveraged to identify areas for strategic planting to contribute to pollution removal. The indicator in the tool identifies areas with higher traffic volume and greater proportions of trucks on regional roads that typically have higher concentrations of particulate matter.

Recommendation 17: Consider developing an education campaign within the City's Trees for Tomorrow Program focused on educating the public about the ecosystem benefits Markham's forest provides.

5.2.2 Effect on Stormwater Runoff

Stormwater runoff is a concern in urbanized landscapes as cities continue to develop and extreme weather events increase in frequency due to climate change. As built infrastructure is implemented, the associated increase in impervious surfaces can function to increase runoff (Hirabayashi, 2012). The increase in impervious land cover allows contaminants such as oils and fertilizers to be transported by runoff into adjacent channels, streams, and ground water. As polluted stormwater feeds into the hydrological system, it can have cascading effects on sensitive species and nutrient imbalances (Kollin, 2006). Green infrastructure can help mitigate these negative impacts by retaining stormwater. The trees of Markham provide a hydrological benefit with a stormwater offset estimated at 742,449 m^3 across the municipality, valued at $1.72 million annually. The *Residential* and *Open Space – Natural Cover* land use strata provide the greatest benefits and remove approximately 258,359 m^3 and 185,026 m^3, respectively.

Green infrastructure, and trees specifically, provide a host of services relevant to stormwater runoff. Foliage and branches intercept precipitation which functionally reduces a portion of precipitation that may otherwise become runoff. Additionally, canopies reduce soil erosion caused by direct rain fall and allow soils to store larger volumes of precipitation (Brandt, 1988). At the ground level, runoff infiltrates the soil, and pollutants are naturally filtered and broken down by roots and microbial life (Schloter et al., 2018).

To have a healthy, functional hydrological network, a balance between green and grey infrastructure should be considered in development planning. For example, green infrastructure provides shading which can improve pavement life while allowing for natural stormwater runoff controls and should be weighted in tandem with grey infrastructure.

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Recommendation 13: Review and enhance tree preservation requirements in municipal guidelines (Trees for Tomorrow Streetscape Manual) and regulations for sustainable streetscape and subdivision design standards (and particularly soil volume) to support tree establishment and eliminate conflict between natural and grey infrastructure.

Green infrastructure should be incorporated into grey infrastructure planning and development as it can function to intercept precipitation, cool paved surfaces, directly remove air pollution, and improve soil content available for runoff capture in urbanized areas.

Recommendation 18: Continue to apply subsurface (Silva) cells on a project-by-project basis and other enhanced rooting environment techniques for street trees, particularly in constrained spaces such as intensification areas.

Utilizing these technologies at selected sites in the short-term may provide a cost-effective means of integrating these systems into the municipal budget. Silva cells can function to improve stormwater runoff channels.

Recommendation 19: Explore the opportunity to utilize the Sustainable Technology Evaluation Program Treatment Train Tool to evaluate and quantity the stormwater benefits of planting trees.

The Low Impact Development Treatment Train Tool provides the ability to design and evaluate different urban tree planting scenarios at the site level to determine stormwater management benefits and can be a very effective way to demonstrate the benefits of urban tree planting.

Recommendation 17: Consider developing an education campaign within the City's Trees for Tomorrow Program focused on educating the public about the ecosystem benefits Markham's forest provides.

5.2.3 Effect on Residential Energy Bills

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 trees or shrubs can insulate or lower building temperatures. McPherson and Simpson (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 percent. Potential greenhouse gas emission reductions from forests are likely to be greatest in regions with large numbers of air-conditioned buildings and long cooling seasons. However, in colder regions where 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 percent 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 & McPherson, 2000). In Markham the annual demand for heating and cooling was reduced by approximately 416,089 MBTU and 11,245 MWH, with an associated annual financial savings of almost $3.2 million. This is a sharp increase in energy and financial savings from 2012, where the estimated energy demand was reduced by 166,200 MBTU and 6,000 MWH, saving approximately $2 million annually. The difference is likely due to the maturation of Markham's forest, where larger residential trees are more capable of blocking solar radiation and wind.

Given Markham's colder winter climate, there were greater savings associated with the reduction of heating ($2.2 million) than cooling ($924,764), primarily related to a decrease in the need for natural gas ($1.8 million). This may also be due to current tree species and placement, which can have significant impact on potential energy savings. For example, evergreen species planted along the south facing wall of a building will block the heat from the winter sun and will increase the need for daytime heating. In contrast, large deciduous trees planted on the east and west sides of a house will shade buildings during hot summer months, but after their leaves have dropped, will allow heat to reach homes in the winter (Ko, 2018). However, as climate projections predict an increase in cooler days, the City should consider whether this might impact species selection. Public education and outreach will be required to communicate these benefits and to provide direction for strategic planting around buildings to enhance energy savings.

Recommendation 1: The City's Urban Forest Management Plan is a study to be undertaken starting in 2023 and should address: local canopy targets; species diversity; forest health, maintenance, and monitoring; invasive species management; soil conservation strategies; and climate change mitigation and adaptation.

Recommendation 20: Following the City of Markham's Official Plan recommendation to encourage tree planting to reduce the urban heat island effect (Section 6.2.3.1. c), consider including the potential of trees to provide energy savings when developing planting guidelines or standards. Consider the use of Letters of Credit or other tools to ensure tree establishment and success in the implementation of the Sustainability Metrics as a green development standard in Markham.

Tree species selection and placement should be targeted to provide summer shade and reduce winter wind speeds around residential buildings.

Recommendation 17: Consider developing an education campaign within the City's Trees for Tomorrow Program focused on educating the public about the ecosystem benefits Markham's forest provides.

5.2.4 Climate Change Mitigation and Adaptation

Trees can mitigate climate change by sequestering atmospheric carbon and then storing it long-term as woody biomass. During photosynthesis, atmospheric carbon dioxide (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). In Markham, trees sequester approximately 8,693 tonnes of carbon annually (value of $1.6 million annually), with net sequestration at 5,424 tonnes per year, and store approximately 265,348 tonnes of carbon (value of $50.1 million). The annual carbon sequestration by trees in Markham is equivalent to the annual carbon emissions from 6,868 automobiles or 4,015 single family homes[34]. Since 2012, annual gross carbon sequestration has remained roughly equivalent (9,200 tC/year in 2012), but net sequestration has decreased from 7,400 tonnes carbon per year. This decline can likely be attributed to the increase of trees in critical, dying, or dead condition from 9 to 14 percent and an increase in dead trees from 8 to 10 percent. In particular, dying and dead ash trees are expected to emit carbon as they decompose (1,325 tC/year). However, the total carbon storage increased from 230,000 tonnes carbon in 2012, which is expected as Markham's forest has matured, increasing its canopy cover, population size, and leaf area.

[34] Values approximated using Markham's gross annual carbon sequestration value in the United States EPA Greenhouse Gas Equivalencies Calculator: https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator

The forest can also decrease carbon dioxide levels by reducing the demand for heating and air conditioning in residential buildings, subsequently avoiding carbon emissions by power plants. In Markham, the annual demand for heating and cooling was reduced by approximately 416,089 MBTU for natural gas use (heating) and 11,245 MWH for electricity (heating and cooling). Ontario's energy grid is currently nuclear and hydro dominant, with relatively low carbon emissions. However, it is projected to become more dependent on natural gas as nuclear plants are being closed for refurbishment or decommissioned. Therefore, the reduced demand for heating due to the forest may have a more substantial impact on natural gas use in the future.

Nowak and Crane (2002) argued that carbon released through tree management activities must be accounted for when calculating the net effect of forests on atmospheric carbon dioxide. Tree care practices often release carbon into the atmosphere due to fossil fuel emissions from maintenance equipment. To compensate for the carbon emissions associated with planting, establishment, pruning, and tree removal, trees planted in the urban landscape must live for a minimum amount of time, dependent on the species. 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 & Crane, 2002). This observation further highlights the importance of selecting low maintenance, well-adapted native species with the goal of maximizing tree health and longevity. Additionally, there should be a shift towards the use of electric tools to reduce the small-scale carbon emissions directly associated with maintenance.

When selecting trees for planting, it is also important to consider which have a greater potential for carbon sequestration and storage. In Markham, sugar maples (*Acer saccharum*) store the greatest volume of carbon (approximately 24% of total carbon stored) and are also responsible for the most annual net sequestration (23% of total net sequestered carbon and 16.0% of gross sequestration). This a native species with only moderate climate change vulnerability, but planting should also consider the diversity of the forest. The second species to sequester and store the most carbon was the highly vulnerable eastern white cedar (*Thuja occidentalis*), which is not recommended for additional planting. Common, invasive species also provide carbon benefits, with the historically popular residential species Norway maple (*Acer platanoides*) being one of the best carbon sequestering and storing species (17.5% of total net sequestered carbon and 12% of carbon storage) and Manitoba maple (*Acer negundo*) sequestering a significant amount of carbon each year (6%). However, while these trees may provide current benefits, future planting should still prioritize native and appropriate non-native species.

As climate change worsens, the role of trees, and to a larger extent the forest, will become increasingly more important as a means to mitigate heat stress especially in urban areas which are already warmer than surrounding regions due to the urban heat island effect. Shade trees can decrease near-surface air temperatures by an average of 3 °C by intercepting solar radiation and evapotranspiration, improving pedestrian thermal comfort, and decreasing human mortalities during heatwaves (Wang et al., 2018; Wong et al., 2021). Thus, by improving and maintaining the forest, Markham is investing in public health.

Recommendation 1: The City's Urban Forest Management Plan is a study to be undertaken starting in 2023 and should address: local canopy targets; species diversity; forest health, maintenance, and monitoring; invasive species management; soil conservation strategies; and climate change mitigation and adaptation.

Recommendation 21: Consider including species' capacity for carbon storage and sequestration when developing planting lists or guidelines and future Urban Forest Management Plans.

The City should explore the potential to modify York Region's Tree Planting Prioritization Tool with species-specific criteria to shift planting recommendations to native and appropriate non-native, non-invasive species that have a higher capacity for carbon storage and sequestration.

5.3 Sustaining a Healthy Forest

5.3.1 Soil Health

The chemical and physical properties of soil influence its fertility and the capacity for plant growth (Pickett et al. 2011). Urban soils are highly vulnerable to disturbances, and often become modified due to direct effects, such as construction activities, and indirect effects, such as pollution (Lehmann & Stahr 2007, Pouyat et al. 2019, Foldal et al. 2022). Consequently, urban soils often have disrupted natural soil structures, mixed soil horizons, and are blended with man-made materials (e.g., bricks, glass, crushed stones) (Pouyat et al. 2007, 2019, Foldal et al. 2022). Additionally, urban soils are characterized by high levels of compaction, salinity, and alkalinity because of intensive human management and deposition of toxic elements from impermeable surfaces (Lehmann & Stahr 2007, Pickett et al. 2011, Pouyat et al. 2007, Pouyat et al. 2019, Foldal et al. 2022).

Results of the Markham soil health assessment showed that soils on private properties across the municipality have a higher compaction, salinity, and pH than soil on public properties (including conservation authority lands). Correspondingly, soil in plots occurring in the *Open Space – Natural Cover* land use stratum (mostly municipal parks and protected areas), had lower compaction, salinity, and pH than plots in built or developed land uses. The observed patterns of higher compaction, salinity, and pH levels in Markham are aligned with prior research examining the properties of urban soils altered by human activities (e.g., soils on developed land, soils adjacent to roads) (Foldal et al. 2022). These factors contribute to lower fertility and sub-optimal conditions for plant growth in urban soils (Pouyat et al. 2007). While tree condition was found to decrease as soil compaction and pH increased, this can likely be explained by the fact that natural areas – which were the least compacted and had lower pH levels – had higher proportions of dead trees (due to EAB and less intensive management strategies).

Human disturbance that causes movement of soil, particularly for construction, in combination with the intensity of land use in urban areas contributes to higher compaction levels in urban soils, impeding healthy plant growth (McDonnell & Pickett 1990, Kaye et al. 2006, Pouyat et al. 2007, Foldal et al. 2022). Higher compaction is typical of urban soils, leading to reduced root growth, lower soil water-holding capacity, restricted oxygen penetration, and greater surface water flow (Pickett et al. 2011, Pouyat et al. 2007). Better management is essential to reduce the compaction of soils and increase their productivity (De Kimpe & Morel 2000, Scharenbroch et al. 2005). Preventing soil compaction is more cost-effective than implementing corrective actions and can be achieved by reducing foot and vehicular traffic on root zones of trees during construction and ensuring adherence to proper soil installation procedures (PCCP 2021). Mulch and underplanting are useful amendments because they help mitigate compaction and protect exposed soils from external pollutants (Pickett et al. 2011, PCCP 2021). Remedial measures should also be considered to improve compacted soils. For example, aerating compacted urban soils, particularly in exposed areas, would be beneficial to improve air flow to roots

(De Kimpe & Morel 2000). Additionally, increasing organic matter content by adding topsoil or compost to urban soils can help add nutrients and soil decomposers to soils (Pickett et al. 2011).

In urban environments, there is concern about the application of road salts in winter resulting in salt accumulation in adjacent soils. Road salts are composed of sodium, calcium, magnesium, and potassium chlorides (Sustainable Technologies Evaluation Program, n.d.). Excess salts hinder plant growth by affecting the soil-water balance. They also decrease soil microorganism activity which in turn impacts important soil processes such as respiration, residue decomposition, nitrification, and denitrification. Soils with a high concentration of sodium salts (sodic conditions) have additional problems, such as poor soil structure, poor infiltration or drainage, and toxicity for many plants (USDA, n.d.). Higher exposure to heavy metals and other pollutants as well as saline or sodic conditions are also indicative features of urban soils (Manta et al. 2002, Pouyat et al. 2007, Pickett et al. 2008, 2011). The results of the salinity analysis were consistent with findings in the literature, showing higher salt levels in the soils of built and developed land use types. The City should engage private landowners so that they can be more aware of the harmful impacts salt has on tree growth and encourage the use of less harmful alternatives to salts for de-icing where feasible.

Urban soils commonly have an increased pH due to leaching of cement or masonry from the built environment (Pouyat et al. 2007; Lehmann & Stahr 2007; Foldal et al. 2022). pH levels influence nutrient availability, uptake, and tree growth (MSU 2019). Soil bacteria transform nutrients in organic matter, making them accessible to trees. These bacteria are most effective in slightly acidic soils, so soils with higher pH levels have a lower availability of certain nutrients. However, it is important to recognize that tree species have different preferred pH levels and tolerances (MSU 2019). Therefore, a finer scale soil assessment in the future would provide a more thorough understanding of the relationship between soil pH and tree health. Species-specific pH tolerances should be considered when tree planting sites are identified in future initiatives.

Recommendation 1: The City's Urban Forest Management Plan is a study to be undertaken starting in 2023 and should address: local canopy targets; species diversity; forest health, maintenance, and monitoring; invasive species management; soil conservation strategies; and climate change mitigation and adaptation.

