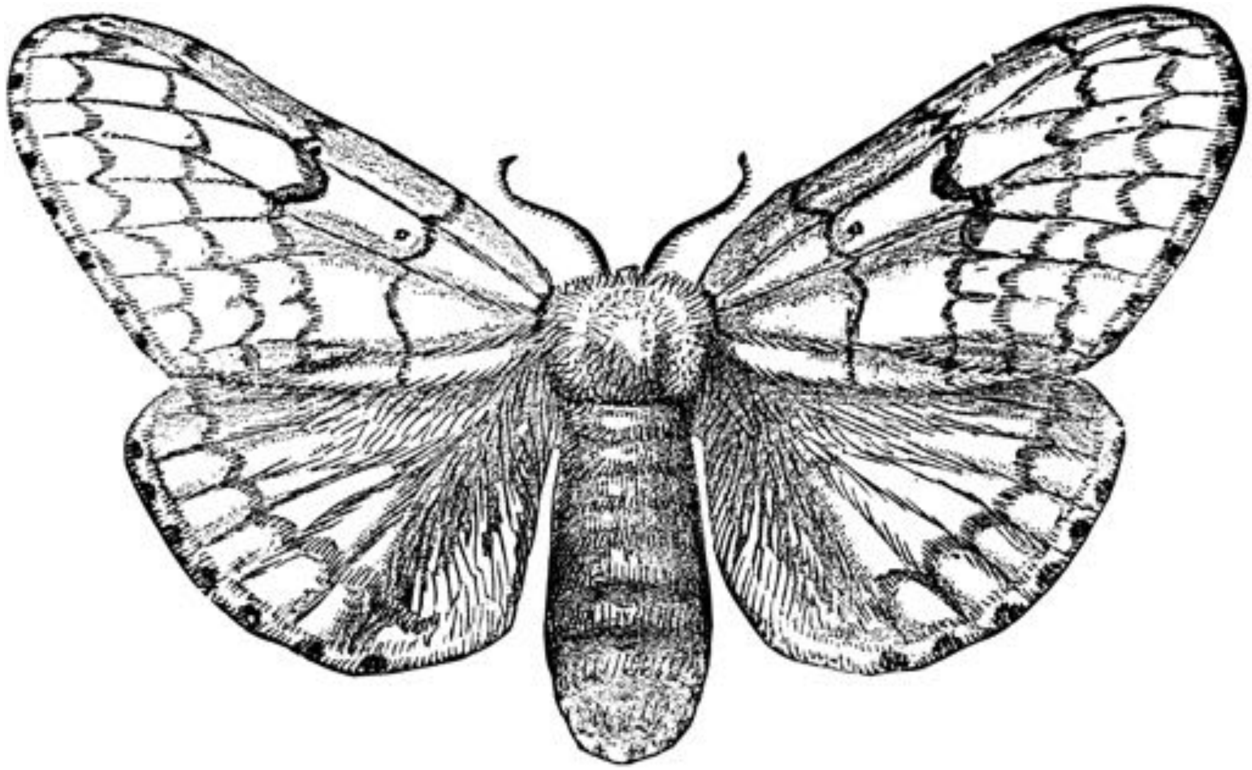

Incorporating best practices for pest management into urban forestry strategies in southern Ontario: a municipal comparison and a feasible gypsy moth (*Lymantria dispar* L.) monitoring program design

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Summary

The urban forest is a vital component of the quality of life within cities. Southern Ontario's forests are highly valued, providing a host of ecosystems services. Therefore, the maintenance of the urban canopy is extremely crucial. The urban canopies of North America are severely affected by a multitude of invasive pests, such as the defoliating European gypsy moth (*Lymantria dispar* L.). In the last decade, many municipalities in southern Ontario have developed and published urban forest management plans. Planning commonly rely on the maintenance of single trees, enhancement of canopy cover, and enhancement of tree diversity, as well as the public education programs, while other considerations such as the implementation of integrate pest management (IPM) strategies are often overlooked. As well, municipalities face budgeting concerns that constrain them from implementing IPM effectively. Here, the urban forest management planning of 6 municipalities in southern Ontario are reviewed, and best management practices (BMPs) for the European gypsy moth are isolated. Through a review of municipal documentation and relevant literature, this research finds that incorporating best management practices for IPM into urban forestry planning can help to increase the capacity of small municipalities to respond to urban forest pests such as gypsy moth, regardless of budget. This document provides a summary of current strategies and feasible monitoring network design to help guide urban forest managers.

List of Figures

List of Tables

List of Appendices

Table of Contents

Introduction

Gypsy moth in North America

The gypsy moth is native to Europe and Asia. Only the European gypsy moth is discussed in this context and it will be hereby referred to as 'gypsy moth'. Professor L. Trovelot brought the gypsy moth from France to Massachusetts in an effort to develop a silkworm industry in North America by crossing gypsy moth with North American silk worms (Barron and Patterson 2008). In 1870, some escaped and within 20 years they established as a serious pest. Since the time of its accidental introduction to North America in the 1860s in Massachusetts, gypsy moth has become one of the most destructive forest insects in the United States and Canada (Liebhold et al. 1992). There has been a quarantine in place since the early 1900s, yet gypsy moth has been advancing westward from the northeastern United States (USDA 1995) (Appendix A, Figure 1).

In Canada, the first moth was detected in British Columbia in 1912 (BioForest 2006). The first infestation was in southwestern Quebec in 1924, and the second in New Brunswick in 1936. Intensive egg removal was conducted to eradicate the pest, yet efforts to completely destroy the pest were unsuccessful (BioForest 2006). The gypsy moth is now established in southern Ontario, New Brunswick, and Nova Scotia (Natural Resources Canada 2003).

Gypsy moth in Ontario

Gypsy moth was first detected in Ontario on Wolfe Island, just South of Kingston (BioForest 2006). In 1981, gypsy moth was detected and serious defoliation occurred in Kaladar, Ontario, and by 1985 it was a serious problem (BioForest 2006) (Appendix A; Figure 2). The distribution of gypsy moth in Ontario includes the southern third of the province, and the northern border runs from North Bay to Sault Ste. Marie (BioForest 2006).

Gypsy moth life cycle

Gypsy moth is in the *Lepidoptera* order, which have a single annual generation with four separate stages of life: egg, larvae, pupa and adult (Appendix B, Table 4). Eggs are laid mid-summer, with weather, food source, and disease affecting their timing (BioForest 2006). Caterpillars spend the winter inside the eggs. Egg masses are generally resistant to dry or cold temperatures unless temperatures drop below -32 ^{o}C for an extended period (BioForest 2006).

As larvae develops, they pass through instars or stages, separated by molts where the larva's skin is shed and replaced with a new one (BioForest 2006). The distinctive features of gypsy moth larvae include fine black hairs and five pairs of blue and six red dots along their backs. While feeding on a tree's crown, first instars spin threads that are caught by the wind, often displacing them onto new tree hosts, which is known as "ballooning" (BioForest 2006). First instars feed by cutting small holes on the leaf's surface. When the host is defoliated, larvae find another suitable host (USDA 1995).

Larvae are active from May to mid-July. In that time each larva eats ~1m^2 of foliage, or 10-15 oak leaves (Nealis and Erb 1993). Once the feeding period has finished, the gypsy moth pupas. The moths emerge approximately two weeks later. Male moths are dark brown to beige, medium in size and fly during the day. Females emit a powerful sex attractant pheromone (Nealis and Erb 1993). Males have antennae that help to detect the pheromone and can do so from a ~1.5 km distance (BioForest 2006). The females lay their egg masses in clusters of 100-1000 on the tree trunks and branches (Nealis and Erb 1993). Eggs are laid close to where the pupation occurred, and the female dies after eggs are laid (Nealis and Erb 1993).

Gypsy moth population outbreaks

Little can be done to entirely halt the spread of this insect (Pederson and Munson 2010). Resources have focused instead on suppression of outbreak populations to reduce spread rate (Pederson and Munson 2010). Gypsy moth has expanded its range to all northeastern states and to the west. The composition of many forests has changed over to less susceptible species due to heavy defoliation of susceptible hosts (Pederson and Munson 2010).

First-instar gypsy moth larvae prefer red oak (*Quercus rubra* L.) as hosts (Maufette et al. 1983). Oak trees are a valuable species to the urban canopy (BioForest 2006). With their characteristic strength and resistance as well as their large canopies, they provide a multitude of aesthetic and functional benefits to society, as well as helping urban forest managers to meet canopy cover goals, and their protection in city environments is often desired by forest managers (Joel Harrison-Off, *personal communication* 2018).

Although it has been found on nearly 500 tree species, gypsy moth larvae preferentially attack red oak (*Quercus rubra* L.) (Maufette et al. 1983) (Appendix B, Figure 5). Damage from gypsy moth occurs when needles or leaves are consumed by caterpillars (Pederson and Munson 2010). In high outbreak periods, complete defoliation may occur. Defoliated trees can refoliate, yet this depletes stored energy and weakens the tree, making them more susceptible to disease and mortality factors over the course of 2-3 years (Pederson and Munson 2010).

The Asian gypsy moth (*Lymantria dispar Asiatica* L.) is another pest affecting North America. It has been detected in California and Oregon and has high damage potential. As well, the Washington State Department of Agriculture has recently proposed an aerial spray of *Bacillus thuringiensis* (Btk), a common bacterium that is often used to suppress gypsy moth populations, over 1,700 acres of land to eradicate multiple introductions of the Asian gypsy moth (Salp 2018). The Asian variety of gypsy moth is of great concern as a pest on the horizon for southern Ontario because they have a broader host range, and the females can fly (Pederson and Munson 2010). As such, monitoring and detection protocols will be different for Asian gypsy moth, although treatment methods are similar (Pederson and Munson 2010).