Recommendation 13: Review and enhance tree preservation requirements in municipal guidelines (Trees for Tomorrow Streetscape Manual) and regulations for sustainable streetscape and subdivision design standards (and particularly soil volume) to support tree establishment and eliminate conflict between natural and grey infrastructure.

Recommendation 22: Ensure best practices for healthy soils, are implemented in Markham's public and private urban areas in the planning of planting programs, from site selection and assessment to species selection. Reference tools and programs such as the Sustainability Metrics and Trees for Tomorrow Standards relating to soil health.

Recommendation 23: Manage compaction, salinity, and pH on public property through amendments and remedial measures like mulching and planting of herbaceous cover and shrubs.

Recommendation 24: Educate private homeowners and industrial and commercial landowners about soil best practices.

For example, private landowners are encouraged to use less harmful alternatives to salts for de-icing. Additionally, education opportunities should be leveraged through planning application processes to ensure developers are aware of soil best practices.

5.3.2 Invasive Plant Species

Invasive species' inherent capacity to outcompete native plants and change plant community composition is a growing biodiversity, economic, and social concern. In Markham, the most commonly found invasive plant species in terms of proportion of plots affected are European buckthorn (*Rhamnus cathartica,* 22%), Norway maple (*Acer platanoides*, 16%), dog strangling vine (*Cynanchum rossicum,* 14%), Manitoba maple (*Acer negundo*, 13%), wintercreeper euonymus (*Euonymus fortunei*, 12%), and garlic mustard (*Alliaria petiolata*, 10%). These species are known to dominate ground vegetation and have various strategies to limit competition with native flora. Some examples of their impacts include the explosive establishment and growth of dog strangling vine from forest edge to interior, the allelopathic properties of garlic mustard to limit native species success while establishing a seed bank for as long as 5 years (Blossey et al. 2017), and the shade density of a broad-leaved Norway maple canopy which can inhibit new growth (Martin 1999). Additionally, European buckthorn's prolific seed production and dispersal ability can lead to the development of blanket thickets of seedlings that, once established along disturbed edge or urban environments, allows the species to easily displace native flora from the ground level up. The capacity for European buckthorn to spread is compounded by other invasive properties, severely limiting the establishment of native plant species in natural, peri-urban, and urban settings.

With respect to the percentage of total stems across the municipality, European buckthorn is the largest concern, and in terms of total leaf area Norway maple is the most dominant invasive plant species. Additionally, European buckthorn is the most dominant invasive species across all land use types, followed by Norway maple and dog strangling vine which permeate nearly all land use strata at a lower intensity. These three species are the most abundant invasive plant species overall and disproportionately represent invasive plant establishment across all land use strata.

An overall invasive score, derived from multiplying the average spread and average number of invasive species, shows that the spread of invasives in *Open Space – Natural Cover* (score of 5.8) is the greatest concern, followed by *Other – Institutional* (4.8) and *Residential* (4.1). In the *Open Space – Natural Cover* and *Residential* land use strata, over 40 percent and 80 percent, respectively, have at least one invasive plant species present. *Residential* and *Open Space – Natural cover* strata often exhibit a tandem effect where residential invasive populations escape and drive the spread of invasives in natural areas leading to cascading negative effects on the capacity of natural areas to deliver ecosystem services (Hands et al. 2018). The incredibly high prevalence of invasives in the *Residential* stratum is of special concern in Markham given this tandem effect.

Natural forested areas and woodlot patches in urban municipalities tend to be highly fragmented and surrounded by highly developed lands making them particularly vulnerable to invasion. Forests, in urban contexts, and woodlot edges are typically degraded and comprised of a microclimate and species composition uncharacteristic of typical, large intact woodlots (Kowarik & Lippe 2011). These exposed forest edges can enable invasive species to gain a footing in woodland patches, which expand further into the woodlot over time (Cadenasso & Pickett 2008). Residential areas in particular are a common source of invasive species (with an average of 3.4 invasive species per residential plot found in this study). Restoring and protecting the edge of urban woodlots and forests with native pioneer species and resilient herbaceous plantings can help provide a buffer against the common dispersal strategies of garden escapees.

Given that invasive plant species tend to have few natural controls to prevent establishment relative to their propagation rate, continued monitoring and action will be required to curb current numbers and limit spread. European buckthorn, dog strangling vine[35], and garlic mustard should be considered high priority and given special emphasis in targeted management and education given their abundance and their potential to outcompete and displace native trees at the ground layer.

Continued effort in selecting healthy and resilient native stock for plantings across all land use strata will improve the native species capacity to outcompete invasive species. Additionally, some hybrid cultivars are well adjusted to harsher environments like the disturbed sites on *Commercial – Industrial* and *Other – Institutional*. Planting species like honey locust (*Gleditsia triacanthos*) and silver maple (*Acer saccharinum*) and their hybrids can limit the success of invasive species like phragmites (*Phragmites australis*) and European buckthorn at the sites where they go unchecked.

Lastly, continuing to share information with the public will help foster the collective effort and citizen science required to mitigate large scale invasive spread. An educational outreach program on common invasive plant species, their consequences on the landscape and next steps for limiting impact should be developed. There are many existing educational resources developed by conservation authorities and other environmental agencies that the City can use and leverage with minimal investments. Staff should also be trained and educated on current best practices for invasive species so that they can best deliver resources to the public (for example, promoting volunteer removal events as part of staff-led seminars).

Recommendation 1: The City's Urban Forest Management Plan is a study to be undertaken starting in 2023 and should address: local canopy targets; species diversity; forest health, maintenance, and monitoring; invasive species management; soil conservation strategies; and climate change mitigation and adaptation.

Recommendation 25: Promote the implementation of natural buffers and fencing along the edges of urban woodlots to protect against the encroachment of invasive species.

Restoration initiatives should be pursued along the edges of woodlots in municipal parks near residential areas to promote native plant diversity. Restoration plantings along the forest edges will create a buffer against wind seed dispersal and anthropogenic dispersal (foot traffic), as well as limit invasive establishment by alleviating edge effects. TRCA's Guideline for Ecosystem Compensation provides recommendations for restoration planting as well as recommended species lists. In new development areas, vegetation protection zones should be established and re-planted with dense woody vegetation to protect forest edges before residents move in.

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[35] In 2018, a three year pilot project to release the noctuid moth *Hypena opulenta,* as a potential biocontrol agent of DSV was undertaken. While the City continues to monitor and detect signs of overwintering success (feeding by larval instars), the populations have not yet reached the point where measurable control has been observed in the area of release sites.

Recommendation 9: Investigate the utility and potential application of pest vulnerability tools, such as the Pest Vulnerability Matrix (PVM) during species selection for municipal tree and shrub planting.

Recommendation 26: Continue targeted removal of high priority invasive plant species at high priority sites following best practices[36].

Recommendation 27: Explore the development and implementation of a municipal-led invasive plant, pest, and disease education and volunteer program to enhance awareness of invasive plants, pests, and pathogens and proper removal practices.

5.3.3 Tree Pests and Diseases

Exotic insect pests pose a serious threat to the health of forests and street trees as no natural controls have been 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 distributions.

Invasive pest species of particular interest are emerald ash borer (EAB, *Agrilus planipennis*) and spongy moth (*Lymantria dispar dispar*). The recent infestation of spongy moth across Markham was pervasive, with the moth present at 30 percent of plots. i-Tree Eco analysis suggests that 18.7 percent of the City's tree population – with a replacement value of $176 million – are susceptible to defoliation by spongy moth. Spongy moth has a cyclical life cycle, with outbreaks occurring every 7 to 10 years. Spongy moth caterpillars – which emerge between early May to mid-July before metamorphosis – do not show strong preferences for select tree species. Most healthy deciduous trees can tolerate one to several years of defoliation by spongy moth since they can recover each growing season. However, coniferous trees that have been defoliated will face severe, detrimental effects as only a small proportion of needles are replenished each year (Ontario Wildlife and Nature, 2014). Thus, there will be a continued need for appropriate management responses.

Unlike spongy moth, EAB specifically targets ash trees (*Fraxinus* spp.). EAB was observed on 12 percent of field plots in this study. The number of ash trees showing signs of EAB represent a large proportion of the ash in Markham. At this stage, EAB has decimated most ash populations in Markham with the remaining population's overall condition being very poor (~34%). A large portion of the green (*Fraxinus pennsylvanica*) and white ash (*Fraxinus americana*) and 100 percent of black ash (*Fraxinus nigra*) have died due to EAB. However, mature urban ash trees deemed to be high value should be continually monitored and treated with TreeAzin following the recommended schedule.

Tree diseases have also become a more prevalent concern as novel diseases begin to shift northwards as their ranges expand. While beech bark disease (BBD, *Neonectria faginata*) (observed in 3 plots) is relatively low, their impacts on natural tree populations are still of concern because Markham falls in the Carolinian Forest Region, which is typically characterized by sugar maple (*Acer saccharum*) and American beech (*Fagus grandifolia*). In the

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[36] Refer to Ontario Invasive Plant Council's best management practices series: https://www.ontarioinvasiveplants.ca/resources/best-management-practices/

remnant Carolinian forest patches and woodlots, the prevalence of BBD can have long term consequences on beech health and should be monitored.

Certain pests and diseases were not observed in Markham, including Asian long-horned beetle (*Anoplophora glabripennis*), hemlock woolly adelgid (HWA, *Adelges tsugae*), and oak wilt (*Bretziella fagacearum*). HWA and oak wilt are impending threats for southern Ontario, given their rapid spread and the damage and mortality they have caused in nearby regions south of the border. A newly discovered established HWA population has been reported in south-eastern Ontario (near Coburg) and there is a reported HWA population in Niagara Region that is being monitored. The Invasive Species Centre and the Canadian Food Inspection Agency (CFIA) have issued a notice to record and report any sightings of HWA and have encouraged practitioners to adopt the CFIA protocol for surveying for HWA. Furthermore, while oak wilt was not observed in Markham yet, a proactive approach to managing the disease should be considered as it begins to appear at the southern extent of the Canadian border.

Recommendation 1: The City's Urban Forest Management Plan is a study to be undertaken starting in 2023 and should address: local canopy targets; species diversity; forest health, maintenance, and monitoring; invasive species management; soil conservation strategies; and climate change mitigation and adaptation.

Recommendation 7: Continue to carry out restoration plantings in the natural heritage system and other naturalized areas.

The reforestation of lands in the natural heritage system should continue in order to expand forest cover and to strengthen ecological linkages. The City of Markham should prioritize large non-treed sites within valleylands and abutting existing forests for the greatest ecological benefits. Other planting opportunities such as understory plantings should also be considered to increase diversity in existing forested areas. 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. Markham should work with local growers to ensure that this demand can be met. Genetic variability 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 forest will have the opposite effect and will increase the vulnerability to invasive pests and diseases.

Recommendation 8: In line with current practices, continue to establish a diverse tree population in intensively managed urban areas, 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 intensively managed tree population both municipal-wide and at the neighbourhood level.

Recommendation 9: Investigate the utility and potential application of pest vulnerability tools, such as the Pest Vulnerability Matrix (PVM) during species selection for municipal tree and shrub planting.

Recommendation 27: Explore the development and implementation of a municipal-led invasive plant, pest, and disease education and volunteer program to enhance awareness of invasive plants, pests, and pathogens, and proper removal practices.

Recommendation 28: Develop a monitoring and action strategy for invasive species, including pests and diseases, and continue taking proactive approaches to address new and emerging invasive species, such as hemlock woolly adelgid and oak wilt.

An invasive plant species strategy is being developed as part of the 2022 Natural Heritage Management Study. The City should consider implementing survey protocols to monitor and report pests and diseases of concern that have yet to reach Markham (e.g., hemlock woolly adelgid and oak wilt) and plan for responsive actions in the case they reach the municipality. Markham should also continue to develop and implement a management plan for managing spongy moths investigate the potential use of biotic control agents.

5.4 Past and Future

5.4.1 Historical Change

Meaningful changes to forest composition, structure, and succession can occur over the span of a decade and have impacts on canopy cover characteristics across an urban landscape. Studies have often considered the significance of decadal growth in natural succession to surmise the effects of a 10-year span on composition and structure in natural settings (Stickney, 1986). The Forest Studies provide an opportunity to compare change through time, given they involve the reassessment of the same pool of randomly distributed plots every 10 years.

There have been significant changes to the extent of canopy cover in Markham since the last forest study in 2012. The UVM canopy analysis determined an increase of three percent canopy cover since 2012 (from an estimated 3.15 million trees in 2012 to 3.3 million in 2022). Such an increase in canopy cover is likely attributed to the natural growth of the canopy across land use strata but particularly in newer developments and residential areas where trees were more recently planted. A study contrasting Canadian urban areas from 1990-2012 found that land use changes from agricultural lands to urban residential landscapes may have an associated increase in canopy cover given new plantings, supporting this assumption (McGovern and Pasher, 2016). In the case of Markham, between 2012-2022, natural growth has largely outpaced losses from extensive and intensive urbanization. This is reflected by a slight decrease in carbon sequestration and an increase in total storage since 2012, which has decreased from 9,200 to 8,693 tonnes of carbon sequestration per year and increased from 230,000 to 265,348 tonnes of total carbon storage. However, it is important to note that there is a continued need for tree planting and restoration plans as many younger street trees show high mortality rates associated with poor soil, nutrients, and growing quality (Smith et al., 2019). This is of special concern in residential areas where much of the canopy cover expansion in Markham is located. A study focusing on street tree morphology shows that while urban street trees show accelerated rates of carbon cycling, up to 4 times as much as their rural counterparts, the mean mortality rates are doubled (Smith et al., 2019). Therefore, the associated increase in canopy cover from urban plantings should be considered in light of their increased mortality rates.

Species composition across Markham's forest has seen a shift in both percentage of total trees and total leaf area. The top 5 species in 2022, by percentage of total trees, represent 59 percent of all tree populations across Markham, a 2 percent increase compared to 2012. Of notable interest is the increase in eastern white cedar (*Thuja occidentalis*) to become the dominant species across Markham, increasing from 21 percent in 2012 to 33 percent in 2022, and the slight decrease in the European buckthorn (*Rhamnus cathartica*) population from 11 percent in 2012 to 9 percent in 2022. However, the decrease in the European buckthorn population may be due to a reduction in the minimum threshold for DBH, from 5 cm to 2.5 cm, for measuring tree species in forested sites. This was done to improve efficiency of data collection in forested areas but given the short and narrow growth forms of European buckthorn seedlings and saplings, they may not have been adequately considered in our analysis. Nonetheless, European buckthorn, being the most prominent invasive tree species, should continue to be monitored and managed as it is still represented in the top 5 species with respect to tree population. Ash species are of interest as well due to their declining numbers. White and green ash (*Fraxinus americana, Fraxinus pennsylvanica*) together have dropped from the fourth most prominent species (where they represented 9% of the tree population) to the fifth (4% of the tree population) for 2022 and was replaced by Manitoba maple (*Acer negundo*). However, since 2012, ash trees (white; green; and black, *Fraxinus nigra*) have decreased substantially in the population as a whole from approximately 320,020 to 157,647 (±61,266), and as a percentage of the population from 10 percent to 5 percent. This stark decrease is largely explained by the decimating impacts of emerald ash borer (EAB, *Agrilus planipennis*) and while white and green ash together are still in the top five species for population, this is likely made up of regenerative younger seedlings and saplings.

In terms of total leaf area, the top 5 species in 2022 represent 57 percent of the leaf area across Markham, a large increase of 12 percent since 2012. Such a jump is of some concern given the need to diversify the canopy across Markham to better adapt to a changing climate and any associated pressures. Of this jump in leaf area across the 5 most dominant species, most notable is the increase in leaf area of sugar maple (*Acer saccharum*) which has increased from 13 percent in 2012 to 23 percent in 2022. While sugar maple still represents the largest proportion of leaf area in Markham (5,579.9 (±2,403)), it now composes the largest proportion of Markham's canopy with a population estimate of approximately 215,623 (±79,783). While the cause of this increase is unclear, given the species prevalence as one of the dominant species in the Carolinian zone, this increase in sugar maple presence may be explained by the species becoming more well established within natural areas and their characteristic broad-leaved canopies growing as natural populations mature. This is positive news for the municipality as a large sugar maple canopy is indicative of healthy, functioning Carolinian stands. Where applicable, sugar maples should be monitored in Carolinian stands for natural regeneration to ensure continued and improved forest health in natural areas. On the other hand, the growth of the Norway maple (*Acer platanoides*) canopy across Markham should continue to be monitored in natural areas, as it is now representing 10 percent of the total leaf area across Markham as opposed to 7 percent in 2012. While previously planted individuals shouldn't be removed given the benefits they provide, particularly in terms of carbon sequestration and shade provision, populations that have encroached into natural areas should be monitored. Due to the incredibly dense canopy of mature Norway maples and the associated impacts on light availability at the ground layer, such canopies can promote conditions that inhibit emerging natural growth (Smith, 1999).

Condition and tree size are relatively similar in 2022 to those of the previous study. Tree size has not increased significantly since 2012 and approximately 72 percent of all trees in Markham are below 15.2 cm, around the same as the last study. Condition, when considering fair to excellent scores, has declined to 79 percent in 2022 from 87 percent in 2012. This shift in condition may be tied to the percentage of trees in poor, critical, dying, or dead condition which has increased from 12 percent in 2012 to 20 percent in 2022. This could reflect a change in condition of urban trees due to urban stressors, the decline in ash condition in response to EAB, and may be indicative of an overall trend towards worsening tree health. However, it should be noted that some of this observation may be related to surveyor consistency as staff could have slightly different observations when assessing tree condition between categories. While there is a standardized process for rating condition, it is impossible to completely account for surveyor variability.

Overall, since the last study, Markham has expanded its canopy cover and increased carbon storage but should continually monitor species composition as more invasive species, such as European buckthorn and Norway maple, have entered the top five species for percent of population or total leaf area. Additionally, management strategies in urban landscapes need to be fully considered and integrated to improve the health of urban street trees and reduce mortality rates for the future.

Recommendation 1: The City's Urban Forest Management Plan is a study to be undertaken starting in 2023 and should address: local canopy targets; species diversity; forest health, maintenance, and monitoring; invasive species management; soil conservation strategies; and climate change mitigation and adaptation.

Recommendation 29: Reassess tree care and maintenance practices for trees in highly urbanized areas. Indicators associated with street tree mortality should be considered, including plant hardiness and tolerances to harsher urban conditions, tree pit enhancements, direct tree care/stewardship, and assessing local traffic and building conditions.

Recommendation 8: In line with current practices, continue to establish a diverse tree population in intensively managed urban areas, 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 intensively managed tree population both municipal-wide and at the neighbourhood level.

Recommendation 30: Monitor stand level dynamics and patterns to select species, specifically sugar maple, targeting Carolinian forest stands across Markham.

Recommendation 31: Continue assessing forest structure, function, and distribution every 10 years through the Urban Studies.

5.4.2 Trajectory and Future Projections

The i-Tree Eco suite includes a forecast component that utilizes structural estimates generated via the i-Tree Eco model, such as number of trees, species composition, size, etc., alongside growth, mortality, and planting rates to estimate future forest conditions across a Thirty-year span. Based on Markham's current planting programs over a thirty-year simulation, expected canopy growth, and the continued impact of EAB, spongy moth (*Lymantria dispar dispar*), and beech bark disease (*Neonectria faginata*) in the next ten years, the outputs of the model show that canopy cover is expected to reach 32.4 percent by 2051. Alternatively, assuming a scenario in which planting inputs are doubled, canopy cover is expected to reach 33.3 percent by 2051. Lastly, under the no planting scenario, canopy cover is expected to reach 31.4 percent by 2051. The forecast predicts a positive trajectory for canopy cover and shows Markham within the recommended canopy range by 2051 under all scenarios. Assuming planting programs are implemented as planned and tree maintenance and management are sustained, the potential increase in canopy cover is likely achievable.

While the potential increase in canopy cover output by the forecast model may be feasible, the projected loss of trees due to increased mortality should be considered in Markham's planting plans. By 2051, the tree population, as derived from the forecast model, is expected to decline from 2.96 million to 2.05 million under the current planting scenario, to 2.3 million under the doubled planting scenario, or to 1.8 million under the no planting scenario. As the canopy across Markham continues to mature (largely consisting of existing trees that have shifted into larger size classes) the overall expected losses are anticipated to outpace the rate of canopy growth over time. The large contrast between expected tree numbers across each scenario further highlights the need to continue plantings and the required maintenance in priority areas. Maintaining the simulated thirty-year planting plans would greatly reduce the loss associated with high mortality rates for trees in urban spaces. Furthermore, to ensure the success of new plantings, there is a need to develop a post-tree planting management strategy to alleviate some of the causes associated with high mortality rates in young, newly planted urban trees (Smith et al., 2019). Ultimately, while the projected canopy cover and tree number estimates provide a lens to the future of Markham's forest, they should be considered in the context of an ever-changing climate, future land use changes, and the impacts of urban conditions on tree health.

The forecast cannot accurately account for complex changing conditions, specifically climate change. Frost-free days were increased in Markham to account for a changing climate, however this does not completely capture the dynamic nature and compounded effects of climate change. One such impact is the shifting geographical ranges of common and dominant tree species. For example, eastern white cedar is at its southernmost extent in Markham and is at risk of being extirpated (as detailed in the climate vulnerability assessment, see Section 5.4.3). Given that the species accounts for the largest tree population, this risk is of the utmost concern. Actions should be taken to encourage planting alternative, less vulnerable native and naturalized species, where possible, and eastern white cedar should be monitored in natural settings for restoration management as they dominate fresh-moist ecosites.

Additionally, the northward shift of species' range can function to introduce pests and diseases novel to the region. As of 2021, oak wilt (*Bretziella fagacearum*) had not yet crossed into Canada from the United States, but hemlock woolly adelgid (*Adelges tsugae*) has been reported in the Niagara Peninsula at Wainfleet and Fort Erie. Both are of concern to Markham in the near future and should be monitored. Successful planning for future, concerning pests and diseases is predicated on the provincial, regional, and city-wide control responses and proactive management.

The forecast outputs should be considered critically given the limited capacity to consider all possible factors that influence future canopy cover in the model and the uncertainty surrounding future climatic changes. However, the results of the forecast are currently very encouraging, and provide guidance to suggest the City should continue with restoration, tree planting, replacement, maintenance, and monitoring on public and private property – especially as Markham continues to urbanize.

Recommendation 1: The City's Urban Forest Management Plan is a study to be undertaken starting in 2023 and should address: local canopy targets; species diversity; forest health, maintenance, and monitoring; invasive species management; soil conservation strategies; and climate change mitigation and adaptation.

Recommendation 32: Develop a post-tree planting management and monitoring strategy to complement the tree maintenance program in order to ensure tree survivorship and mitigate common stressors in the urban environment.

It is recommended that management, monitoring, and maintenance begin directly after tree planting. Monitoring of municipal plantings should be undertaken for at least five years following planting (year 1, 3 and

5). Some stressors to mitigate include soil compaction, salt pollution, mechanical injuries, and drought related stress.

5.4.3 Climate Vulnerability and Resilience

Changes in climate conditions are expected to profoundly alter the environmental conditions across Southern Ontario, limiting the capacity of many tree species to cope as their optimal climatic ranges shift. A critical assessment of the climate vulnerability of Markham's most common species was conducted to understand the expected impacts on the City's forest, and ensure the adequate protection, planning, planting, and monitoring of trees across the municipality.

The results of the climate vulnerability assessment showed that of the twenty most abundant tree species in Markham, eleven of the species were rated as highly or extremely vulnerable to climate change, including the three of the top five species (eastern white cedar; European buckthorn; and eastern white pine, *Pinus strobus*). These eleven species make up 75 percent of the total population of trees across the Markham Forest. Only six of the top twenty species were assigned a low vulnerability score, two of which are not recommended for planting because they are invasive (Manitoba maple; and black locust, *Robinia pseudoacacia*). Three species were given a moderate vulnerability score.

The limited diversity of species is evidenced by the fact that the five most common species make up 59 percent of the population of trees across the municipality. The dominance of the population by a few species makes the forest more vulnerable to the impacts of climate change. The two most dominant species – eastern white cedar and European buckthorn – account for 34 percent and 9 percent of the tree population in Markham, respectively. Eastern white cedar represents the largest concern with respect to climate vulnerability, given that it is the most prevalent species across the city and represents a third of the tree population. The species is currently at the southern extent of its suitable climatic range, and as a result there is a risk the species will be extirpated from Markham. There is a strong need to monitor the population as the impacts of climate change worsen. Eastern white cedar is planted extensively by private landowners, particularly in hedgerows. Therefore, Markham should actively encourage private landowners to plant alternative species in place of eastern white cedar. Additionally, European buckthorn is the second most pervasive species in Markham, which is concerning given that it is highly invasive. However, climate change impacts could potentially help efforts to control this species because it is highly sensitive to drought. Nonetheless, effective European buckthorn removal and restoration programs are necessary to control the population across Markham (see Section 5.3.2). Effective control of the species will allow for natural regeneration of less vulnerable, native forest species found in the region such as sugar maple.

Another important factor for the vulnerability of Markham's forest to climate change is the size distribution of the dominant species. The populations of the top five most common species (with the exception of sugar maple) are primarily small, measuring less than 15.2 cm diameter. While overall, there are more trees in the second smallest size class (7.7 – 15.2 cm diameter class) in 2022 compared to 2012 (26 percent versus 32 percent, respectively) it is likely that climate change impacts will affect seedling establishment, particularly in natural areas as they continue to become more fragmented.

Trees that are already in poor condition are more vulnerable to the stressors of climate change. While the condition score for excellent, good, and fair trees in the forest is 79 percent, white and green ash (eighth and thirteenth most abundant) have the worst condition scores at 39 percent and 29 percent, respectively. This is within expected conditions for ash species due to the impacts of EAB. However, the other prevalent species that are highly and extremely vulnerable to climate change impacts will require greater maintenance and monitoring, given that they are likely to decline in condition and suffer higher mortality rates due to more extreme precipitation and flood events, and increased drought.

The resilience of Markham's forest to climate change can be improved through the adoption of the following recommendations, in conjunction with those of the York's Region Forest Management Plan, Markham's Greenprint Sustainability Plan, and Markham's Trees for Tomorrow Program. One of the objectives of the Markham Greenprint Sustainability Plan is to identify ecosystem integrity as a sustainability priority. The plan calls for future-oriented objectives aligned with this climate vulnerability assessment which include increasing biodiversity, increasing city wide canopy cover to 30 percent, and supporting habitat. Given that 60 percent of the population of trees across Markham are considered highly or extremely vulnerable to climate change, the future health and survival of the City's forest is at risk if proactive, adaptive management is not undertaken.

Recommendation 1: The City's Urban Forest Management Plan is a study to be undertaken starting in 2023 and should address: local canopy targets; species diversity; forest health, maintenance, and monitoring; invasive species management; soil conservation strategies; and climate change mitigation and adaptation.

Recommendation 33: Increase proactive, long-term monitoring of species identified as highly and extremely vulnerable to climate change to assess and evaluate the condition of the at-risk species as incremental climate change impacts advance.

Recommendation 34: Assess the City's current recommended planting list based on the climate vulnerability of each species. Shift recommendations to native and appropriate non-native, non-invasive species that have a higher tolerance and lower vulnerability to climate change impacts.

Recommendation 35: Educate and incentivize private landowners to plant a greater diversity of native, resilient species as part of the Markham Trees for Tomorrow Program, to increase the functional diversity of species planted in Markham. Encourage private landowners to plant alternatives to eastern white cedar, given its high vulnerability to climate change.

Recommendation 11: Utilize native planting and appropriate non-native, non-invasive stock in both intensively and extensively managed areas. Increase genetic diversity of tree populations by using the guidance provided by the Ontario Tree Seed Transfer Policy. The policy is intended to help managers source seed based on the projected changes in climate to increase the likelihood of producing trees well-adapted to current and future conditions.

Recommendation 36: Assisted range expansion and assisted migration should be further investigated. The City should undertake systematic testing of species from warmer ecodistricts that could be suitable to replace the eleven highly vulnerable and extremely vulnerable species that are at the greatest risk as a result of climate change.

5.5 Forestry and Asset Management

Asset management planning is intended to support the management of municipal assets over their entire life cycle to ensure sustainable service delivery, manage risks to an acceptable level, and keep costs to a minimum. In recognition of the essential role played by green infrastructure in municipal service provision, *Ontario Regulation 588/17 Asset Management Planning for Municipal Infrastructure* (*O.Reg.588/17*) directs municipalities to include green infrastructure assets in asset management plans by July 2024. The regulation defines green infrastructure as "an infrastructure asset consisting of natural or human-made elements that provide ecological and hydrological functions and processes and includes natural heritage features and systems, parklands, stormwater management systems, street trees, urban forests, natural channels, permeable surfaces and green roofs."[37] This presents an opportunity to prioritize green infrastructure assets in conjunction with traditional assets to support their long-term funding needs for development, maintenance, enhancement, and replacement.

The City of Markham Asset Management Plan (AMP) was revised in 2021, and incorporated certain green infrastructure assets, including:

- 270 Parks locations representing 19.69 hectares of parkland;
- 177,368 trees associated with parks with an Average Asset Life Cycle of 40 years, Average Remaining Useful Life of 20 years, and an estimated replacement value of $97.6M; and
- Stormwater management infrastructure including 57 wet ponds, 41 dry ponds, and 5 underground storage tanks.

Markham is currently planning to undertake a Natural Assets Inventory and Evaluation which will include the inventory of natural features within the Greenway System such as wetlands, woodlands, and riparian areas. The project will involve the identification, monetary valuation, age, and condition of natural assets. The Natural Assets Inventory and Evaluation will allow City staff to form a business case to operate, maintain and enhance natural assets alongside traditional capital assets.