Gypsy moth impacts

Gypsy moth invasion can cause both short and long-term impacts. In the short term, high larval populations cause defoliation that affects the value of an infested area (BioForest 2006). Leaf loss is most noticeable when a tree has sustained 30-40% defoliation (BioForest 2006). Egg masses can also be a daily nuisance because they are laid on a variety of surfaces (BioForest 2006). In the long term, gypsy moth infestation causes branch and twig mortality, and whole tree mortality in some cases. It can also lead to invasion from secondary pests such as rot, as well as thinning tree canopies.

The way that a tree responds to defoliation is based on a number of factors. The amount of foliage removed, weather or climatic patterns, the consecutive number of years of defoliation that have occurred, and the timing of defoliation affect the tree's response to stress, as does the presence of other insects and disease, the health of the tree, and habitat constraints (OMNR undated). Healthy oak trees can withstand a year of moderate to severe defoliation, yet two or three years of heavy defoliation (≥50%) could result in high mortality rates (BioForest 2006). The condition of a tree's crown plays a part in its ability to survive defoliation. A tree with <25% dead branches in its crown is more likely to survive defoliation than a tree with >50% dead branches (Gottschalk 1993), and highly stressed trees can die after just one year (OMNR undated).

Mid-season defoliation may be more damaging than spring defoliation because trees do not have time to replenish reserves and new buds cannot harden before autumn (Gottschalk 1993). Location plays a role in tree susceptibility, as moths prefer ridge top sites and steep south or west-facing slopes because they tend to host oak species that are often lower in vigor with deep bark fissures, providing good habitat (Gottschalk 1993). Tree composition can also affect damage caused by gypsy moth, as areas with mostly oak, poplar and birch are more susceptible than areas with ash, pine, spruce or sugar maple (OMNR undated).

Management goals

Total eradication of gypsy moth has been conducted for gypsy moth populations in the western United States (USDA 1995). Through early detection, delimitation traps and insecticide applications are believed to have been successful (Pederson and Munson 2010). Detection and eradication, however, are not always designed in the most economically or biologically affective manner (Bogich et al. 2008). Gypsy moth eradication has rarely been successful, with insect capture recurring in eradication areas (Myers 1998). The first 90-99% is not as costly as the last 1-10% of eradication, as detection at low threshold levels can be extremely difficult to achieve (Myers 1998).

The benefit of eradication is that no further control is necessary. This can be difficult to achieve with smaller municipal budgets, especially if there is not active management occurring on private lands. Therefore, suppression and management of gypsy moth levels is the most sensible option for urban forest managers. A common goal for the maintenance of aesthetic value across various municipalities is referred to as "keeping the trees green", or maintaining the visual appeal of the urban canopy. This is often used as a goal when protecting against defoliating pests such as gypsy moth. In 2008, Bogich et al. developed a model to improve the efficacy of detection programs for isolated efforts by optimizing detection efforts relative to growth rates and program duration (Bogich et al. 2008). It is important to balance the costs and benefits of detection and eradication when developing monitoring programs (Straka et al. 1997). In municipalities with limited budget, cost minimization must be balanced with efficacy of treatment.

Management in southern Ontario

In 2018, the Cities of Hamilton, Mississauga and Oakville conducted an aerial spray of Btk for controlling gypsy moth populations (BioForest 2016). In 2017, the City of Toronto also conducted an aerial spray (BioForest 2017; BioForest 2018). Because gypsy moth populations fluctuate from low density to high, aerial sprays are often conducted cyclically. The control of gypsy moth is of high priority value to these municipalities, as defoliators directly affect urban forestry goals and poses a risk to the public. When managing trees in the urban environment, municipal forestry managers are constantly balancing a variety of sociopolitical factors.

The Canadian Food Inspection Agency is responsible for prevention of the spread of the European gypsy moth as affects Canada's plant resources (CFIA 2017). The Ontario Ministry of Natural Resources and Forestry (OMNRF) also conducts research on gypsy moth populations in Ontario as it is a prominent and well-established forest pest, as well as funding partner organizations such as the Invasive Species Centre and Ontario Invasive Plant Council to aid municipalities in the fight against invasive species (Raynor 2017).

Meanwhile, municipalities are tasked with the effects of the gypsy moth on the urban canopy once it is an established pest (BioForest 2016). Therefore, in order to meet desired management goals, urban forest managers must strategically address urban pest issues such as gypsy moth. In municipal areas where the gypsy moth problem is currently being addressed, often defoliation surveys and egg mass densities are measured in order to assess population levels and prioritize areas for treatment.

An integrated pest management approach

Integrated pest management (IPM) has been utilized greatly in agriculture to increase crop yields and manage plant pests (Bottrell 1979). However, it has also been adopted into forest management. IPM is the selection, integration and implementation of pest control based on predicted consequences. An integrated pest management (IPM) approach to urban forestry uses sound scientific data, knowledge of pest biology, population dynamics, tree and stand dynamics in order to form the basis of decision-making processes, often relying primarily on natural control agents such as weather, diseases, and predators and parasites (Bottrell 1979).

The objective of IPM is to reduce the frequency and severity of future pest outbreaks and respond preventatively to pest issues (Bottrell 1979). A pre-emptive strategy for controlling pests such as gypsy moth that affect the urban canopy is necessary to maintain ecosystem services and to meet management goals. An IPM approach utilizes cost-benefit analysis, stakeholder participation, and pest monitoring.

Forest pest monitoring

Monitoring for urban forest pests is a major component of a proactive IPM approach. Considerable research has been conducted for developing a monitoring system in order to effectively make control decisions at a local level, using pheromone traps and egg mass surveys

(Ravlin et al. 1990). This is based on the assumed relationship between egg mass size and defoliation (Ravlin et al. 1990).

In the United States, several models for gypsy moth monitoring have been applied. The moths per trap model is used to predict an egg mass density category and the male wing length model which suggests that frequencies of moth wing size will predict egg mass density (Reardon 1991). The integration of pheromone-baited traps to prioritize areas for egg mass sampling is useful in some cases and has been utilized in the Slow the Spread (STS) program across the United States as part of their National Gypsy Moth Management Strategy (USDA 2012).

Low-cost methods such as walk-through surveys and windshield surveys can provide a broad understanding of egg mass frequency and distribution in a given area. However, the establishment of a permanent monitoring plot network is likely the most effective method for monitoring gypsy moth populations in order to make sound management decisions (Ravlin et al. 1990). Some municipalities have adopted an IPM approach that includes a monitoring network into urban forest management planning, which has proven successful (Wassenaer et al. 2014).

Sampling challenges to urban forest monitoring

Fleischer *et al.* (1992) define urban and suburban environments as having a minimum of one house per ten acres (4.04 ha). While the urban environment is similar to forested environments, generally there are unique distinctions that separate them and influence pest problems (Coulson and Witter 1984). Consequently, this influences management.

In urban forests, the diversity of host species is often larger, host trees consist of both natives and exotics, there is a greater range of age-classes, and a high value is often placed on mature trees (BioForest 2006). Little is known about the optimization of field data collection in urban environments (Nowak et al. 2008). Urban trees are subject to a variety of stressors, including compaction, salt and air pollution, construction, and drought. Predicting the impacts of pest outbreaks becomes difficult in this setting, as trees are generally not as resilient under stress. Distribution of egg masses are more concentrated than in forest environments due to the presence of man-made objects (Fleischer et al. 1992). Other sampling methods have been developed to survey for gypsy moth egg masses in urban environments. For example, a double-modified Kaladar plot method is used by Lallemand Inc./BioForest to sample urban trees, yet there is still no standardized method used across municipalities to address this issue (BioForest 2006).

Although egg mass surveys are thought to be the most effective method of measuring gypsy moth populations, there is a great deal of variation in the relationship between egg mass densities observed and defoliation occurrence (Liebhold et al. 1994). Prioritizing sampling areas is a major budgeting concern for small municipalities.

Problem definition

In urbanized areas, much of the tree canopy has been affected by a multitude of pests. Gypsy moth (*Lymantria dispar* L.) is one such pest that is an ongoing nuisance for urban forest managers. For many municipalities, sampling and tree health surveys have been conducted to evaluate treatment options. Before a pest can be properly contained, urban forest management strategies must be properly outlined and defined. This process, however, can be expensive and tedious. Very few municipalities have adopted and IPM approach into urban forest management plans (UFMPs). As well, a lack of continuity in urban pest management exists because strategies are not continuous across the landscape.

To strategically prepare for the effects of defoliators like gypsy moth in an urban environment, urban forestry goals and attributes must be properly defined, and preventative strategies put in place that address a landscape scale of treatment. A review of municipal planning can help to isolate effective strategies that are currently being utilized. In order to create a strategy that helps municipalities to effectively face current and future gypsy moth issues, a balance must be struck between efficacy and feasibility (Oudenhoven et al. 2018). Where budget constraints affect municipalities ability to respond to invasive species that cause urban canopy decline, it is assumed that development of a comprehensive monitoring network for gypsy moth can assist in allocating resources efficiently.

Three hypotheses will be addressed in this paper. (1) Adopting IPM into urban forest management planning can strengthen municipal response to pests, (2) collaboration across municipal boundaries can help to strengthen gypsy moth management in southern Ontario, and (3) implementing a monitoring program is an effective method for gypsy moth control with the lowest-cost and most effective methods of detection prioritized.