Recommendation 37: Continue to integrate green infrastructure into asset management planning, particularly for other municipal natural assets like woodlands and wetlands that have not yet been incorporated.

[37] Definition sourced from *O.Reg.588/17* at https://www.ontario.ca/laws/regulation/r17588.

5.6 Progress Towards 2012 Recommendations

Number	Markham Forest Study (2012) Recommendations	2012-2021 Progress
State of the Forest: Existing and Possible Forest Distribution		
1	Refine the results of the urban tree canopy (UTC) analysis to develop an urban forest cover target.	• A 30 percent canopy target has been identified in the City's Strategic Plan. York Region has identified a canopy target of 20 – 35 percent in the York Region Forest Management Plan.
2	Build on the results of the urban tree canopy analysis (UTC) and the priority planting index to prioritize tree planting and establishment efforts to improve the distribution of ecosystem services, including urban heat island mitigation and stormwater management. Explore the development of criteria to guide the prioritization process.	• The 2012 Urban Forest Study is one input into the planning of reforestation and tree planting programs. Other considerations include the TRCA's Integrated Restoration Prioritization Tool and City of Markham's natural heritage inventories. • It is recommended that the City leverage and customize the York Tree Planting Prioritization Tool for the municipality.
3	Increase leaf area in canopied areas by planting suitable tree and shrub species under existing tree cover. Planting efforts should continue to be focused in areas of the municipality that currently support a high proportion of ash species.	• Understory plantings are considered lower priority in comparison to the establishment of new forests and wetlands. It is currently only considered an option where a dedicated community partner is available to steward and look after trees. One example is the Grandview Park Woodlot where some understory plantings have occurred, after invasive species were removed in the understory. • It is recommended that this continue to be a recommendation for implementation in the next 10-year period.
State of the Forest: Tree Species Effects		
4	Utilize the Pest Vulnerability Matrix during species selection for municipal tree and shrub planting.	• Not completed. The City currently follows the 10-20-30 approach to diversifying tree species for large planting projects.
5	Establish a diverse tree population in which no species represents more than five percent of the tree population, no genus represents more than 10 percent of the tree population, and no family	• Not completed. The City currently follows the 10-20-30 approach to diversifying tree species for large planting

Number	Markham Forest Study (2012) Recommendations	2012-2021 Progress
	represents more than 20 percent of the intensively managed tree population both municipal-wide and at the neighbourhood level.	projects, however species like eastern white cedar continue to be popular choices for homeowners.
6	In collaboration with the Toronto Region Conservation Authority consider the development of an invasive species strategy that will comprehensively address existing infestations as well as future threats posed by invasive insect pests, diseases, and exotic plants	• An invasive plant species strategy is being developed as part of the 2022 Natural Heritage Management Study.
7	Utilize native planting stock grown from locally adapted seed sources in both intensively and extensively managed areas.	• It is a City practice to source locally-grown, native plant stock for all reforestation and restoration projects in the natural heritage system. • Non-native (non-invasive trees) are used occasionally in manicured parklands and within boulevards.
State of the Forest: Tree Size Effects		
8	Evaluate and develop the strategic steps required to increase the proportion of large, mature trees in the urban forest. This can be achieved using a range of tools including Official Plan planning policy, by-law enforcement and public education. Where tree preservation cannot be achieved, Official Plan policy can be considered that will require compensation for the loss of mature trees and associated ecosystem services.	• Markham's Private Tree By-law protects all trees over 20 cm DBH. Preservation of large trees is reviewed for all development applications and tree replacement is provided where removal cannot be avoided.
9	Explore the application of 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.	• Subsurface soil cells will continue to be considered on a project-by-project basis, particularly in constrained spaces such as intensification areas.
Forest Function: Climate Change Mitigation		
10	Reduce energy consumption and associated carbon emissions by providing direction, assistance and incentives to residents and businesses for strategic tree planting and establishment around buildings.	• The City of Markham currently offers a backyard tree planting program through LEAF.
Forest Function: Heat Island Mitigation		

Number	Markham Forest Study (2012) Recommendations	2012-2021 Progress
11	Consider the application of a detailed thermal mapping analysis to identify the thermal "hot-spots" where tree planting efforts can be prioritized in the context of a range of biophysical and social considerations identified through the implementation of Recommendation 2.	• Not implemented.
12	Develop a Tree Protection Guidelines for tree protection zones and other protection measures to be undertaken for all publicly and privately owned trees.	• This has been implemented through the Trees for Tomorrow Streetscape Manual. Tree protection fencing standard has been prepared and is used across multiple departments.
Creating a Sustainable Forest: Stewardship and Education		
13	Research and pursue new partnerships and opportunities to enhance urban forest stewardship in the City of Markham	• The City has strong partnerships with non-profit tree planting groups such as Friends of the Rouge Watershed and 10,000 Trees for the Rouge. Both groups focus on reforestation projects in the natural heritage system. The City also offers a backyard tree planting program through LEAF.
14	Engage businesses in Markham in tree planting activities in commercial and industrial areas.	• Not implemented.
15	Explore the development and implementation of a municipal staff training program to enhance awareness of tree health and maintenance requirements generally, and of proper tree protection practices to be used during construction activities more specifically.	• Arborists are employed by the municipalities in both Community Services and Development Services Commissions to review and provide recommendations on tree planting and protection practices.
16	Establish an interagency Urban Forest Working Group to liaise with existing stakeholders and build new partnerships.	• Not implemented.
Creating a Sustainable Forest: Urban Landscape Ecology		
17	Explore the development of targets for ecosystem services; integrate such targets into the Greenway System.	• Not implemented.
Creating a Sustainable Forest: Adaptive Forest Management		
18	Monitor the distribution, structure and function of the urban forest using the methods employed in this baseline study. A potential monitoring scenario may consist of a cover mapping assessment	• York Region and the TRCA have led this ten-year update to the field-based assessment of the Markham Forest.

Number	Markham Forest Study (2012) Recommendations	2012-2021 Progress
	(UTC) at a five-year interval and a field-based assessment (i-Tree Eco) at a ten-year interval.	• It is recommended that future updates review the land cover classifications – particularly as it relates to natural heritage lands as the current MPAC classification splits natural heritage lands across two different land classes.
19	Pursue research partnerships to study the impacts of climate change on the urban forest, and to evaluate the potential for planting more hardy and southern species in select locations.	• Not implemented.
Forest Management Plan		
20	Develop and implement an urban forest management plan for the City of Markham.	• Not implemented. Recommended in the 2022 study.
21	Utilize the criteria and performance indicators developed by Kenney et al. (2011) to inform the creation of a strategic urban forest management plan and to assess the progress made towards urban forest sustainability.	• Not implemented.

6.0 SUMMARY OF RECOMMENDATIONS

Recommendation 1: The City's Urban Forest Management Plan is a study to be undertaken starting in 2023 and should address: local canopy targets; species diversity; forest health, maintenance, and monitoring; invasive species management; soil conservation strategies; and climate change mitigation and adaptation.

Recommendation 2: The next Official Plan update should include a commitment to at least 30 percent canopy cover target to align with the Markham Greenprint Sustainability Plan. However, it is recommended to aim for a more ambitious target of 35 percent. Additionally, the development of a woodland cover target should be further explored as a component of an overall canopy target by assessing the feasible restoration potential in the Greenway System.

Recommendation 3: Develop canopy cover targets for all land use types within the Official Plan.

Recommendation 4: Work with York Region to customize and utilize the Region's tree planting prioritization tool for Markham to improve equitable canopy cover distribution, the maximization of ecological benefits and ecosystem services, and target areas impacted by invasive pests.

Recommendation 5: Develop mechanisms to encourage and support private landowners (particularly commercial and industrial landowners, and property developers) to protect and enhance canopy and educate those landowners about maintenance best practices.

Recommendation 6: Continue to plant, prune and replace trees on municipal roads, parks and other municipal properties. Evaluate planting and maintenance budgets regularly as the City grows and assumes responsibility for new roads, parks and facilities.

Recommendation 7: Continue to carry out restoration plantings in the natural heritage system and other naturalized areas.

Recommendation 8: In line with current practices, continue to establish a diverse tree population in intensively managed urban areas, 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 intensively managed tree population both municipal-wide and at the neighbourhood level.

Recommendation 9: Investigate the utility and potential application of pest vulnerability tools, such as the Pest Vulnerability Matrix (PVM)[38] during species selection for municipal tree and shrub planting.

Recommendation 10: Consider the development of an education campaign focused on educating private landowners about the importance of species diversity for a resilient forest, particularly in the context of climate change.

Recommendation 11: Utilize native and appropriate non-native, non-invasive planting stock in both intensively and extensively managed areas. Increase genetic diversity of tree populations by using the guidance provided by the Ontario Tree Seed Transfer Policy. The policy is intended to help managers source seed based on the projected changes in climate to increase the likelihood of producing trees well-adapted to current and future conditions.

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[38] For detailed methodology, please see Laçan and McBride (2008). The PVM tool can be obtained by contacting the author. Additionally, see research conducted by Vander Vecht, & Conway (2015) which applied the PVM to explore pest vulnerability of the species in Toronto's urban forest.

Recommendation 12: Evaluate and develop the strategic steps required to increase the number and proportion of large, mature trees across Markham's forest including the City's Greenway System, street and park trees and trees on private lands.

Recommendation 13: Review and enhance tree preservation requirements in municipal guidelines (Trees for Tomorrow Streetscape Manual) and regulations for sustainable streetscape and subdivision design standards (and particularly soil volume) to support tree establishment and eliminate conflict between natural and grey infrastructure.

Recommendation 14: Where appropriate, select and plant long lived, low maintenance, and low volatile organic compound (VOC) emitting tree species.

Recommendation 15: Bolster evergreen tree population across the municipality to improve year-round pollution removal services.

Recommendation 16: Engage in strategic tree planting in high emissions zones.

Recommendation 17: Consider developing an education campaign within the City's Trees for Tomorrow Program focused on educating the public about the ecosystem benefits Markham's forest provides.

Recommendation 18: Continue to apply subsurface (Silva) cells on a project-by-project basis and other enhanced rooting environment techniques for street trees, particularly in constrained spaces such as intensification areas.

Recommendation 19: Explore the opportunity to utilize the Sustainable Technology Evaluation Program Treatment Train Tool to evaluate and quantity the stormwater benefits of planting trees.

Recommendation 20: Following the City of Markham's Official Plan recommendation to encourage tree planting to reduce the urban heat island effect (Section 6.2.3.1. c), consider including the potential of trees to provide energy savings when developing planting guidelines or standards. Consider the use of Letters of Credit or other tools to ensure tree establishment and success in the implementation of the Sustainability Metrics as a green development standard in Markham.

Recommendation 21: Consider including species' capacity for carbon storage and sequestration when developing planting lists or guidelines and future Urban Forest Management Plans.

Recommendation 22: Ensure best practices for healthy soils, are implemented in Markham's public and private urban areas in the planning of planting programs, from site selection and assessment to species selection. Reference tools and programs such as the Sustainability Metrics and Trees for Tomorrow Standards relating to soil health.

Recommendation 23: Manage compaction, salinity, and pH on public property through amendments and remedial measures like mulching and planting of herbaceous cover and shrubs.

Recommendation 24: Educate private homeowners and industrial and commercial landowners about soil best practices.

Recommendation 25: Promote the implementation of natural buffers and fencing along the edges of urban woodlots to protect against the encroachment of invasive species.

Recommendation 26: Continue targeted removal of high priority invasive plant species at high priority sites following best practices.

Recommendation 27: Explore the development and implementation of a municipal-led invasive plant, pest, and disease education and volunteer program to enhance awareness of invasive plants, pests, and pathogens and proper removal practices.

Recommendation 28: Develop a monitoring and action strategy for invasive species, including pests and diseases, and continue taking proactive approaches to address new and emerging invasive species, such as hemlock woolly adelgid and oak wilt.

Recommendation 29: Reassess tree care and maintenance practices for trees in highly urbanized areas. Indicators associated with street tree mortality should be considered, including plant hardiness and tolerances to harsher urban conditions, tree pit enhancements, direct tree care/stewardship, and assessing local traffic and building conditions.

Recommendation 30: Monitor stand level dynamics and patterns to select species, specifically sugar maple, targeting Carolinian forest stands across Markham.

Recommendation 31: Continue assessing forest structure, function, and distribution every 10 years through the Forest Studies.

Recommendation 32: Develop a post-tree planting management and monitoring strategy to complement the tree maintenance program in order to ensure tree survivorship and mitigate common stressors in the urban environment.

Recommendation 33: Increase proactive, long-term monitoring of species identified as highly and extremely vulnerable to climate change to assess and evaluate the condition of the at-risk species as incremental climate change impacts advance.

Recommendation 34: Assess the City's current recommended planting list based on the climate vulnerability of each species. Shift recommendations to native and appropriate non-native, non-invasive species that have a higher tolerance and lower vulnerability to climate change impacts.

Recommendation 35: Educate and incentivize private landowners to plant a greater diversity of native, resilient species as part of the Markham Trees for Tomorrow Program, to increase the functional diversity of species planted in Markham. Encourage private landowners to plant alternatives to eastern white cedar, given its high vulnerability to climate change.

Recommendation 36: Assisted range expansion and assisted migration should be further investigated. The City should undertake systematic testing of species from warmer ecodistricts that could be suitable to replace the eleven highly vulnerable and extremely vulnerable species that are at the greatest risk as a result of climate change.

Recommendation 37: Continue to integrate green infrastructure into asset management planning, particularly for other municipal natural assets like woodlands and wetlands that have not yet been incorporated.

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APPENDIX A: MPAC LAND USE CATEGORIES

Table 29: Description of Land Use Classes (specific MPAC codes for each class are listed in Appendix B)

	Generalized Land Use Class	MPAC Land Uses within each Generalized Class
1	Open space	Municipal park, golf courses, cemeteries, ski resorts, campgrounds, large land holdings. Open space was combined with the natural cover land use class for this report.
2	Residential Low	Single family detached houses, semi-detached houses, residence with a commercial unit, residence with commercial/industrial use building, linked homes, community lifestyle homes, townhouse/row houses, clergy residences, house-keeping cottages, group homes, student housing, bed & breakfasts. The residential low land use category was combined with the residential medium/high land use stratum.
3	Residential Medium / High	Townhouse blocks, row housing (3 – more) under single ownership, residential property with four self-contained units, rooming or board houses; bachelorettes, cooperative housing, multi-residential (7 or more), condominium units. Residential medium/high was combined with the residential land low use class.
4	Commercial	Office buildings, retail, Beer Stores or LCBOs, restaurants, cinemas, concert halls, entertainment complexes, automotive service centres, fuel stations, automotive shops/dealers, shopping centres, department stores, banks and financial institutions, supermarkets, hotels, motels, lodges, inns, resorts, commercial condominiums, parking lots or garages, funeral homes, bowling alleys, casinos, crematoriums, vacant commercial lands The commercial land use category was combined with industrial land use.
5	Utilities & Transportation	Communication buildings, hydraulic, fossil or nuclear generating stations, transformer stations, Hydro Right of Ways, wind turbines, airports, public transportation-easements and rights, bridges/tunnels, pipelines, compressor stations, railway right of ways, railway buildings and lands, rail stations/yards, airport leasehold or hangers, subway stations, transit garages, public transportation, lighthouses, wharves and harbours, canals and locks, navigational facilities, historic site/monuments, communication. Utilities & transportation lands were combined with rights-of-way for this assessment.
6	Industrial	Mines, mine tailings, oil/gas wells, sawmill/lumber mills, forest products, heavy manufacturing, pulp and paper mills, cement/asphalt manufacturing, steel mills, automotive assembly or parts plant, shipyards, steel production, smelters, foundries, distilleries/breweries, grain elevators and handling, process elevators, slaughterhouses, food processing plants, freezer plants, warehouses, dry cleaning, R&D facilities, other industrial, printing plants, truck terminals, major distribution centres, petro-chemical plants, oil refineries, tank farms, bulk oi,/fuel distribution terminals, gravel pits, quarries, sand pits, peat moss operations, heat or steam plants, sewerage treatments, water treatments, recycling plants, power dams, vacant industrial lands.

		The industrial land use category was combined with the commercial land use category.
7	Institutional	Post-secondary educational, educational residence, school, day care, other education, institutional residence, hospital, senior care facility/retirement/nursing/old age homes, other heath care facilities, penitentiary or correctional facilities, places of worship, museums or art galleries, libraries, conference centres, banquet or assembly halls, clubs, research facilities, military properties, post offices/depots, fire halls, ambulance stations, police stations. The institutional land use category was combined with the other land use category for this assessment.
8	Agricultural	Farms with or without buildings, farms with or without residence, wineries, grain/seed and feed operations, tobacco farms, ginseng farms, exotic farms, nut orchards, farms with gravel pit, farms with campground, intensive farm operations, large scale greenhouses, large scale swine or poultry operations, agricultural research facilities, farms with oil/gas, portion being farmed
9	Natural Cover	Managed forest properties, provincial or federal parks, lands designated/zoned for open space, conservation authority lands. Natural cover was combined with the open space land use class for this report.
10	Other	Water, marina, billboard, island, time-share, seasonal/recreational dwelling, mining lands, non-buildable land walkways, buffer/berm, stormwater management pond, vacant residential land, vacant lot, residential dockominium, boathouse, vacant recreational, common land, co-ownership, life lease, racetrack, exhibition/fair grounds, sports complex, amusement park, sport club, golf centre/driving range, condominium development land, property in process of redevelopment, residential development land, cooperative housing, vacant land condominium, condominium parking space/locker unit. The other land use category was combined with the institutional land use category for this assessment.
11	Right-of-way	Right of ways including smaller roads and adjacent ROW. Added to land use layer by UVM by filling in the gaps between parcel boundaries. Right-of-ways were included in the utilities-transportation stratum for this report.

APPENDIX B: PARAMETERS USED FOR I-TREE FORECAST

Table 30: General simulation parameters used for i-Tree Forecast

Parameter	Value	Comments
Simulation period	• 2021 – 2050 (30 years)	
Length of frost-free season	• 178 days	Average of current frost-free season and projected frost-free season according to Historical and Future Climate Trends in York Region
Base annual tree mortality rate for healthy trees (dieback < 50 %)	• 1.6%	The base annual mortality rate for health trees was set at 4.0 % by i-Tree Eco. However, the York Region Green Infrastructure Asset Management Plan listed an annual mortality rate of 1.3% for rural trees, 1.6% for suburban trees, and 2% for urban trees. Given that Markham contain a mix of land uses, the average value was used for healthy trees.
Base annual tree mortality rate for sick trees (dieback 50-75 %)	• 13.1% (default)	Default values were used as no locally applicable data on the impact of health on annual mortality.
Base annual tree mortality rate for dying trees (>76 % dieback)	• 50% (default)	
Base annual tree mortality rate for dead trees (100% die back)	• 100% (default)	

Table 31: Simulation parameters for pests

Insect	Start of outbreak and duration	Annual mortality rate from outbreak[39]	Plant host trees during event (i.e. plant trees affected by pest/disease)?	Notes
EAB	2021, 3 years	Default value: 3.3 %[40]	No	Mortality rates in Michigan at the peak of the outbreak were as high as 100% (Klooster et al., 2014). However, since we are passed the peak in Ontario the lower value recommended by i-Tree Eco will be used. EAB is nearing past its peak and phasing out in Ontario according to TRCA staff.
LDD	2021, 3 years	4.4%	No	Mortality rate depends on the crown condition prior to defoliation, the extent of defoliation, and the number of years defoliation was seen (Davidson et al., 1999). Davidson et al. (1999) found that mortality rates within 5 years could be as high as 50% following two consecutive severe defoliations of a tree with fair crown condition and as low as 7% for a single year of defoliation in a tree with good crown condition. The default value of 10% annual mortality rate is consistent with assuming two severe defoliations of a tree with fair or poor crown condition. A more conservative estimate would be to assume 2 years of defoliation of a tree in good crown condition. Davidson et al. (1999) found a mortality rate of 22 % over 5 years, translating to an annual mortality rate of 4.4%. The default value provided by i-Tree Eco is 10.0 %.
Beech Bark Disease (BBD)	2021, 10 years	2.35 % (Default is 4.7%)	No	According to Reed et al. (2021) BBD has been in Ontario since the 2000s and is moving eastwards and northwards. Mortality also occurs within a long time frame of five to ten years. So it is anticipated that it will be here for still many years. Their study of plots around Lake Erie indicated that 4% of Beech trees were affected. Mortality rate for trees with a high density of scale was 50% within 10 years. That translates to 0.5 % per year. Therefore, the annual mortality rate was reduced from the default mortality rate of 4.7% to 2.35 % (0.5 x 4.7). The default value provided by i-Tree Eco is 4.7%.

[39] Mortality rates only apply to species affected by pest.

[40] Default morality rates are based on a synthesis of literature by the i-Tree Eco team.

Markham Tree Planting Parameters

Planting programs

Development Services Commission: From 2022 to 2026, Markham anticipates planting between 4,000 to 8,000 trees (65% of 8,000) shrubs (35% of 8,000) in the Natural Heritage System. The vast majority will be potted container stock with small amounts of bare root, seedlings, and 40 mm caliper sized stock. Assume 1,000 of the 5,200 trees will be 40 mm caliper sized trees

Trees for Tomorrow Program: An additional 7,000 trees (65% of 7,000) and shrubs (35% of 7,000) (1-3 gallon container stock and some bare root), along with 1,000 to 1,500 45-60 mm caliper trees for the next five year period are also likely to be planted.

The above was used to extrapolate planting parameters per land use stratum.

Table 32: Tree planting simulation parameters for current annual rate of planting in Markham

Stratum/Strata	Annual Planting Rate	DBH at planting	Start	Duration (years)	Comments
Open Space - Natural Cover	1,000 / year	4 cm	2021	30	Development Services Commission planting efforts in the NHS
Open Space - Natural Cover	8,750	1 cm	2021	30	Development Services Commission planting efforts in the NHS
Other - Institutional; Open Space - Natural Cover	4,550	1 cm	2021	30	Trees for Tomorrow Program. Annual planting rate is split evenly between the Open Space – Natural Cover and Other – Institutional strata
Open Space - Natural Cover; Utilities - Transportation	1,250	5 cm	2021	30	Trees for Tomorrow Program. One quarter of the annual planting rate is allocated to the Open Space – Natural Cover strata and three quarters to the Utilities – Transportation strata

APPENDIX C: LAND COVER AND CANOPY COVER METRICS

Table 33. Canopy cover metrics by MPAC Land uses

General Land Use	Land Area ha	Existing Canopy	Possible Vegetated	Possible Impervious	Canopy - Possible Area	Unsuitable	Existing Canopy	Possible Vegetated	Possible Impervious	Canopy - Possible Percent	Canopy Cover as a Percent of Total CC
	ha	ha	ha	ha	ha	ha	%	%	%	%	%
Agriculture	6571.59	914.98	5610.33	24.49	5634.83	21.78	13.9%	85.4%	0.4%	85.7%	21.1%
Commercial	875.86	109.76	256.30	340.13	596.43	169.67	12.5%	29.3%	38.8%	68.1%	2.5%
Industrial	1057.50	77.65	300.58	385.67	686.25	293.61	7.3%	28.4%	36.5%	64.9%	1.8%
Institutional	517.76	100.26	285.20	68.32	353.51	63.98	19.4%	55.1%	13.2%	68.3%	2.3%
Natural Cover	837.07	410.53	421.55	2.69	424.24	2.30	49.0%	50.4%	0.3%	50.7%	9.5%
Open Space	1361.39	432.13	885.68	36.56	922.24	7.02	31.7%	65.1%	2.7%	67.7%	9.9%
Other	1375.10	468.73	743.55	118.26	861.82	44.55	34.1%	54.1%	8.6%	62.7%	10.8%
Residential Low	4600.93	1171.04	1847.34	259.12	2106.46	1323.43	25.5%	40.2%	5.6%	45.8%	26.9%
Residential Medium / High	190.44	43.37	53.35	28.14	81.49	65.57	22.8%	28.0%	14.8%	42.8%	1.0%
ROW	3302.16	548.32	1623.60	274.59	1898.18	855.66	16.6%	49.2%	8.3%	57.5%	12.6%
Utilities & Transportation	410.46	69.07	198.30	62.23	260.53	80.86	16.8%	48.3%	15.2%	63.5%	1.6%
Markham	21100.26	4345.86	12225.77	1600.20	13825.97	2928.43	20.6%	57.9%	7.6%	65.5%	100.0%

APPENDIX D: FOREST COMPOSITION AND STRUCTURE

Table 34. Markham Composition and Structure by Species

Species	Common Name	Trees		Leaf Area		Leaf Biomass		Tree Dry Weight Biomass		Average Condition
		Number	SE	ha	SE	metric ton	SE	(metric ton)	SE	(%)
Thuja occidentalis	Eastern white cedar	1095457	±305,662	2,716.496	±964.130	5,224.031	±1,854.096	95,074.319	±29,929.514	85.18
Rhamnus cathartica	European buckthorn	306639	±103,140	473.627	±172.101	210.501	±76.490	10,729.564	±4,589.063	70.17
Acer saccharum	Sugar maple	215623	±79,783	5,579.942	±2,403.444	3,361.613	±1,447.945	126,615.752	±59,063.026	89.81
Acer negundo	Manitoba Maple	209446	±154,223	573.704	±278.386	524.841	±254.676	5,341.229	±2,530.009	90.88
Pinus strobus	Eastern white pine	90157	±71,447	628.211	±361.079	404.02	±232.220	10,039.795	±5,506.217	93.35
Tsuga canadensis	Eastern hemlock	88438	±61,138	1,387.703	±996.295	1,288.968	±925.408	19,350.010	±13,702.626	77.96
Acer platanoides	Norway maple	88369	±21,189	2,506.604	±698.408	1,352.946	±376.967	63,186.954	±20,206.921	91.94
Fraxinus americana	White ash	81281	±43,902	98.247	±80.815	55.825	±45.920	2,865.548	±1,182.781	39.34
Tilia americana	American basswood	79979	±36,833	538.682	±244.497	157.27	±71.382	5,133.357	±2,463.664	89.27
Picea glauca	White spruce	56706	±17,875	516.032	±268.361	828.967	±431.101	7,654.067	±3,559.625	96.73
Robinia pseudoacacia	Black locust	56464	±44,672	370.558	±361.269	199.503	±194.502	7,840.908	±7,796.063	74.31
Ostrya virginiana	Eastern hophornbeam	51182	±47,833	503.452	±454.259	328.667	±296.552	5,280.808	±4,828.060	76.23
Fraxinus pennsylvanica	Green ash	45831	±32,403	12.289	±11.813	8.016	±7.705	7,234.762	±7,159.969	28.67
Ulmus americana	American elm	45782	±19,306	243.408	±146.063	177.037	±106.235	3,502.637	±1,678.645	60.48
Acer tataricum ssp. ginnala	Amur maple	43823	±33,645	64.609	±54.355	36.365	±30.593	1,289.078	±1,063.797	95.79
Populus tremuloides	Quaking aspen	42282	±32,191	97.333	±61.167	76.646	±48.167	5,147.244	±4,822.011	46.43
Juglans nigra	Black walnut	37512	±22,483	296.185	±183.182	237.385	±146.816	4,040.006	±2,977.838	61.21
Gleditsia triacanthos	Honeylocust	35716	±13,901	569.4	±215.469	596.293	±225.645	6,995.349	±2,983.704	88.02
Picea abies	Norway spruce	33720	±22,878	1,658.580	±965.297	2,764.301	±1,608.828	20,985.864	±12,589.327	96.17
Picea pungens	Blue spruce	32870	±18,918	553.626	±365.052	921.788	±607.812	10,657.109	±6,713.873	83.61
Crataegus punctata	Dotted hawthorn	31415	±19,373	71.662	±59.680	53.983	±44.957	2,691.790	±1,819.487	55.89
Tilia cordata	Littleleaf linden	30565	±11,130	1,001.153	±493.493	749.984	±369.686	13,974.128	±6,895.310	88.27
Betula alleghaniensis	Yellow birch	28952	±21,266	353.63	±305.258	146.43	±126.401	17,648.260	±12,791.960	56.66
Taxus baccata	English yew	28100	±14,984	73.835	±51.348	90.141	±62.688	1,600.226	±1,000.040	87.4
Fraxinus nigra	Black ash	27723	±27,719	0	±0.000	0	±0.000	2,275.865	±2,275.537	0
Quercus robur	English oak	26924	±13,306	225.271	±137.425	149.991	±91.501	10,135.265	±6,804.945	81.83
Fagus grandifolia	American beech	23592	±23,587	30.688	±30.681	13.077	±13.074	595.169	±595.042	81
Pinus sylvestris	Scots pine	17721	±9,496	224.692	±176.601	216.571	±170.218	6,026.951	±3,498.393	57.89
Pyrus calleryana	Callery pear	17720	±9,610	144.966	±93.496	109.063	±70.340	2,565.641	±1,629.176	91.71
Pinus resinosa	Red pine	17688	±17,684	131.021	±130.995	192.678	±192.640	6,487.816	±6,486.532	92.79