Methods

This research was conducted in two steps. A matrix of criteria and indicators was used to evaluate current strategies in order to identify areas of strength and weakness in urban forest management (Ordonez and Duinker 2013). A monitoring plot network for gypsy moth was created to incorporate essential management objectives, as well as elements of scalability and treatment based on three budget scenarios. This provides an overview of options available for forest managers across southern Ontario, and helps to address the research hypotheses outlined.

Step 1: matrix of criteria and indicators

Municipal forestry plans, invasive species strategies, and by-law documentation of municipalities in southern Ontario were reviewed using a matrix of criteria and indicators. Literature on urban forest management has focused primarily on budget issues, zoning and regulation, community programs, policies, and urban forest programs, yet not on documentation (Ordonez and Duinker 2013). Criteria and indicators provide a framework for the formulation of policy options which helps to advance co-operation and provides an assessment of the positive and negative changes occurring in management (Jalilova et al. 2012).

Municipalities were arranged based on population size (2016) (Appendix B, Table 6). Norfolk County, the Town of Oakville, the City of Hamilton, the City of Mississauga, the City of Burlington, and the City of Toronto were reviewed (Appendix B, Table 6). Review of municipal documents such as UFMPs helps to provide an overview of current strategies related to gypsy moth management in urban settings, as well as an empirical assessment of the inadequacies of municipal planning activities. The comprehensiveness of information available to the public was examined, helping to to gain working knowledge of current pest and urban forest management approaches in southern Ontario (Ordonez and Duinker 2013).

A qualitative method of analysis was developed. The standardized method utilized specified each management theme into criteria and indicators of best management practices (BMPs). These indicators were assigned either a categorical or numeric measurement. To illustrate this analysis, shades were used to indicate the level of specificity achieved in planning. This information was processed and criteria lumped into "themes" to give a view of the level of specificity achieved (Ordonez and Duinker 2013).

The criteria for this project were developed with the assistance of Professor and Entomologist Sandy Smith and Urban Forest Health Manager Allison Craig, as well as from a research paper produced in 2013 by Camilo Ordonez and Peter Duinker. The criteria included in this matrix are divided into themes of maintenance, management, environmental, education (awareness), education (engagement), monitoring, treatment, cultural identity, legislative, economic, and temporal-spatial. The criteria included are pruning, removal, tree replacement, staffing, UFMP, private subsidies, tree inventory, hazard trees, tree size, tree age, tree diversity, climate, canopy cover, communication, volunteering, plantings, workshops, sampling, historical infestation, egg mass surveys, pheromone-baited traps, gypsy moth/invasive species control, spray of Btk, banding, threshold, heritage trees, municipal documentation, practitioners, municipal continuity, climate change strategy, finances, scale of treatment and resource continuity (across ownership). Criteria and indicators are described in detail in Appendix B, Table 7.

Step 2: gypsy moth monitoring network design

Stratified random-sample design

Application of a stratified random sample design involves dividing the population into homogenous groupings, and then randomly selecting from each stratum. In the case of this monitoring network, the land-use categories of residential, open space, and park and recreational areas were utilized as strata to prioritize areas for sampling (Appendix A; Table 5). Park and woodlot areas were merged. Using land-use maps to stratify a municipality can help to better identify priority areas, such as areas that experience greater public usage (Kim 2016).

Mapping

Maps were developed using *ArcMaps 10.6.1* in the Map and Data Library at Robarts Library on the University of Toronto's campus in Toronto, Ontario. The Town of Oakville was used as an exemplary case for plot network development (Appendix A, Figures 9 & 10). Oakville's tree inventory was accessed via their online Open-Data Portal. Each tree that was selected as a plot centre is defined as an oak tree ≥30cm DBH. Land-use maps were downloaded from the Scholars GeoPortal online, and Lallemand Inc./BioForest with permission from the Town of Oakville.

Threshold levels

Before decisions are based about gypsy moth, it is critical to determine the population level and define management objectives. Treatment goals typically include suppression, prevention of defoliation, or a combination. Counts of egg masses are generally made to support these decisions. The USFS *Slow the Spread* program recommends a threshold of 1,000 egg masses/acre as a reasonable threshold for treatment implementation (USDA 1995). The intervention threshold of 600 egg masses per hectare has been widely used in management (Liebhold et al. 1994). Intervention thresholds gypsy moth differ based on management goals (Table 1). Thresholds for the different municipal budget scenarios were developed based on hypothetical management goals for each level of funding allotted toward gypsy moth monitoring.

Table 1: Threshold levels for gypsy moth and their corresponding management goals.
Sources: BioForest 2006, Liebhold et al. 1994.

Threshold (egg masses/ha)	% defoliation	Management goal
1,250	30%	Prevention of noticeable defoliation
1,750	40%	Prevention of growth loss
2,500	60%	Prevention of tree mortality

5-tree cluster plots

Fixed-area plots, or Modified Kaladar Plots (MKPs), are thought to be the most accurate for gypsy moth egg mass assessments in natural forest environments, and the most cost effective (Thorpe and Ridgeway 1992). In the 5-tree cluster method, one tree is selected as plot centre with its GPS coordinates recorded. This tree, as well as four others (preferably mature oaks) in as close proximity to plot centre as possible were selected (BioForest 2017). The survey is completed by scanning both sides of the tree with a partner and recording egg masses observed (Appendix A; Figure 3). Defoliation forecast calculations are completed based on new and old egg masses observed for treatment the following spring season (Appendix A; Figure 4).

For the purposes of plot establishment, only oak trees ≥30cm diameter at breast height (DBH) were selected as the centre of tree plots because they are gypsy moth's preferred host (Appendix B, Table 5). Plot centers were determined in this manner because older oak trees are more susceptible to mortality, and oak trees ≥30cm DBH were considered mature. The other four trees to be assessed during egg mass surveys are oak trees >10cm DBH if possible, or other host trees identified as hosts in the absence of oak trees (Appendix B, Table 5) (BioForest 2017).

Scalability

The municipalities examined in the matrix portion of this analysis varied according to population, size, and budget, meaning that they vary in their capacity to deal with gypsy moth issues. Therefore, the network model developed is scalable, implementing different sampling tools for assessment of gypsy moth populations at various budget levels depending on severity of the infestation and management goals outlined. The USDA recommends between 4 and 10 plots per km^2, while the Canadian Forest Service recommends 3 plots per km^2 (USDA 1995; BioForest 2016). Three scenarios have been developed based on a low (<$20,000 annually), medium

($20,000-$50,000 annually), and high ($50,000+ annually) budget in order to showcase the options available for urban forest managers. It should be noted that a tree inventory is necessary for the proper implementation of a plot network. It is also important to note that density of egg masses is not the only factor. The design of this monitoring network also considers the variability in gypsy moth population, tree size, stand composition, and the manager's error tolerance.

Margin of error

As well as density, the design of an acceptable program should consider variability in the population, tree size, stand composition, as well as error margins deemed acceptable. The acceptable margin of error will differ depending on the manager's tolerance for error, which depends on the constraints of the management program and the density being estimated.

If a margin of 50% error considered acceptable, it would not matter if the density was 2,000 egg masses/ha or 6,000 egg masses/ha, because treatment would be required at 2,000 egg masses/ha. However, if the estimated density was 400 egg masses/ha and treatment threshold 500 egg masses/ha, the decision for treatment would depend upon the actual density. Therefore, an error margin of 50% would not be considered acceptable (Liebhold et al. 1994). The margins of error developed in the three scenarios for management of gypsy moth are hypothetical and can be adapted based on individual goals (Appendix A; Figure 12).

Plot selection

For the low-budget scenario, drive-throughs of residential areas are prioritized, with heritage trees identified for egg mass sampling. Nowak et al. recommend the utilization of a network of 200 plots for an approximately 12% relative standard error for sampling in an urban environment (Nowak et al. 2008). Therefore, the medium budget scenario utilizes a network of 200+ plots. In sampling of urban street tree populations, i-Tree experts recommend 2,000-2,300 samples to provide the best assessment of accuracy (Jaenson et al. 1992). Therefore, 400 plots with 5 trees sampled is the BMP of assessment, and is utilized in the high budget scenario. A grid network was used to make sure that there were fewer than 10 plots per 1km^2 area (USFS, 1990) (Appendix A; Figures 9&10).

Results: matrix of criteria and indicators

The chart below shows the key findings of the matrix of criteria and indicators. Specifically, it showcases the top 5 strengths and weaknesses of each municipality's urban forest management strategies. Most municipalities were revealed to have strong tree maintenance cycles, a partial tree inventory, canopy cover goals, and volunteer programs in place, as well as at least mentioning climate change strategies. Some municipalities have an urban forest management plan in place with mention of hazard, heritage trees, tree age, tree diversity, and tree size. Some mention gypsy moth treatment and implement preventative strategies such as population monitoring. In contrast, only Mississauga currently adopts an IPM approach into their UFMP, with an Invasive Species Control Plan to be implemented by 2020. The City of Hamilton provides private subsidies to homeowners, which is a unique feature. Full results of criteria and indicators matrix are described in detail in Appendix B; Tables 7 and 8, and Appendix C.

Table 2: Key results from matrix of criteria and indicators.