Quercus rubra	Northern red oak	14606	±7,458	195.369	±122.459	155.672	±97.577	3,094.293	±2,005.155	85.12
Acer palmatum	Japanese maple	14050	±5,996	24.372	±12.268	13.717	±6.905	557.903	±275.831	98.5
Juniperus virginiana	Eastern red cedar	14050	±8,260	27.743	±23.423	77.084	±65.081	1,023.220	±710.927	65.5
Frangula alnus	Glossy buckthorn	13862	±13,860	2.515	±2.515	1.118	±1.118	42.787	±42.780	54.88
Morus alba	White mulberry	13599	±7,153	32.074	±17.342	23.463	±12.687	322.888	±192.345	99.5
Pinus nigra	Austrian pine	12923	±6,661	584.957	±330.630	563.814	±318.679	9,509.184	±5,361.654	91.32
Syringa reticulata	Japanese tree lilac	11240	±8,825	39.473	±29.530	38.079	±28.488	1,632.892	±1,203.348	91
Catalpa speciosa	Northern catalpa	10789	±6,658	155.145	±148.819	94.457	±90.605	2,905.944	±2,787.405	95.59
Amelanchier arborea	Downy serviceberry	10312	±6,268	3.572	±2.305	2.178	±1.405	130.674	±87.762	74.05
Larix decidua	European larch	8430	±8,428	186.747	±186.714	120.747	±120.726	2,318.107	±2,317.695	94.5
Prunus avium	Sweet cherry	8430	±4,757	23.523	±17.494	18.201	±13.536	1,454.465	±1,368.546	93.83
Syringa vulgaris	Common lilac	8430	±4,757	9.932	±5.654	9.581	±5.454	240.511	±146.876	92.17
Quercus macrocarpa	Bur oak	8184	±5,853	45.799	±43.495	45.003	±42.738	592.793	±565.160	91.04
Crataegus	hawthorn spp	7821	±5,809	19.174	±19.171	6.897	±6.896	1,437.517	±1,195.668	64.12
Carya cordiformis	Bitternut hickory	6931	±6,930	191.351	±191.323	120.286	±120.269	1,850.434	±1,850.167	99.5
Magnoliopsida	Hardwood	6931	±6,930	5.175	±5.175	3.903	±3.903	130.004	±129.986	99.5
Platanus occidentalis	American sycamore	6931	±6,930	2.061	±2.061	0.998	±0.998	12.413	±12.411	60
Salix alba	White willow	6931	±6,930	92.783	±92.770	58.776	±58.767	931.55	±931.416	81
Populus balsamifera	Balsam poplar	6116	±4,362	35.122	±31.355	25.343	±22.624	181.201	±128.566	83.46
Betula populifolia	Gray birch	5620	±5,619	31.613	±31.608	18.776	±18.773	278.93	±278.880	94.5
Caragana arborescens	Siberian pea tree	5620	±5,619	22.523	±22.519	19.086	±19.082	611.556	±611.447	99.5
Acer rubrum	Red maple	5302	±5,301	17.234	±17.231	11.607	±11.605	256.365	±256.317	88.5
Prunus serotina	Black cherry	5302	±5,301	4.403	±4.402	3.415	±3.414	162.839	±162.808	41.25
Malus pumila	Paradise apple	5236	±3,702	2.665	±2.664	2.297	±2.297	683.778	±587.180	49.12
Acer saccharinum	Silver maple	5169	±3,668	156.35	±112.819	82.294	±59.382	1,838.108	±1,465.185	99.5
Gymnocladus dioica	Kentucky Coffee tree	5169	±3,668	18.077	±13.861	15.319	±11.745	197.657	±154.711	99.5
Pyrus communis	Common pear	5169	±3,668	16.405	±12.475	12.342	±9.385	677.187	±555.479	94.5
Alnus glutinosa	European alder	3465	±3,465	1.049	±1.048	0.764	±0.764	4.083	±4.082	82.5
Carpinus caroliniana	American hornbeam	3465	±3,465	22.655	±22.651	13.648	±13.646	163.931	±163.907	82.5
Fagus sylvatica	European beech	3465	±3,465	10.486	±10.485	5.248	±5.247	108.281	±108.266	99.5
Liriodendron tulipifera	Tulip tree	3465	±3,465	1.79	±1.790	1.055	±1.055	6.728	±6.727	99.5
Salix x bebbii	Bebb's hybrid willow	3465	±3,465	0	±0.000	0	±0.000	22.951	±22.948	0
Acer x freemanii	Freeman maple	2810	±2,809	3.187	±3.187	1.794	±1.794	228.607	±228.567	82.5
Betula papyrifera	Paper birch	2810	±2,809	103.715	±103.697	72.533	±72.520	1,387.884	±1,387.637	94.5
Cornus kousa	Kousa dogwood	2810	±2,809	5.549	±5.548	3.409	±3.408	287.061	±287.010	99.5
Euonymus europaeus	European spindletree	2810	±2,809	4.346	±4.345	3.238	±3.237	129.774	±129.751	99.5
Fraxinus	ash spp	2810	±2,809	0	±0.000	0	±0.000	7,822.215	±7,820.823	0
Larix laricina	Tamarack	2810	±2,809	41.466	±41.459	26.811	±26.806	498.94	±498.852	82.5

Lonicera	honeysuckle spp	2810	±2,809	6.402	±6.401	3.154	±3.153	104.19	±104.171	99.5
Prunus armeniaca	Apricot	2810	±2,809	72.566	±72.553	56.148	±56.138	1,943.151	±1,942.805	94.5
Prunus nigra	Canada plum	2810	±2,809	3.355	±3.354	2.596	±2.595	352.324	±352.262	94.5
Malus baccata	Siberian crabapple	2810	±2,809	11.84	±11.837	10.207	±10.206	265.356	±265.309	82.5
Rhus typhina	Staghorn sumac	2810	±2,809	1.247	±1.247	1.108	±1.108	2.028	±2.027	99.5
Crataegus mollis	Downy hawthorn	2651	±2,650	4.05	±4.049	3.051	±3.050	771.592	±771.447	37.5
Acer	maple spp	2359	±2,359	0.874	±0.874	0.492	±0.492	9.162	±9.160	99.5
Buxus	boxwood spp	2359	±2,359	0.819	±0.819	1.463	±1.463	5.031	±5.030	99.5
Cotinus coggygria	Smoke tree	2359	±2,359	5.115	±5.114	4.994	±4.993	64.519	±64.505	99.5
Juniperus chinensis	Chinese juniper	2359	±2,359	2.919	±2.919	8.111	±8.109	278	±277.941	99.5
Picea	spruce spp	2359	±2,359	0.825	±0.825	1.374	±1.374	49.832	±49.822	99.5
Picea mariana	Black spruce	2359	±2,359	0.99	±0.990	1.868	±1.868	52.214	±52.203	82.5
Salix fragilis	Crack willow	2359	±2,359	5.274	±5.273	3.341	±3.340	23.855	±23.850	99.5
Ulmus pumila	Siberian elm	2359	±2,359	4.633	±4.632	3.156	±3.155	20.347	±20.343	99.5
Ulmus rubra	Slippery elm	2359	±2,359	2.642	±2.642	1.183	±1.183	34.036	±34.029	94.5
Zelkova serrata	Japanese zelkova	2359	±2,359	2.711	±2.711	1.756	±1.755	19.216	±19.212	94.5
Markham		**3295310**	**±496,829**	23,912.265	±4,072.578	22,253.854	±3,933.244	530,695.981	±93,802.326	80.5

Table 35. Markham Composition and Structure by Stratum

Stratum	Species	Trees		Leaf Area		Leaf Biomass		Tree Dry Weight Biomass		Average Condition
		Number	SE	(ha)	SE	(metric ton)	SE	(metric ton)	SE	(%)
Agriculture	hawthorn spp	5170	±5,169	19.17	±19.171	6.90	±6.896	273.26	±273.209	97.00
	Dotted hawthorn	15510	±15,507	58.61	±58.599	44.15	±44.142	1,249.529	±1,249.287	85.17
	White ash	5170	±5,169	0.00	±0.000	0.00	±0.000	316.67	±316.605	0.00
	Paradise apple	2585	±2,584	2.67	±2.664	2.30	±2.297	106.16	±106.141	99.50
	Austrian pine	2585	±2,584	22.90	±22.894	22.07	±22.067	431.46	±431.377	82.50
	Scots pine	5170	±5,169	170.50	±170.465	164.34	±164.303	2,424.009	±2,423.540	99.50
	European buckthorn	31020	±28,505	107.06	±106.507	47.58	±47.337	3,767.908	±3,762.240	88.00
	Eastern white cedar	10340	±10,338	107.72	±107.701	207.16	±207.118	3,024.127	±3,023.542	94.50
	Total	**77549**	**±65,063**	**488.63**	**±347.537**	**494.49**	**±355.234**	**11,593.124**	**±9,039.766**	**84.00**
Commercial - Industrial	Amur maple	12634	±12,631	11.47	±11.467	6.46	±6.454	256.51	±256.456	92.10
	Norway maple	5054	±5,053	151.11	±151.075	81.56	±81.543	1,975.586	±1,975.195	88.50
	Sugar maple	22741	±22,737	771.56	±771.405	464.82	±464.730	32,854.528	±32,848.027	94.06
	Honeylocust	2527	±2,526	142.57	±142.537	149.30	±149.269	2,230.481	±2,230.040	94.50
	White spruce	7580	±5,522	45.98	±36.424	73.87	±58.513	1,454.265	±1,268.349	96.17
	Blue spruce	7580	±7,579	135.64	±135.609	225.84	±225.790	3,154.409	±3,153.785	82.50
	Red pine	17688	±17,684	131.02	±130.995	192.68	±192.640	6,487.816	±6,486.532	92.79
	English oak	5054	±5,053	58.65	±58.638	39.05	±39.042	2,153.131	±2,152.705	50.00
	European buckthorn	63170	±60,543	90.00	±87.772	40.00	±39.010	1,107.367	±1,087.335	69.98
	American elm	12634	±12,631	14.58	±14.581	10.61	±10.605	225.91	±225.861	51.90
	Total	**156661**	**±117,737**	**1,552.568**	**±1,057.427**	**1,284.172**	**±825.829**	**51,899.997**	**±41,766.640**	**78.60**
Open Space - Natural Cover	Boxelder	26509	±19,816	271.85	±198.783	248.70	±181.853	2,621.328	±1,958.645	93.80
	Red maple	5302	±5,301	17.23	±17.231	11.61	±11.605	256.37	±256.317	88.50
	Sugar maple	60971	±29,227	1,630.660	±1,110.381	982.38	±668.944	28,037.996	±23,849.043	92.15

	Downy serviceberry	7953	±5,807	1.58	±1.160	0.96	±0.707	62.24	±54.967	66.50
	Yellow birch	18556	±18,553	300.69	±300.634	124.51	±124.486	6,829.756	±6,828.467	73.00
	hawthorn spp	2651	±2,650	0.00	±0.000	0.00	±0.000	1,164.255	±1,164.035	0.00
	Downy hawthorn	2651	±2,650	4.05	±4.049	3.05	±3.050	771.59	±771.447	37.50
	Dotted hawthorn	15905	±11,613	13.05	±11.305	9.83	±8.516	1,442.261	±1,322.806	27.33
	White ash	39763	±34,598	79.76	±79.743	45.32	±45.311	1,067.120	±799.498	52.07
	Green ash	29160	±29,154	0.00	±0.000	0.00	±0.000	7,160.985	±7,159.634	0.00
	Honeylocust	10604	±10,602	64.16	±64.147	67.19	±67.176	393.82	±393.744	91.50
	Black walnut	13254	±8,506	213.23	±164.208	170.90	±131.609	1,269.312	±1,102.013	96.50
	Paradise apple	2651	±2,650	0.00	±0.000	0.00	±0.000	577.62	±577.507	0.00
	Eastern hophornbeam	47716	±47,707	451.35	±451.261	294.65	±294.596	4,805.522	±4,804.615	77.22
	White spruce	2651	±2,650	222.41	±222.371	357.29	±357.222	2,642.350	±2,641.852	99.50
	Eastern white pine	82178	±71,300	359.47	±247.607	231.18	±159.243	7,304.482	±4,809.472	92.92
	Balsam poplar	2651	±2,650	4.02	±4.021	2.90	±2.901	82.93	±82.917	62.50
	Quaking aspen	37113	±31,981	80.80	±59.563	63.63	±46.904	4,959.125	±4,819.045	39.04
	Black cherry	5302	±5,301	4.40	±4.402	3.42	±3.414	162.84	±162.808	41.25
	English oak	2651	±2,650	0.73	±0.729	0.49	±0.485	36.05	±36.041	99.50
	European buckthorn	84829	±56,789	110.08	±62.508	48.93	±27.781	2,720.756	±1,769.426	66.72
	Black locust	42414	±42,406	361.22	±361.148	194.47	±194.437	7,797.413	±7,795.942	65.97
	Eastern white cedar	55669	±43,792	728.45	±620.671	1,400.863	±1,193.598	19,608.858	±17,362.658	61.21
	American basswood	26509	±19,057	293.30	±191.814	85.63	±56.001	3,427.506	±2,237.263	92.10
	Eastern hemlock	37113	±37,106	567.69	±567.578	527.29	±527.195	8,744.434	±8,742.784	84.21
	American elm	23858	±13,618	179.01	±137.340	130.20	±99.891	2,695.343	±1,613.164	65.00
	Total	**686582**	**±219,710**	**5,959.188**	**±2,335.366**	**5,005.391**	**±2,107.427**	**116,642.254**	**±49,626.643**	**69.88**
Residential	Freeman maple	2810	±2,809	3.19	±3.187	1.79	±1.794	228.61	±228.567	82.50
	Boxelder	28100	±11,993	104.30	±69.149	95.42	±63.259	1,220.877	±742.170	99.00
	Japanese maple	14050	±5,996	24.37	±12.268	13.72	±6.905	557.90	±275.831	98.50
	Norway maple	50580	±15,804	1,777.585	±644.032	959.46	±347.618	49,906.445	±19,366.320	95.94
	Silver maple	2810	±2,809	62.20	±62.184	32.74	±32.730	440.33	±440.256	99.50