Municipality	Key strengths	Key weaknesses
Norfolk County	• Tree removal • 3 foresters on full-time staff • Forest health monitoring (Norfolk County Woodlot Owners Association, 300+ members) • Gypsy moth monitoring (conducted by summer students, OMNRF) every 2-3 years • 25% landscape forest cover	• No current UFMP • Private subsidies (25,045 private households in Norfolk) • Tree replacement currently on a roughly 3:1 ratio • No gypsy moth/invasive species control plan • No current threshold for treatment of gypsy moth
City of Burlington	• UFMP in place (2011-2030) • Basic street tree inventory • Municipal documentation • Town's Official Plan (2017) prioritizes natural heritage areas, tree protection, by-law updates • 7-year grid pruning cycle	• Did not participate in 2018 spray of Btk • Lack of private subsidies • Lack of co-ordination between municipal and utility pruning cycles • No current gypsy moth/invasive species control plan • Tree replacement, size, age, replacement not addressed in planning (1,000 trees planted annually)
Town of Oakville	• 20-year UFSMP • Volunteer programs, plantings, workshops • Annual egg mass surveys conducted • Municipal street tree and open space inventory, publicly available with regular updates • Municipal continuity (co-ordination of treatment with neighbouring municipalities) • High canopy cover (29.1%)	• Mostly part-time, contract staff • No gypsy moth treatment conducted on private land, no subsidies for private land • 28% maple species in canopy • Communication (no public information centre) • No gypsy moth/invasive species control plan • No specific objectives for climate change mitigation/adaptation
City of Hamilton	• Municipal documentation • Community Climate Change Action Plan (2015) • Threshold for gypsy moth treatment (2,500 egg masses/ha) • Publicly available working inventory (not comprehensive) • Communication (public information centre) • City provides $30/treatment for private homeowners TreeAzin injections	• No current UFMP, plan for Urban Forest Strategy by December 2019 • Lack of volunteering programs • Tree size, age, removal, diversity goals not mentioned • No gypsy moth/invasive species control plan • Absence of planting ratio
City of Mississauga	• Invasive species control plan • UFMP in place • "One Million Trees" program (20-year strategy since 2012) • Proactive pruning, removal, replacement cycles • Volunteer workshops, planting	• No private subsidies, only private tree removal • Low tree diversity (22% Norway maple) • Low tree size (+60% trees <15.3cm DBH) • No climate change strategy (only regional level) • Canopy cover (increase from 15%-25% over 20 years)
City of Toronto	• 10-year strategic FMP (2013-2023) • Trained, full-time staff • Collaboration with community groups (LEAF, Gord, etc.), volunteer planting • Aerial spray of Btk conducted in 2017 • Canopy goals (27%-40% by 2020) • High proportion of native tree species (64%)	• No private subsidies provided • No climate strategy, lack of mitigation and adaptation goals • High proportion of old oak trees in decline • No gypsy moth/invasive species control plan • Municipal continuity: lack of co-ordination • Low tree size (~68% trees >15.2cm DBH)

Results: gypsy moth monitoring network design

The table below highlights the key features of a gypsy moth monitoring network design. For a low budget scenario (>$20,000 annually), prevention of tree mortality is prioritized, with a threshold over 2,500 egg masses/ha for treatment implementation, and a margin of error of 25%. Data collection would be conducted via forest health volunteers along with the municipal forestry staff and consultancy groups. Sampling methods prioritize less accurate yet lower cost methods such as windshield surveys, and walk-throughs performed in park and woodlot areas for prioritizing egg mass survey sampling efforts (Straka et al. 1997). As per the town's requests, heritage trees could be identified. In the case of Oakville, City of Oakville staff identified a tree at 2355 Yolanda Drive, and the Great White Bronte Oak Heritage Tree at 1151 Bronte Road as significant, as well as the white oaks at the north end of Iroquois Shoreline Wood (BioForest 2016) (Appendix A; Figure 6). Heritage tree features are included across all three scenarios.

For a medium budget scenario ($20,000-$50,000 annually), prevention of growth loss is prioritized. Therefore, a threshold of 1,750 egg masses/ha is deemed acceptable. A monitoring network of 200+ plots was developed with residential areas and parks and woodlots prioritized for sampling efforts, as hazard prevention is a high priority for treatment effort with a constrained budget. Initial 5-minute walk-throughs can be performed in woodlots and parks to determine if a plot should be removed or added based on gypsy moth egg masses observed. Because the threshold level for treatment is lower in this scenario, a margin of error of 12% is deemed acceptable. Walk-through efforts and egg mass surveys are the main sampling methods used, which allows for higher accuracy of population assessment (Appendix A; Figure 7).

For the high-budget scenario (+$50,000 annually), prevention of noticeable defoliation is prioritized. Therefore, a threshold of 1,250 egg masses/ha is deemed acceptable. A monitoring network of 400 plots was developed with residential, parks and woodlots, and open-space areas prioritized. Most data collection will be conducted by in-house staff with some assistance from consultancy firms in the urban forestry sector. Egg mass surveys will be the main sampling method utilized, which allows for higher accuracy in assessment (Appendix A; Figure 8).

Table 3: Key results from gypsy moth monitoring network design.

Scenario	Budget ($/year)	Goals	Threshold (egg masses/ha)	Number of Plots	Margin of error	Data collection	Sampling method	Land-use targeted	Expansion criteria
Low Budget	>$20,000	-Human health -Prevention of tree mortality	2,500 (60% defoliation)	3+ (heritage trees)	25%	In-house efforts, consultants, volunteers	Walk-through, windshield, egg mass surveys	Residential	Infestation history, oak concentration, climate data
Medium Budget	$20,000-$50,000	-Human health -Prevention of growth loss	1,750 (40% defoliation)	200+	12%	In-house efforts, consultants, volunteers	Walk-throughs, egg mass surveys	Residential, parks and woodlots	Infestation history, oak concentrations, climate data

High Budget	$50,000+	-Human health -Prevention of noticeable defoliation	1,250 (30% defoliation)	400	<10%	In-house efforts, consultants	Egg mass surveys	Residential, parks and woodlots, open-space	Call volumes

Discussion

(1) *Adopting IPM into urban forest management planning can help to strengthen municipal response to pests*

The objective of an IPM system is to reduce the frequency and severity of future outbreaks. It is a methodology for dealing with destructive insects affecting urban trees (Wassenaer 2014). Components include monitoring and decision-making based on relevant data. For gypsy moth, this could include egg mass densities and quality, larval counts, male moth captures, defoliation estimates, stand susceptibility, environmental sensitivity, and incident of disease.

The IPM decision-making process results from an evaluation of treatment options available and an analysis of impacts (BioForest 2006). IPM strategies also include a cost-benefit analysis, and participation from all stakeholders involved (BioForest 2006). The goal of an IPM system is to maintain tolerable gypsy moth populations at any point in time and make sure that outbreaks are properly controlled (treatment methods are listed in detail in Appendix E). This can include implementing an invasive species management plan with distinct goals and targets to be reached, as seen in the City of Mississauga.

The strategies utilized by the City of Mississauga are among most effective of the municipalities reviewed. However, it should be noted that the City of Mississauga only has 15% canopy cover, which is quite low. The number of trees may be affecting the overall success of their IPM approach to urban forest management planning. Therefore, the first hypothesis that adopting IPM into urban forest management planning can strengthen municipal response to pests cannot be successfully confirmed or denied.

Best management practices for gypsy moth control

The matrix is intended to question the best management practices for gypsy moth management across districts. The standard developed with information provided publicly is a start to answering this question. The most useful information from the analysis is filtered out by the matrix approach. Targets are, however, arbitrarily set by municipalities, at it is up to it which one fits best in reality based on individual goals and budget concerns (Ordonez and Duinker 2013).

Developing a BMP list builds upon existing frameworks described in literature and draws attention to vague areas of urban forest management such as pest management by pointing out how ambitious municipalities are addressing them, as in the case of the City of Hamilton and Peel region's climate change adaptation strategies, or Mississauga's invasive species management plan (Ordonez and Duinker 2013; Peel Region 2011).

Some management themes like tree maintenance are more concrete with practical applications (Ordonez and Duinker 2013). Due to this, they are shared by many UFMPs and do not have much room to improve. In contrast, integrating pest management, development of an invasive species plan, monitoring, treatment options and scale of treatment require more specificity in future planning (Ordonez and Duinker 2013). BMPs for urban pests were permanent, annual monitoring, development of an invasive species plan, and IPM (Appendix B, Table 7). Urban forest management could benefit from the future implementation of BMPs.

Incorporating IPM into UFMP

Many gypsy moth programs utilize IPM techniques for effective management of gypsy moth. For example, in the United States, the National Gypsy Moth Management Program focuses on "Slow the Spread" (STS) as their slogan. IPM for the STS program focuses on reducing damage and the frequency of new infestations in transition areas. IPM programs in the United States involve mass trapping, sterile moth release, Btk and mating disruption, as well as insect growth regulators like Gypchek (Pederson and Munson 2010; El-Sayed et al. 2006).

In 2008, Tobin et al. found that decreasing the size of action zones (or treatment reduction) and increasing evaluation zones resulted in trapping savings and treatment cost (Tobin et al. 2008). This could be useful knowledge to developing an IPM strategy. Future management and regulation costs may end up completely outweighing the cost of monitoring (Tobin et al. 2008). In order to be considered successful, future monitoring programs should contain a method for low density detection and effective treatment tactics. This will be different for each municipality based on individual features and management goals.

Alteration of the scale of the program would affect its cost. The STS program provides a template to federal and provincial program managers with which to make decisions as to how to co-ordinate STS given financial constraints (Tobin et al. 2008). In the absence of an IPM program, the spread of GM would be ~21.7km year in the United States (Tobin et al. 2008). This would be much lower in Canada due to different climatic conditions. Therefore, incorporating IPM into UFMP is considered to be an effective and feasible strategy for gypsy moth control in North America, and the first hypothesis can be accepted.