Sugar maple	2810	±2,809	20.85	±20.851	12.56	±12.561	200.44	±200.408	99.50
Paper birch	2810	±2,809	103.72	±103.697	72.53	±72.520	1,387.884	±1,387.637	94.50
Gray birch	5620	±5,619	31.61	±31.608	18.78	±18.773	278.93	±278.880	94.50
Siberian pea tree	5620	±5,619	22.52	±22.519	19.09	±19.082	611.56	±611.447	99.50
Northern catalpa	8430	±6,226	150.43	±148.744	91.58	±90.559	2,866.065	±2,787.120	94.50
Kousa dogwood	2810	±2,809	5.55	±5.548	3.41	±3.408	287.06	±287.010	99.50
European spindletree	2810	±2,809	4.35	±4.345	3.24	±3.237	129.77	±129.751	99.50
ash spp	2810	±2,809	0.00	±0.000	0.00	±0.000	7,822.215	±7,820.823	0.00
Green ash	2810	±2,809	0.48	±0.484	0.32	±0.316	4.64	±4.641	99.50
Honeylocust	8430	±4,757	175.34	±99.406	183.62	±104.101	2,298.111	±1,450.972	86.50
Kentucky Coffee tree	2810	±2,809	5.24	±5.243	4.44	±4.443	51.86	±51.855	99.50
Eastern red cedar	14050	±8,260	27.74	±23.423	77.08	±65.081	1,023.220	±710.927	65.50
European larch	8430	±8,428	186.75	±186.714	120.75	±120.726	2,318.107	±2,317.695	94.50
Tamarack	2810	±2,809	41.47	±41.459	26.81	±26.806	498.94	±498.852	82.50
honeysuckle spp	2810	±2,809	6.40	±6.401	3.15	±3.153	104.19	±104.171	99.50
White mulberry	11240	±6,753	21.92	±14.064	16.04	±10.288	272.18	±185.543	99.50
Norway spruce	33720	±22,878	1,658.580	±965.297	2,764.301	±1,608.828	20,985.864	±12,589.327	96.17
White spruce	33720	±12,976	227.67	±144.883	365.74	±232.744	3,283.917	±2,011.108	95.58
Austrian pine	5620	±3,929	344.51	±247.958	332.05	±238.996	6,535.225	±4,701.031	88.50
Blue spruce	25290	±17,334	417.99	±338.929	695.95	±564.318	7,502.700	±5,927.034	83.94
Eastern white pine	5620	±3,929	267.66	±262.807	172.14	±169.018	2,733.375	±2,680.933	97.00
Scots pine	5620	±3,929	54.19	±46.149	52.24	±44.481	1,449.091	±1,314.334	91.00
Quaking aspen	2810	±2,809	13.61	±13.604	10.71	±10.712	167.93	±167.897	99.50
Apricot	2810	±2,809	72.57	±72.553	56.15	±56.138	1,943.151	±1,942.805	94.50
Sweet cherry	8430	±4,757	23.52	±17.494	18.20	±13.536	1,454.465	±1,368.546	93.83
Canada plum	2810	±2,809	3.36	±3.354	2.60	±2.595	352.32	±352.262	94.50
Siberian crabapple	2810	±2,809	11.84	±11.837	10.21	±10.206	265.36	±265.309	82.50
Callery pear	8430	±6,226	52.24	±43.029	39.30	±32.372	1,216.641	±1,085.819	92.17
Common pear	2810	±2,809	11.45	±11.450	8.62	±8.614	537.81	±537.718	94.50
English oak	16860	±11,786	142.26	±122.019	94.72	±81.243	7,099.053	±6,399.585	88.50

	Northern red oak	2810	±2,809	83.25	±83.234	66.33	±66.322	1,184.476	±1,184.265	99.50
	European buckthorn	47770	±21,392	95.60	±62.438	42.49	±27.750	1,343.120	±888.809	66.88
	Staghorn sumac	2810	±2,809	1.25	±1.247	1.11	±1.108	2.03	±2.027	99.50
	Black locust	14050	±14,047	9.34	±9.340	5.03	±5.028	43.50	±43.487	99.50
	Japanese tree lilac	11240	±8,825	39.47	±29.530	38.08	±28.488	1,632.892	±1,203.348	91.00
	Common lilac	8430	±4,757	9.93	±5.654	9.58	±5.454	240.51	±146.876	92.17
	English yew	28100	±14,984	73.84	±51.348	90.14	±62.688	1,600.226	±1,000.040	87.40
	Eastern white cedar	890763	±289,962	1,234.222	±439.568	2,373.503	±845.323	52,476.744	±18,365.751	89.50
	American basswood	5620	±5,619	1.53	±1.534	0.45	±0.448	6.48	±6.475	97.00
	Littleleaf linden	14050	±8,260	694.09	±411.895	519.96	±308.559	11,171.501	±6,461.970	79.60
	Eastern hemlock	2810	±2,809	1.09	±1.085	1.01	±1.008	53.09	±53.079	99.50
	Total	**1371270**	**±322,833**	**8,321.072**	**±2,024.878**	**9,527.129**	**±2,546.577**	**197,790.812**	**±43,025.510**	**89.51**
Utilities - Transportation	Boxelder	2359	±2,359	16.01	±16.007	14.65	±14.644	82.10	±82.080	99.50
	Norway maple	18874	±7,691	378.57	±164.229	204.33	±88.643	8,837.110	±5,041.583	77.50
	Silver maple	2359	±2,359	94.16	±94.135	49.56	±49.547	1,397.773	±1,397.477	99.50
	Sugar maple	42466	±33,598	846.92	±842.777	510.23	±507.728	24,108.060	±23,951.475	74.11
	Red Ash	2359	±2,359	0.78	±0.782	0.35	±0.348	4.24	±4.236	99.50
	Downy serviceberry	2359	±2,359	1.99	±1.991	1.22	±1.214	68.43	±68.416	99.50
	boxwood spp	2359	±2,359	0.82	±0.819	1.46	±1.463	5.03	±5.030	99.50
	Northern catalpa	2359	±2,359	4.72	±4.719	2.87	±2.873	39.88	±39.870	99.50
	Smoke tree	2359	±2,359	5.12	±5.114	4.99	±4.993	64.52	±64.505	99.50
	American beech	23592	±23,587	30.69	±30.681	13.08	±13.074	595.17	±595.042	81.00
	White ash	25952	±25,946	10.02	±10.020	5.70	±5.693	452.14	±452.045	30.82
	Honeylocust	14155	±7,199	187.34	±110.061	196.19	±115.259	2,072.938	±1,291.922	85.17
	Kentucky Coffee tree	2359	±2,359	12.83	±12.831	10.88	±10.873	145.79	±145.762	99.50
	Chinese juniper	2359	±2,359	2.92	±2.919	8.11	±8.109	278.00	±277.941	99.50
	White mulberry	2359	±2,359	10.15	±10.147	7.43	±7.423	50.71	±50.698	99.50

	spruce spp	2359	±2,359	0.83	±0.825	1.37	±1.374	49.83	±49.822	99.50
	White spruce	2359	±2,359	4.89	±4.893	7.86	±7.860	157.87	±157.834	99.50
	Black spruce	2359	±2,359	0.99	±0.990	1.87	±1.868	52.21	±52.203	82.50
	Austrian pine	4718	±4,717	217.55	±217.506	209.69	±209.644	2,542.499	±2,541.960	99.50
	Eastern white pine	2359	±2,359	1.09	±1.085	0.70	±0.698	1.94	±1.938	99.50
	Quaking aspen	2359	±2,359	2.93	±2.928	2.31	±2.306	20.19	±20.188	99.50
	Callery pear	2359	±2,359	10.36	±10.354	7.79	±7.789	142.65	±142.615	99.50
	Common pear	2359	±2,359	4.95	±4.952	3.73	±3.725	139.37	±139.344	94.50
	Bur oak	4718	±4,717	2.36	±2.362	2.32	±2.321	28.26	±28.252	88.50
	English oak	2359	±2,359	23.63	±23.625	15.73	±15.730	847.03	±846.853	82.50
	Northern red oak	11796	±6,909	112.12	±89.824	89.34	±71.573	1,909.818	±1,618.074	81.70
	European buckthorn	7078	±5,219	5.09	±3.822	2.26	±1.698	48.86	±38.025	99.50
	Crack willow	2359	±2,359	5.27	±5.273	3.34	±3.340	23.86	±23.850	99.50
	Eastern white cedar	58981	±54,227	45.75	±42.666	87.98	±82.049	3,917.363	±3,773.388	71.56
	American basswood	23592	±19,330	129.71	±99.797	37.87	±29.136	867.42	±610.158	92.40
	Littleleaf linden	16515	±7,459	307.06	±271.805	230.03	±203.615	2,802.627	±2,405.878	95.64
	American elm	2359	±2,359	47.49	±47.475	34.54	±34.530	359.46	±359.384	99.50
	Siberian elm	2359	±2,359	4.63	±4.632	3.16	±3.155	20.35	±20.343	99.50
	Slippery elm	2359	±2,359	2.64	±2.642	1.18	±1.183	34.04	±34.029	94.50
	Japanese zelkova	2359	±2,359	2.71	±2.711	1.76	±1.755	19.22	±19.212	94.50
	Total	**306702**	**±116,200**	**2,535.091**	**±981.395**	**1,775.847**	**±629.099**	**52,186.737**	**±25,809.098**	**79.38**
Other - Institutional	Amur maple	31189	±31,184	53.14	±53.132	29.91	±29.905	1,032.571	±1,032.422	97.28
	Boxelder	152478	±152,456	181.54	±181.512	166.08	±166.052	1,416.926	±1,416.722	88.74
	Norway maple	13862	±10,701	199.35	±152.319	107.60	±82.215	2,467.813	±1,986.538	98.25
	Sugar maple	86635	±62,109	2,309.946	±1,799.395	1,391.617	±1,084.038	41,414.723	±35,594.353	94.42
	Red Ash	6931	±6,930	5.34	±5.339	2.37	±2.373	73.37	±73.357	99.50
	European alder	3465	±3,465	1.05	±1.048	0.76	±0.764	4.08	±4.082	82.50
	Yellow birch	10396	±10,395	52.94	±52.931	21.92	±21.918	10,818.505	±10,816.944	27.50
	American hornbeam	3465	±3,465	22.66	±22.651	13.65	±13.646	163.93	±163.907	82.50

	Bitternut hickory	6931	±6,930	191.35	±191.323	120.29	±120.269	1,850.434	±1,850.167	99.50
	European beech	3465	±3,465	10.49	±10.485	5.25	±5.247	108.28	±108.266	99.50
	White ash	10396	±5,520	8.47	±8.465	4.81	±4.810	1,029.621	±674.679	31.50
	Black ash	27723	±27,719	0.00	±0.000	0.00	±0.000	2,275.865	±2,275.537	0.00
	Green ash	13862	±13,860	11.81	±11.803	7.70	±7.699	69.14	±69.126	74.63
	Black walnut	24258	±20,812	82.95	±81.187	66.49	±65.069	2,770.695	±2,766.421	41.93
	Tulip tree	3465	±3,465	1.79	±1.790	1.06	±1.055	6.73	±6.727	99.50
	Eastern hophornbeam	3465	±3,465	52.11	±52.098	34.02	±34.011	475.29	±475.218	62.50
	White spruce	10396	±10,395	15.07	±15.068	24.21	±24.205	115.67	±115.650	99.50
	Scots pine	6931	±6,930	0.00	±0.000	0.00	±0.000	2,153.850	±2,153.540	0.00
	American sycamore	6931	±6,930	2.06	±2.061	1.00	±0.998	12.41	±12.411	60.00
	Balsam poplar	3465	±3,465	31.10	±31.096	22.44	±22.437	98.27	±98.254	99.50
	Callery pear	6931	±6,930	82.37	±82.358	61.97	±61.960	1,206.355	±1,206.181	88.50
	Bur oak	3465	±3,465	43.44	±43.431	42.68	±42.675	564.54	±564.453	94.50
	European buckthorn	72773	±49,498	65.79	±52.448	29.24	±23.310	1,741.553	±1,341.814	66.05
	Glossy buckthorn	13862	±13,860	2.52	±2.515	1.12	±1.118	42.79	±42.780	54.88
	White willow	6931	±6,930	92.78	±92.770	58.78	±58.767	931.55	±931.416	81.00
	Bebb's hybrid willow	3465	±3,465	0.00	±0.000	0.00	±0.000	22.95	±22.948	0.00
	Eastern white cedar	79704	±66,225	600.35	±581.098	1,154.525	±1,117.495	16,047.225	±15,285.052	62.48
	American basswood	24258	±24,254	114.14	±114.124	33.32	±33.319	831.96	±831.839	81.36
	Eastern hemlock	48516	±48,509	818.93	±818.815	760.67	±760.556	10,552.488	±10,550.965	71.93
	American elm	6931	±4,708	2.33	±2.329	1.69	±1.694	221.93	±188.095	47.25
	Total	**696546**	**±250,494**	**5,055.791**	**±2,197.679**	**4,165.148**	**±1,827.613**	**100,521.495**	**±44,639.201**	**73.60**
Markham		**3295310**	**±496,829**	**23,912.339**	**±4,072.583**	**22,252.180**	**±3,933.246**	**530,634.419**	**±93,802.642**	**80.46**

APPENDIX E: INVASIVE PLANTS, PESTS, AND DISEASES

Table 36. Invasive plant species by percentage of plots affected, average number of plants by plot and spread

LandUse	Agriculture	Commercial - Industrial	Open Space – Natural Cover	Other - Institutional	Residential	Utilities - Transportati on	Markham
Number of plots	63	19	21	14	46	39	202
Percentage of plots with invasives	3.175	42.105	42.857	64.286	80.435	56.41	43.069
Average number of invasive plants	2	1.875	3.444	3.667	3.676	1.864	2.989
Average invasive plant spread	1.167	1.25	1.692	1.315	1.105	1.205	1.227
Percentage of plots with Black alder	0	0	0	7.143	0	0	0.495
Average spread of Black alder	0	0	0	1	0	0	1
Percentage of plots with Manitoba maple	0	5.263	28.571	21.429	28.261	7.692	12.871
Average spread of Manitoba maple	0	1	1.333	1.667	1.077	1	1.192
Percentage of plots with Norway maple	0	5.263	9.524	28.571	41.304	17.949	16.337
Average spread of Norway maple	0	1	1	1	1.158	1.143	1.121
Percentage of plots with Callery pear	0	0	0	7.143	6.522	5.128	2.97
Average spread of Callery pear	0	0	0	1	1	1	1
Percentage of plots with Ivory silk lilac	0	0	0	0	6.522	2.564	1.98
Average spread of Ivory silk lilac	0	0	0	0	1.333	1	1.25
Percentage of plots with Black locust	0	0	4.762	0	2.174	2.564	1.485
Average spread of Black locust	0	0	3	0	2	1	2
Percentage of plots with Tree of heaven	0	0	0	0	0	0	0
Average spread of Tree of heaven	0	0	0	0	0	0	0
Percentage of plots with Common buckthorn	3.175	15.789	33.333	57.143	36.957	17.949	21.782
Average spread of Common buckthorn	1.5	2	2	1.5	1.235	1.143	1.455
Percentage of plots with Morrows honeysuckle	0	0	0	14.286	0	0	0.99
Average spread of Morrows honeysuckle	0	0	0	1	0	0	1
Percentage of plots with Non-native honeysuckle	1.587	15.789	14.286	21.429	6.522	7.692	7.921
Average spread of Non-native honeysuckle	1	1.333	1	1	1	1	1.062
Percentage of plots with Winged spindle tree	0	5.263	4.762	0	13.043	7.692	5.446
Average spread of Winged spindle tree	0	1	1	0	1	1	1
Percentage of plots with Shrub honeysuckle	0	5.263	0	0	0	0	0.495