(2) *Collaboration across municipal boundaries can help to strengthen gypsy moth management in southern Ontario*

The presence of a UFMP does not necessarily mean best practice. As we can see from Norfolk county, for example, the commitment of the homeowner's association to forest management and coordination that takes place between the Long Point Conservation Authority, the City of Norfolk and the OMNRF has strengthened their response to gypsy moth and other invasive pests (Appendix A; Figure 11). In Burlington, however, where there is a UFMP in place, there is a lack of co-ordination with other municipalities on a landscape scale and with the general public, which has caused disconnection in pest response and co-ordination.

The presence of definitive goals, targets, and by-laws, however, as well as implementing BMPs for gypsy moth, seem to be the most effective for long-term pest control on a municipal budget. Mississauga and Oakville provide strategic examples of this. The implementation of IPM including long-term monitoring as well as co-ordination with neighbouring municipalities, large landowners such as conservation groups, regions, and public involvement is a viable strategy when working on a municipal budget, and captures the largest variety of urban forestry goals.

The standards developed here are quite vague, with most objectives defined as "increase" or "enhance". The standard was developed from the most specific examples across all plans. Therefore, its vagueness reflects the vagueness of the planning itself (Ordonez and Duinker 2013). Lack of specificity is due to lack of information, the fact that some indicators cannot be quantified, and the fact that forest managers developing the plans are not in tune to specific criteria (Ordonez and Duinker 2013). This creates issues in urban forestry definitions across the landscape. Development of a common approach to management based on goals for canopy cover, diversity and size can help to address common goals across municipalities such as loss and lack of species diversity, and increasing environmental and human benefits (Ordonez and Duinker 2013).

In the Spring of 2018, Oakville, Mississauga, and Hamilton collaborated with each other in coordinating a spray program (BioForest 2018). This helped to ease costs to all three municipalities by adopting a strategy across jurisdictional boundaries. As well, the monitoring and treatment conduction in Norfolk County in affiliation with the Norfolk Homeowners Association and OMNRF for gypsy moth illustrates the effectiveness of co-operation on pest control issues in areas with smaller budgeting or staff (Biddle 2017).

To allow good interpretation of data, a wide perspective of data must be collected in the adjoining geographic regions, and standardized protocols in place (Ravlin et al. 1990). From the examples observed in the matrix, the best and least-cost practices for gypsy moth were strengthened by cross-jurisdictional co-ordination. Therefore, the second hypothesis, collaboration across municipal boundaries can help to strengthen gypsy moth management in southern Ontario, can be accepted. If proper urban forest strategies are implemented and upkept successfully, pest management will become easier and more integrated in municipal management.

Urban forest management strategies

Certain urban forest management strategies must be implemented across all municipalities in order for an IPM approach to be successfully implemented. Routine maintenance can be strengthened by the presence of an up-to-date tree inventory, and hazard trees prioritized (Ambrosii 2004). Inventories can be used to gain knowledge for researchers and practitioners. Applications for tree inventories include tree condition reporting, invasive species mapping, hazard abatements such as inspection, ensuring safety of urban trees, tree care, and meeting canopy cover goals (Ambrosii 2004).

BMP for urban tree inventories use Arc-GIS technology, and programs such as i-Tree and Neighbourwoods can be utilized for collection and analysis of inventory data. These programs can also be used for tree valuation and can be applied to policy decision (Jaenson et al. 1992).

Citizen science can be useful in creation of inventories, because data collection does not necessarily have to be conducted at a professional level. In turn, the collection of volunteer data helps with public participation and engagement in urban forestry. The monitoring of street trees presents an opportunity for volunteer contributions and facilitates learning (Johnson et al. 2018). Acts of engagement such as contribution to tree inventory data can strengthen connections to social-ecological systems (Johnson et al. 2018). Public engagement can be a very low-cost way to monitor for pests in residential areas (BioForest 2016). In order to strengthen volunteer data collection, a focus on field-instruction and technical assistance should be increased, and decisions to use volunteer data should be based on the level of specificity and training methods used for a given project (Johnson et al. 2018).

Implementing an IPM program for managing gypsy moth can benefit from an effective education program (BioForest 2006). In Oakville, the Town Forestry department partners with a private consulting form to deliver the Forest Health Ambassadors Program (Barker et al. 2018). The program trains volunteers to do basic tree health assessments and to look for signs and symptoms of select pests such as gypsy moth (Barker et al. 2018). The consideration of volunteer motivations when designing volunteer programs can positively affect turnout and retention (Johnson et al. 2018). Developing community outreach programs can help foster a thorough understanding of forest pests and their environments.

In Oakville, the Gypsy Moth Activity Database is kept up to date with information from Oakville Forestry staff and other municipal departments, as well as Oakville residents, Forest Health Volunteers, and Forestry contractors (Kenney et al. 2008). This has proved to be useful to identify new areas of concern and target new sites for annual monitoring.

The Early Detection and Distribution Mapping System of Ontario (EDD MapS Ontario 2018) could be a very useful tool in collection of citizen science data. EDD MapS encourages real-time tracking of invasive species occurrences based on user participation (EDD MapS Ontario 2018). This type of monitoring can generate large quantities of data over jurisdictional boundaries. Users enter information into a standardized form, which allows specific information about infestations to be added (EDD MapS Ontario 2018). The information is then verified by the OMNRF and other forestry professionals in Ontario. The utilization of tools such as EDD MapS can be a useful, low-cost strategy for the promotion of long-term forest health and helps to engage community members.

(3) *Implementing a monitoring program is an effective method for gypsy moth control with the lowest-cost and most effective methods of detection prioritized*

There is strong evidence that points toward the development of a monitoring system for urban pests as the most effective method of urban pest control (Ravlin et al. 1990). In order to optimize benefits for urban forest managers, the design of this system should be based on BMPs. Monitoring can help arrange resources optimally and increase efficacy of treatment application. Annual surveys help to define new populations, initiate control activities, and mitigate impacts of potential future outbreaks (BioForest 2017) (sampling methods listed in detail in Appendix D).

Although implementing a monitoring program can be costly depending on treatment methods used, often the cost of not treating is significantly higher. The “do nothing” option is the most widely used for Canadian pest outbreaks (Hayes et al 1998). Consequences of doing nothing have environmental repercussions. Mature forests will be most heavily affected by gypsy moth outbreaks. Defoliation over large areas of forest reduces water use by trees and results in fluctuations in run-off and soil temperature (Benoit and Lachance 1990). Less-favored species and understory vegetation may experience direct benefits from defoliation through increases in light, moisture and nutrients (Campbell 1979). As well, infestations can alter shrub, grass, and herb growth, which can affect species composition. Frass and oak leaf tannin abundance in streams can result in reductions to water quality. Canopy cover loss due to defoliation can cause increases in stream temperature which can affect stream organisms (Gottschalk 1993).

Gypsy moth outbreaks also impact economics. Outdoor activities are reduced when populations area high, impacting tourism business. Defoliation can aesthetically affect an area, reducing the number of visitors for periods of several years beyond the outbreak's duration. In areas where property owners are affected, they can incur costs for removal of egg masses or caterpillars, treatment of gypsy moth with pesticide, tree pruning, replacing dead or damaged trees and shrubs, and increased liability costs (BioForest 2006). Municipalities will have to pay for tree removal and replacement costs, loss of aesthetic value, increased inspection costs, increased pruning and maintenance costs, and liability costs or lawsuits (BioForest 2006).

Public health

In smaller municipalities, urban forest managers must make mindful decisions in order to prioritize public health, often at the risk of urban forest health. For example, some urban forest managers choose to treat only public trees, while others provide subsidies for treatment on private lands (Curtis Marcoux, *personal communication* 2018). Urban forest managers must be mindful of which trees they choose to manage, especially when this may or may not impact targeted pests. In the case of landscape pests such as the gypsy moth, identifying areas of concern can be difficult when private properties are not assessed, creating political and safety issues.

Gypsy moth outbreaks can negatively affect human health. During high population periods, allergic reactions to gypsy moth larval hairs have been reported, as well as rashes and eye, skin and respiratory tract irritations as a result of contact with caterpillars (BioForest 2006). Safety hazards can be caused by dead limbs breaking or falling to the ground, as well as droppings making walkways or roads slippery (BioForest 2006). Human health can also be affected indirectly by increased air pollution, climate extremes, and noise pollution.

Every municipality, however, will have different risk thresholds, budgets, tolerance levels, public support, and resources. For example, the Norfolk County Woodlot Owners Association is a prominent association that plays a major role in municipal pest issues (Adam Biddle, *personal communication* 2018). This is due to the high proportion of private land in Norfolk County. Other municipalities will have different circumstances according to geographical and infrastructural features.

Population assessment

Due to its association with many different tree species, activity during larval stage, and fluctuations between low endemic and high outbreak populations over short periods of time, accurate assessment gypsy moth populations and forecasting of damage can be a challenge (Nealis and Erb 1993). The tendency of early instar larvae to disperse by ballooning in large numbers also complicates assessments and forecasts, as it can result in areas with high defoliation rates in some areas even if egg mass densities are low (BioForest 2006).

Gypsy moth population fluctuations are strongly influenced by climatic changes. Increases in population density are related to significantly high December temperatures (Pernek 2008). Extreme weather conditions such as prolonged cold temperatures (≤32 ^{o}C) can kill eggs, which keeps densities low or helps decrease populations. Eggs below the snow line usually less susceptible to winter mortality, as the snow helps to insulate the eggs and protect them from cold temperatures (BioForest 2006). Outbreak collapses are related to higher precipitation in March. These events occur during the gypsy moth population cycle and help to moderate their populations. Knowledge of gypsy moth behaviour and climate data from previous winters can be used to predict short term outbreak forecasts to reduce forest damage (Pernek 2008).

In Oakville, for example, winter temperatures in 2016-2017 and 2017-2018 never fell below -32˚C. In the winter of 2018, January temperatures were lowest at -22˚C (Appendix B, Table 9). Therefore, no die-off of gypsy moth would have been experienced due to severely low temperatures. As gypsy moth continue to move northward, however, low winter temperatures will affect the population's ability to spread.

These challenges can be addressed by implementing the correct management strategies and treatment options at the correct time, which is one of the main components of IPM programs. Although population assessment can be difficult, it is revealed here that the cost of doing nothing would be significantly higher with less effectiveness. Therefore, a plot network design must be based off of individual factors and altered for each year. From this analysis alone, it is not possible to assert that a monitoring program is the most effective method of gypsy moth control. However, it can be a useful strategy and is certainly cost effective.

Recommendations

Based on the findings from this research, the need for developing standardized methods for enhancing tree health and controlling invasive pests is crucial to implementing proper pest management in an urban setting. The evaluation UFMPs and other municipal documentation in a matrix of criteria and indicators reveals the need for strengthened and specific documentation when it comes to invasive species, pre-emptive measures for tree care, common goal setting across municipalities, and access to public information on a large scale.

The establishment of clear goals and urban pest strategies allows for strategic collaboration across districts, which is especially crucial when it comes to landscape pests such as gypsy moth. This is described as regular updates to inventory and bylaws, as well as strategic budget usage. In areas where BMPs are implemented in urban forest planning (the establishment of specific targets, goals and objectives through UFMPs and relevant documentation), an IPM approach can be taken, regardless of budget concerns. This means strategically allocating resources toward urban forestry professionals such as consultant groups, or hiring of qualified people to address pest-specific or tree-care specific issues.

Based on the acceptance of the first and second hypothesis through a review of municipal urban forest management documentation and relevant literature, it is recommended that the plot network outlined be implemented to some degree across southern Ontario, as it is a cost-effective and useful strategy. It is also recommended that a current gypsy moth activity be kept up to date across southern Ontario to track the population spread of gypsy moth. EDD MapS could be utilized as a tool for this data collection across jurisdictions.

Conclusion & Possible Extensions of the Work

Certain aspects of urban pest management require further research and development. For example, the sampling protocol for gypsy moth sampling protocol in an urban setting is not standardized. Egg mass sample plot spacing is generally only standardized in a naturalized forest setting (USDA 1995). In an urban forest setting, however, the tendency of gypsy moth populations to cluster must be properly addressed. As well, the 5-tree cluster plot that is utilized by some consultancy firms adopts a modified-MKP method, and has not yet been assessed for accuracy (BioForest 2016). The effects of a no intervention scenario for gypsy moth should also be explored in greater detail to assess the repercussions to urban forest management.

A similar concept could be applied perhaps in a larger capacity to other forest pests and help outline their interactions, allowing forest managers to view a large, integrated network and giving them options to manage their forests. The use of websites like EDDMapS Ontario provides an accessible, scientific and reliable way to advise on pest issues (EDDMapS 2018). Many municipalities cannot seek outside consultation due to budget constraints, and lack of pre-emptive tree data collection such as tree inventories leads pests such as gypsy moth to spread.

Tree diseases and pests know no borders, and, if left untreated, the implications can be grave. The hypotheses for this research were (1) Adopting IPM into urban forest management planning can strengthen municipal response to pests, (2) collaboration across municipal boundaries can help to strengthen gypsy moth management in southern Ontario, and (3) adopting a monitoring program is an effective method for gypsy moth control with the lowest-cost and most effective methods of detection prioritized. The first two hypotheses were accepted through this analysis and review of available literature on gypsy moth, and the third recommended. Incorporating low-cost IPM strategies into urban forest management planning, such as creating a comprehensive monitoring network for pests such as gypsy moth as well as common goal setting across municipalities could help remedy budgeting issue and create cohesion and co-operation. Ultimately, this will help to mitigate the negative outcomes associated with gypsy moth outbreak and help urban forest managers to meet municipally outlined goals.

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Appendix A: Figures

Figure 1: Areas in North America quarantined for European gypsy moth
Source: USDA.

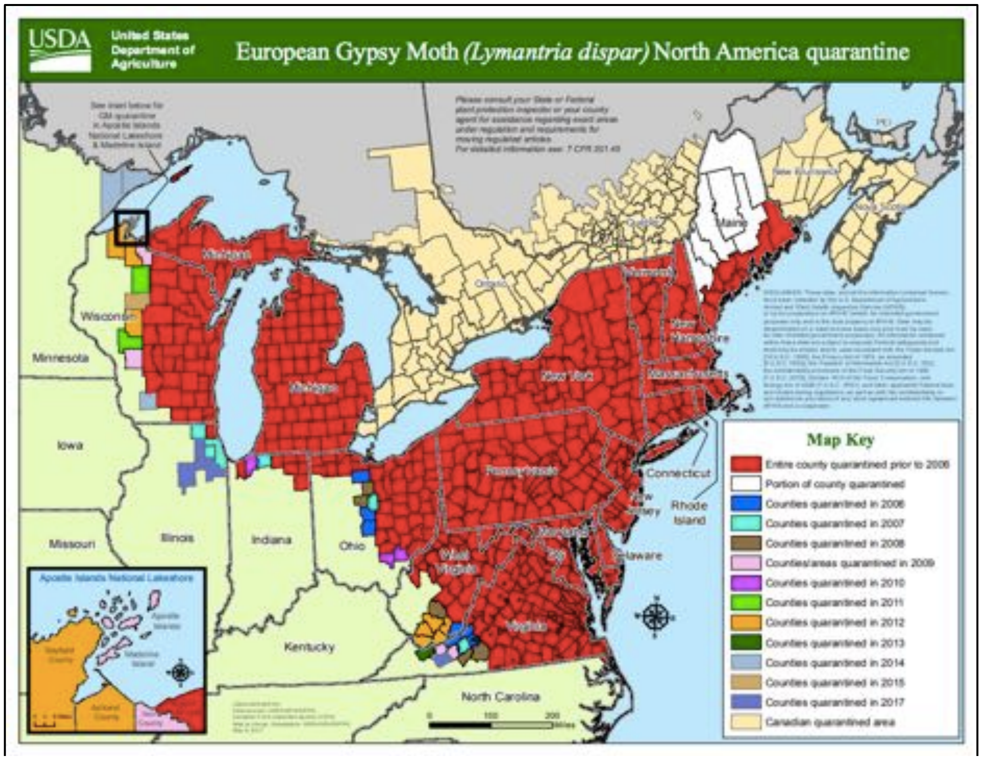


Figure 2: Gypsy moth defoliation in Ontario, 1981-2005.
Source: BioForest 2006

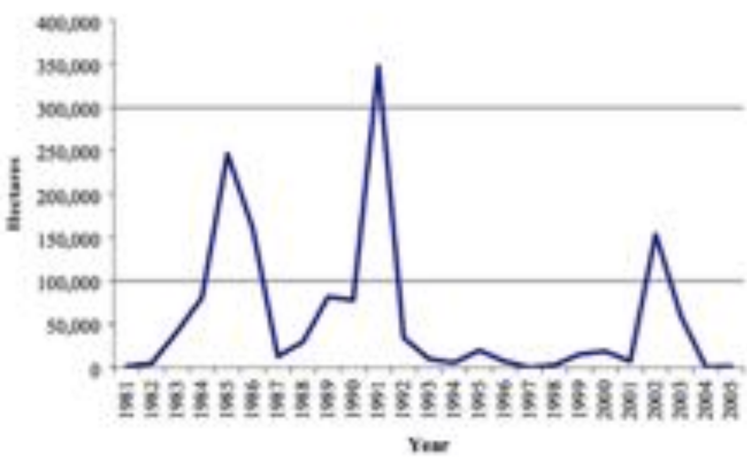


Figure 3: Egg mass survey methodology. Examination of tree crowns from 2 opposing vantage points. Source: Aurora Lavender, 2018. Scott Cassidy and Ahmad Alamad pictured.