Average spread of Shrub honeysuckle	0	1	0	0	0	0	1
Percentage of plots with European spindle tree	0	0	0	0	6.522	0	1.485
Average spread of European spindletree	0	0	0	0	1	0	1
Percentage of plots with Japanese knotweed	0	0	0	0	2.174	0	0.495
Average spread of Japanese knotweed	0	0	0	0	1	0	1
Percentage of plots with Tartarian honeysuckle	0	0	0	0	0	0	0
Average spread of Tartarian honeysuckle	0	0	0	0	0	0	0
Percentage of plots with European fly honeysuckle	0	0	0	0	0	0	0
Average spread of European fly honeysuckle	0	0	0	0	0	0	0
Percentage of plots with Dog strangling vine	0	10.526	23.81	28.571	23.913	15.385	13.861
Average spread of Dog strangling vine	0	1.5	2.2	1.5	1.273	1.833	1.607
Percentage of plots with Winter creeper euonymus	0	5.263	0	14.286	36.957	12.821	12.376
Average spread of Winter creeper euonymus	0	1	0	1	1.118	1.2	1.12
Percentage of plots with Lily of the valley	0	0	0	7.143	17.391	0	4.455
Average spread of Lily of the valley	0	0	0	1	1.125	0	1.111
Percentage of plots with Goutweed	0	0	0	0	13.043	2.564	3.465
Average spread of Goutweed	0	0	0	0	1	1	1
Percentage of plots with Periwinkle	0	0	0	0	19.565	0	4.455
Average spread of Periwinkle	0	0	0	0	1.222	0	1.222
Percentage of plots with Oriental bittersweet	0	0	0	0	2.174	0	0.495
Average spread of Oriental bittersweet	0	0	0	0	1	0	1
Percentage of plots with Himalayan balsam	0	0	4.762	0	4.348	0	1.485
Average spread of Himalayan balsam	0	0	1	0	1	0	1
Percentage of plots with Garlic mustard	0	10.526	14.286	21.429	26.087	2.564	10.396
Average spread of Garlic mustard	0	1	1.667	2	1	1	1.238
Percentage of plots with Wild parsnip	0	0	9.524	7.143	0	0	1.485
Average spread of Wild parsnip	0	0	3.5	2	0	0	3
Percentage of plots with Phragmites	1.587	5.263	0	0	2.174	2.564	1.98
Average spread of Phragmites	1	2	0	0	1	1	1.25

Table 37. Invasive pest species by percentage of plots affected and spread

LandUse	Number of plots	Percentage of plots with EAB damage	Average spread of EAB damage	Percentage of plots with Lymantriadispar	Average spread of Lymantriadispar
Agriculture	63	1.587	1	1.587	2
Commercial - Industrial	19	5.263	1	21.053	1
Open Space - Natural	21	42.857	1.556	62.5	2.571
Other - Institutional	14	71.429	1.4	67.74	2.5
Residential	46	0	0	19.565	1
Utilities - Transportation	39	7.692	3	41.026	2.125
Markham	202	11.881	1.625	30.693	2.097

APPENDIX G: LEAF AREA AND STEM COUNT BY NATIVE OR NON-NATIVE

Table 38: Composition and Structure by Native Species

Species	Common Name	Trees		Leaf Area		Leaf Biomass		Tree Dry Weight Biomass		Average Condition
		Number	SE	(ha)	SE	(metric ton)	SE	(metric ton)	SE	(%)
Thuja occidentalis	Eastern white cedar	1095457	±305,662	2,716.496	±964.130	5,224.031	±1,854.096	95,074.319	±29,929.514	85.18
Acer saccharum	Sugar maple	215623	±79,783	5,579.942	±2,403.444	3,361.613	±1,447.945	126,615.752	±59,063.026	89.81
Pinus strobus	Eastern white pine	90157	±71,447	628.21	±361.079	404.02	±232.220	10,039.795	±5,506.217	93.35
Tsuga canadensis	Eastern hemlock	88438	±61,138	1,387.703	±996.295	1,288.968	±925.408	19,350.010	±13,702.626	77.96
Fraxinus americana	White ash	81281	±43,902	98.25	±80.815	55.83	±45.920	2,865.548	±1,182.781	39.34
Tilia americana	American basswood	79979	±36,833	538.68	±244.497	157.27	±71.382	5,133.357	±2,463.664	89.27
Picea glauca	White spruce	56706	±17,875	516.03	±268.361	828.97	±431.101	7,654.067	±3,559.625	96.73
Ostrya virginiana	Ironwood	54,647	±51,298	526.11	±476.91	342.32	±310.198	5,444.738	±4,991.967	76.23
Fraxinus pennsylvanica	Green ash	45831	±32,403	12.29	±11.813	8.02	±7.705	7,234.762	±7,159.969	28.67
Ulmus americana	American elm	45782	±19,306	243.41	±146.063	177.04	±106.235	3,502.637	±1,678.645	60.48
Populus tremuloides	Trembling aspen	42282	±32,191	97.33	±61.167	76.65	±48.167	5,147.244	±4,822.011	46.43
Juglans nigra	Black walnut	37512	±22,483	296.19	±183.182	237.39	±146.816	4,040.006	±2,977.838	61.21
Gleditsia triacanthos	Honeylocust	35716	±13,901	569.40	±215.469	596.29	±225.645	6,995.349	±2,983.704	88.02
Crataegus punctata	Dotted hawthorn	31415	±19,373	71.66	±59.680	53.98	±44.957	2,691.790	±1,819.487	55.89
Betula alleghaniensis	Yellow birch	28952	±21,266	353.63	±305.258	146.43	±126.401	17,648.260	±12,791.960	56.66
Fraxinus nigra	Black ash	27723	±27,719	0.00	±0.000	0.00	±0.000	2,275.865	±2,275.537	0.00
Fagus grandifolia	American beech	23592	±23,587	30.69	±30.681	13.08	±13.074	595.17	±595.042	81.00
Pinus resinosa	Red pine	17688	±17,684	131.02	±130.995	192.68	±192.640	6,487.816	±6,486.532	92.79
Quercus rubra	Northern red oak	14606	±7,458	195.37	±122.459	155.67	±97.577	3,094.293	±2,005.155	85.12
Juniperus virginiana	Eastern red cedar	14050	±8,260	27.74	±23.423	77.08	±65.081	1,023.220	±710.927	65.50
Amelanchier arborea	Downy serviceberry	10312	±6,268	3.57	±2.305	2.18	±1.405	130.67	±87.762	74.05
Quercus macrocarpa	Bur oak	8184	±5,853	45.80	±43.495	45.00	±42.738	592.79	±565.160	91.04
Carya cordiformis	Bitternut hickory	6931	±6,930	191.35	±191.323	120.29	±120.269	1,850.434	±1,850.167	99.50
Platanus occidentalis	American sycamore	6931	±6,930	2.06	±2.061	1.00	±0.998	12.41	±12.411	60.00
Populus balsamifera	Balsam poplar	6116	±4,362	35.12	±31.355	25.34	±22.624	181.20	±128.566	83.46
Betula populifolia	Gray birch	5620	±5,619	31.61	±31.608	18.78	±18.773	278.93	±278.880	94.50

Species	Common Name	Trees		Leaf Area		Leaf Biomass		Tree Dry Weight Biomass		Average Condition
Acer rubrum	Red maple	5302	±5,301	17.23	±17.231	11.61	±11.605	256.37	±256.317	88.50
Prunus serotina	Black cherry	5302	±5,301	4.40	±4.402	3.42	±3.414	162.84	±162.808	41.25
Acer saccharinum	Silver maple	5169	±3,668	156.35	±112.819	82.29	±59.382	1,838.108	±1,465.185	99.50
Gymnocladus dioicus	Kentucky Coffee tree	5169	±3,668	18.08	±13.861	15.32	±11.745	197.66	±154.711	99.50
Liriodendron tulipifera	Tulip tree	3465	±3,465	1.79	±1.790	1.06	±1.055	6.73	±6.727	99.50
Salix x bebbii	Bebb's hybrid willow	3465	±3,465	0.00	±0.000	0.00	±0.000	22.95	±22.948	0.00
Acer x freemanii	Freeman maple	2810	±2,809	3.19	±3.187	1.79	±1.794	228.61	±228.567	82.50
Betula papyrifera	Paper birch	2810	±2,809	103.72	±103.697	72.53	±72.520	1,387.884	±1,387.637	94.50
Cornus kousa	Kousa dogwood	2810	±2,809	5.55	±5.548	3.41	±3.408	287.06	±287.010	99.50
Larix laricina	Tamarack	2810	±2,809	41.47	±41.459	26.81	±26.806	498.94	±498.852	82.50
Prunus nigra	Canada plum	2810	±2,809	3.36	±3.354	2.60	±2.595	352.32	±352.262	94.50
Rhus typhina	Staghorn sumac	2810	±2,809	1.25	±1.247	1.11	±1.108	2.03	±2.027	99.50
Crataegus mollis	Downy hawthorn	2651	±2,650	4.05	±4.049	3.05	±3.050	771.59	±771.447	37.50
Picea mariana	Black spruce	2359	±2,359	0.99	±0.990	1.87	±1.868	52.21	±52.203	82.50
Ulmus rubra	Slippery elm	2359	±2,359	2.64	±2.642	1.18	±1.183	34.04	±34.029	94.50
Study Area		**2,223,632**	**±333,5445**	**14,693.73**	**±2,497.93**	**13,837.97**	**±2,449.32**	**340,059.77**	**±60,190.58**	**74.83**

Table 39: Composition and Structure by Non-native Species

Species	Common Name	Trees		Leaf Area		Leaf Biomass		Tree Dry Weight Biomass		Average Condition
		Number	SE	(ha)	SE	(metric ton)	SE	(metric ton)	SE	(%)
Rhamnus cathartica	European buckthorn	306639	±103,140	473.63	±172.101	210.50	±76.490	10,729.564	±4,589.063	70.17
Acer negundo	Manitoba maple	209446	±154,223	573.70	±278.386	524.84	±254.676	5,341.229	±2,530.009	90.88
Acer platanoides	Norway maple	88369	±21,189	2,506.604	±698.408	1,352.946	±376.967	63,186.954	±20,206.921	91.94
Robinia pseudoacacia	Black locust	56464	±44,672	370.56	±361.269	199.50	±194.502	7,840.908	±7,796.063	74.31
Acer tataricum ssp. ginnala	Amur maple	43823	±33,645	64.61	±54.355	36.37	±30.593	1,289.078	±1,063.797	95.79
Picea abies	Norway spruce	33720	±22,878	1,658.580	±965.297	2,764.301	±1,608.828	20,985.864	±12,589.327	96.17
Picea pungens	Blue spruce	32870	±18,918	553.63	±365.052	921.79	±607.812	10,657.109	±6,713.873	83.61
Tilia cordata	Littleleaf linden	30565	±11,130	1,001.153	±493.493	749.98	±369.686	13,974.128	±6,895.310	88.27
Taxus baccata	English yew	28100	±14,984	73.84	±51.348	90.14	±62.688	1,600.226	±1,000.040	87.40
Quercus robur	English oak	26924	±13,306	225.27	±137.425	149.99	±91.501	10,135.265	±6,804.945	81.83
Pinus sylvestris	Scots pine	17721	±9,496	224.69	±176.601	216.57	±170.218	6,026.951	±3,498.393	57.89
Pyrus calleryana	Callery pear	17720	±9,610	144.97	±93.496	109.06	±70.340	2,565.641	±1,629.176	91.71
Acer palmatum	Japanese maple	14050	±5,996	24.37	±12.268	13.72	±6.905	557.90	±275.831	98.50
Rhamnus frangula	Glossy buckthorn	13862	±13,860	2.52	±2.515	1.12	±1.118	42.79	±42.780	54.88
Morus alba	White mulberry	13599	±7,153	32.07	±17.342	23.46	±12.687	322.89	±192.345	99.50
Pinus nigra	Austrian pine	12923	±6,661	584.96	±330.630	563.81	±318.679	9,509.184	±5,361.654	91.32
Syringa reticulata	Japanese tree lilac	11240	±8,825	39.47	±29.530	38.08	±28.488	1,632.892	±1,203.348	91.00
Catalpa speciosa	Northern catalpa	10789	±6,658	155.15	±148.819	94.46	±90.605	2,905.944	±2,787.405	95.59
Larix decidua	European larch	8430	±8,428	186.75	±186.714	120.75	±120.726	2,318.107	±2,317.695	94.50
Prunus avium	Sweet cherry	8430	±4,757	23.52	±17.494	18.20	±13.536	1,454.465	±1,368.546	93.83
Syringa vulgaris	Common lilac	8430	±4,757	9.93	±5.654	9.58	±5.454	240.51	±146.876	92.17
Crataegus	hawthorn spp	7821	±5,809	19.17	±19.171	6.90	±6.896	1,437.517	±1,195.668	64.12
Magnoliopsida	Hardwood	6931	±6,930	5.18	±5.175	3.90	±3.903	130.00	±129.986	99.50
Salix alba	White willow	6931	±6,930	92.78	±92.770	58.78	±58.767	931.55	±931.416	81.00
Caragana arborescens	Siberian pea tree	5620	±5,619	22.52	±22.519	19.09	±19.082	611.56	±611.447	99.50
Malus pumila	Paradise apple	5236	±3,702	2.67	±2.664	2.30	±2.297	683.78	±587.180	49.12
Pyrus communis	Common pear	5169	±3,668	16.41	±12.475	12.34	±9.385	677.19	±555.479	94.50

Species	Common Name	Trees		Leaf Area		Leaf Biomass		Tree Dry Weight Biomass		Average Condition
Alnus glutinosa	European alder	3465	±3,465	1.05	±1.048	0.76	±0.764	4.08	±4.082	82.50
Fagus sylvatica	European beech	3465	±3,465	10.49	±10.485	5.25	±5.247	108.28	±108.266	99.50
Euonymus europaeus	European spindletree	2810	±2,809	4.35	±4.345	3.24	±3.237	129.77	±129.751	99.50
Fraxinus spp.	ash spp	2810	±2,809	0.00	±0.000	0.00	±0.000	7,822.215	±7,820.823	0.00
Lonicera spp.	honeysuckle spp	2810	±2,809	6.40	±6.401	3.15	±3.153	104.19	±104.171	99.50
Prunus spp.	Plum spp	2810	±2,809	72.57	±72.553	56.15	±56.138	1,943.151	±1,942.805	94.50
Malus baccata	Siberian crabapple	2810	±2,809	11.84	±11.837	10.21	±10.206	265.36	±265.309	82.50
Acer spp.	maple spp	2359	±2,359	0.87	±0.874	0.49	±0.492	9.16	±9.160	99.50
Buxus spp.	boxwood spp	2359	±2,359	0.82	±0.819	1.46	±1.463	5.03	±5.030	99.50
Cotinus spp.	Smoke tree	2359	±2,359	5.12	±5.114	4.99	±4.993	64.52	±64.505	99.50
Juniperus chinensis	Chinese juniper	2359	±2,359	2.92	±2.919	8.11	±8.109	278.00	±277.941	99.50
Picea spp.	spruce spp	2359	±2,359	0.83	±0.825	1.37	±1.374	49.83	±49.822	99.50
Salix fragilis	Crack willow	2359	±2,359	5.27	±5.273	3.34	±3.340	23.86	±23.850	99.50
Ulmus pumila	Siberian elm	2359	±2,359	4.63	±4.632	3.16	±3.155	20.35	±20.343	99.50
Zelkova serrata	Japanese zelkova	2359	±2,359	2.71	±2.711	1.76	±1.755	19.22	±19.212	94.50
Study Area		**1,071,674**	**±160,751**	**9,218.58**	**±1,567.16**	**8,415.92**	**±1,489.62**	**188,636.21**	**±33,388.61**	**89.22**

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