Figure 4: Table showing gypsy moth defoliation forecasts based on gypsy moth egg mass densities per hectare. Source: BioForest, 2006

Egg masses/ha	Defoliation forecast
0	Nil
1-1235	Light (1-40%)
1236-6175	Moderate (40-75%)
6176+	Severe (>75%)

Figure 5: Residential, open space, and parks and recreation land-use areas in Oakville, Ontario.
Source: StatsCan.
Developed in ArcMap 10.6.1

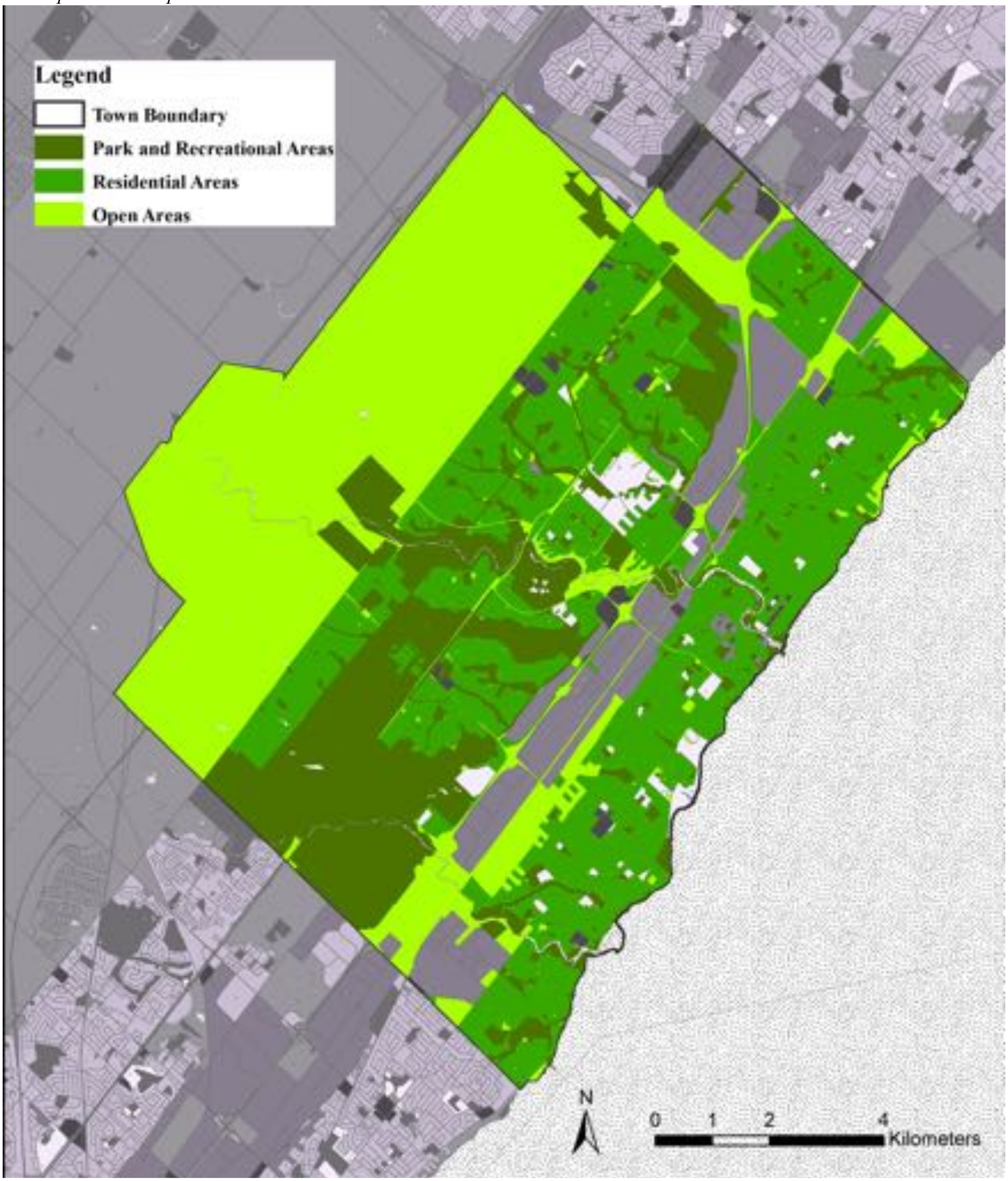


Figure 6: Gypsy moth monitoring network for low budget scenario in residential, open space, and parks and recreation land-use areas of Oakville, Ontario.
Source: Oakville Tree Inventory
Developed in ArcMap 10.6.1

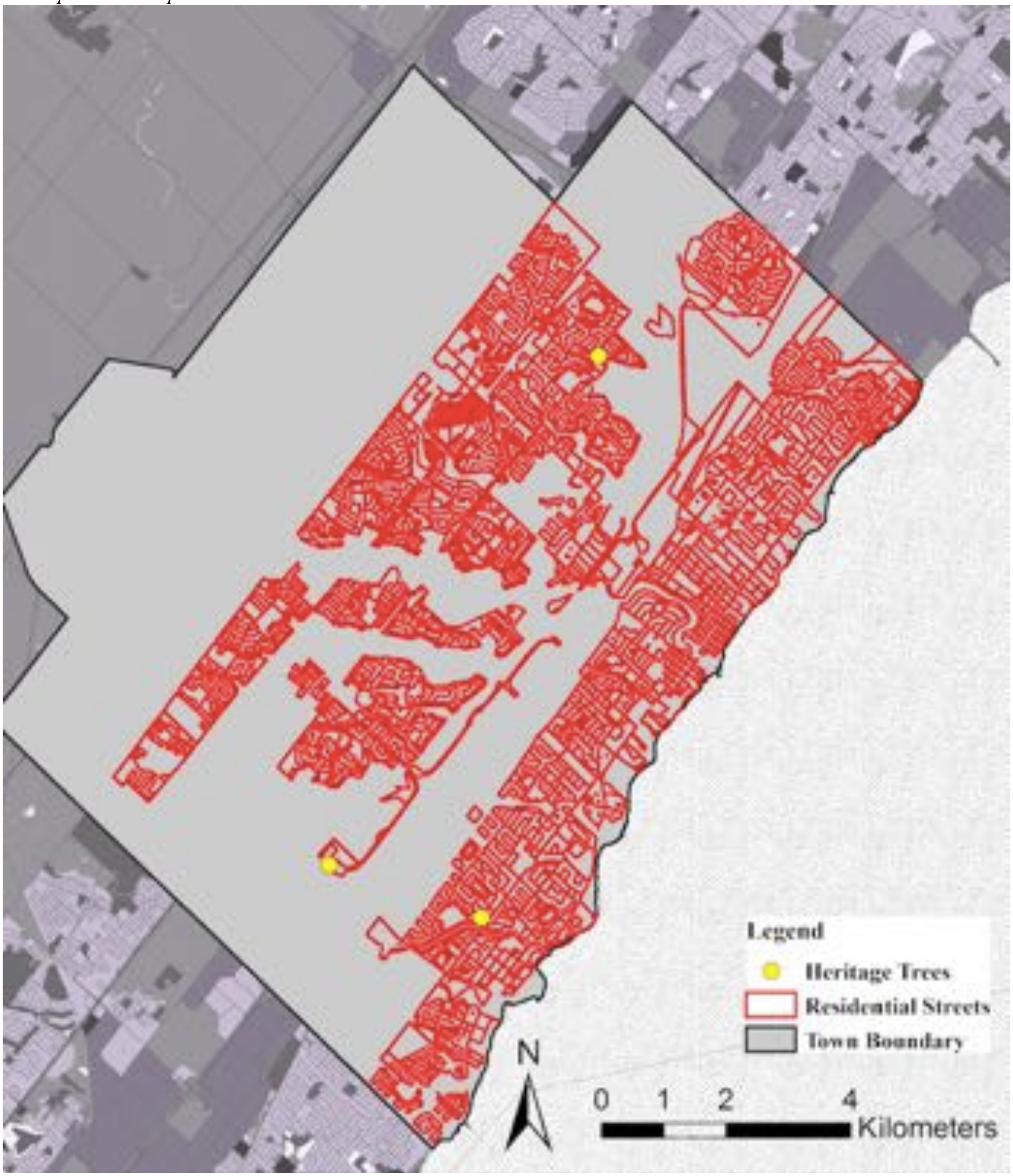


Figure 7: Gypsy moth monitoring network for medium budget scenario in residential, open space, and parks and recreation land-use areas of Oakville, Ontario.
Source: Oakville Tree Inventory
Developed in ArcMap 10.6.1

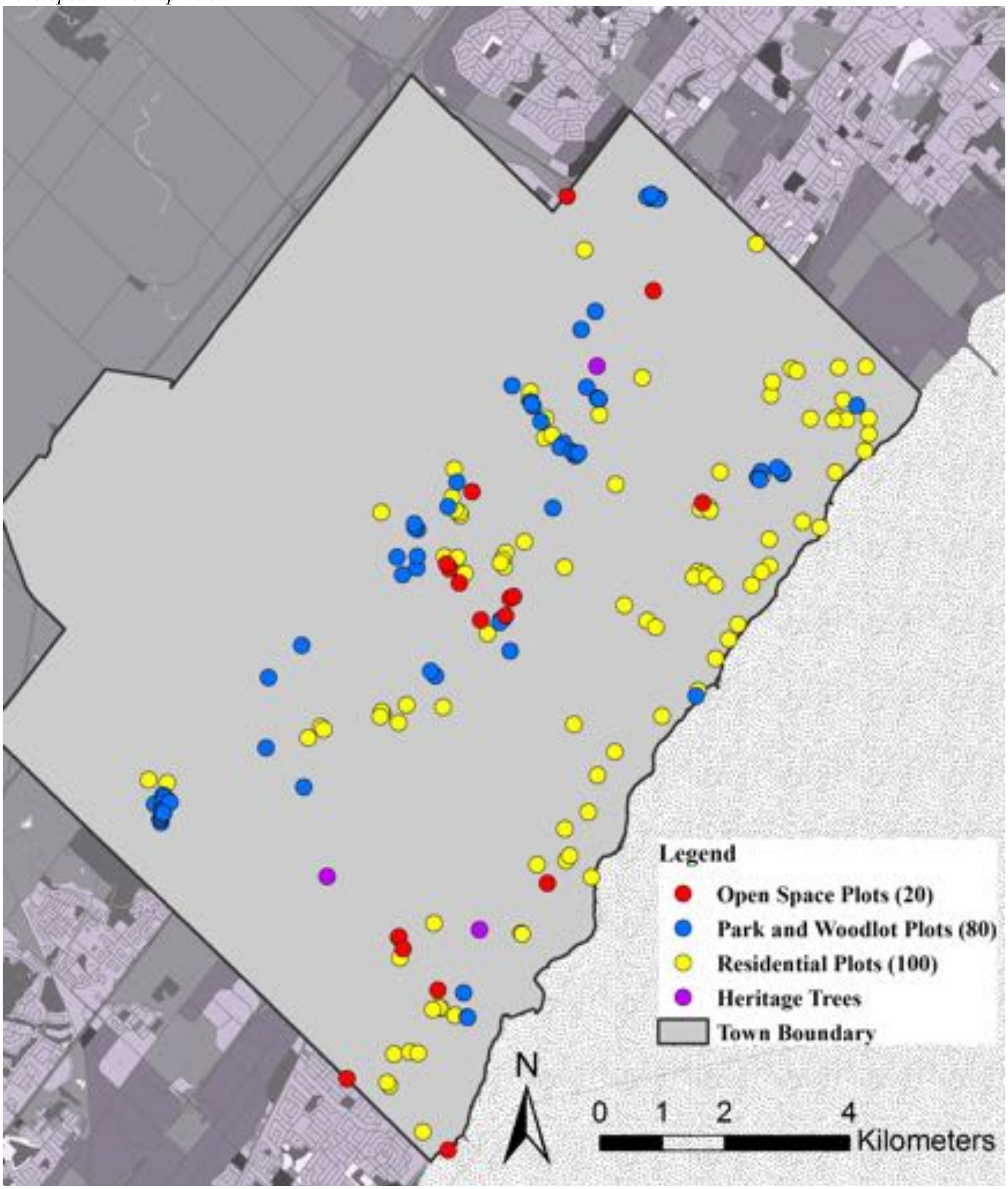


Figure 8: Gypsy moth monitoring network for high budget scenario in residential, open space, and parks and recreation land-use areas of Oakville, Ontario.
Source: Oakville Tree Inventory
Developed in ArcMap 10.6.1

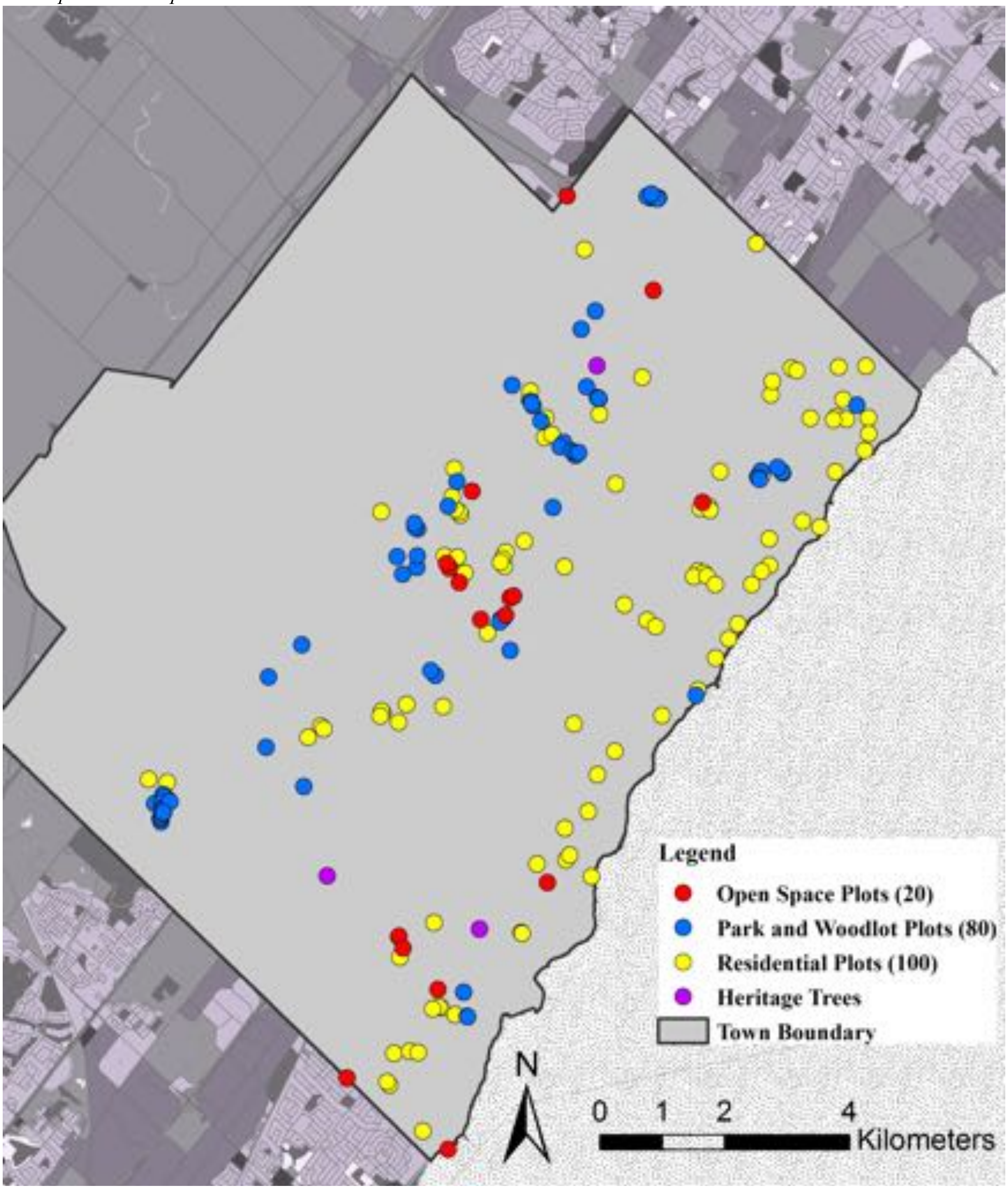
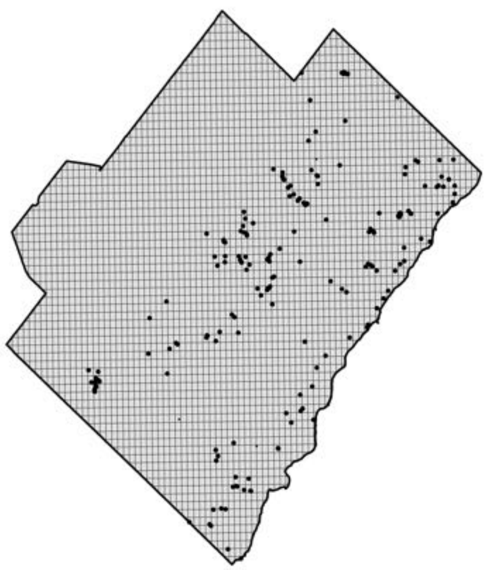


Figure 9: Grid network stratified-random PSPs for medium budget scenario in residential, open space, and parks and recreation land-use areas of Oakville, Ontario.
Figure 10: Grid network stratified-random PSPs for high budget scenario in residential, open space, and parks and recreation land-use areas of Oakville, Ontario.
Source: Oakville Tree Inventory
Developed in ArcMap 10.6.1



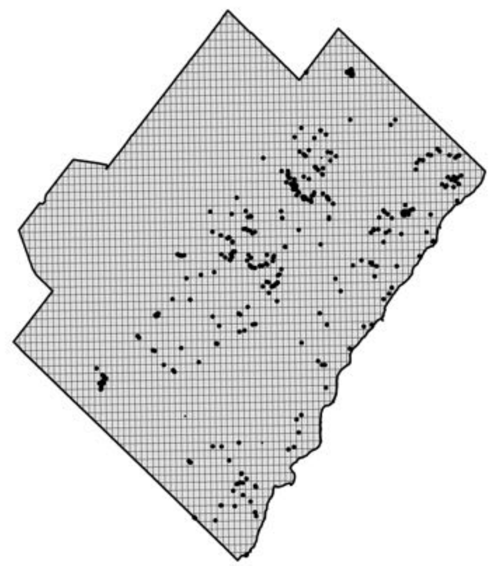


Figure 11: Historical vs. proposed gypsy moth management in Norfolk County, Ontario.
Source: County of Norfolk, 2008

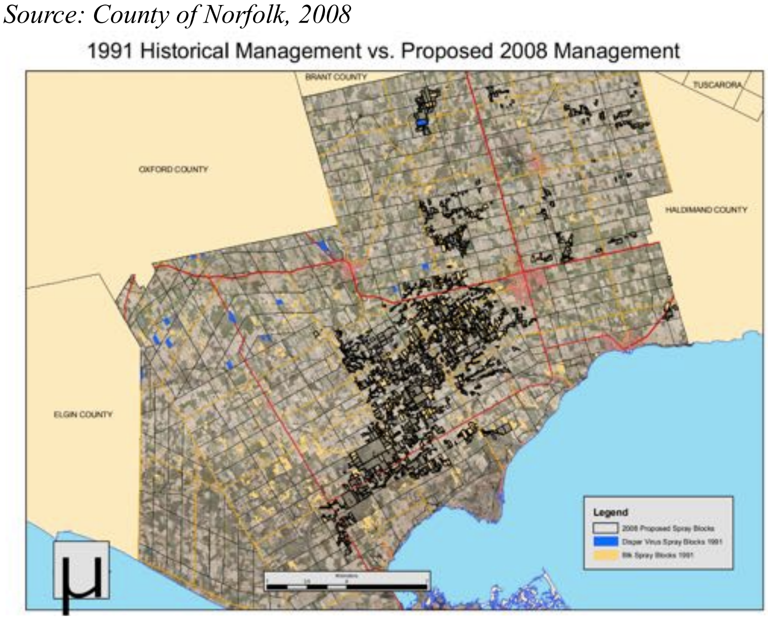
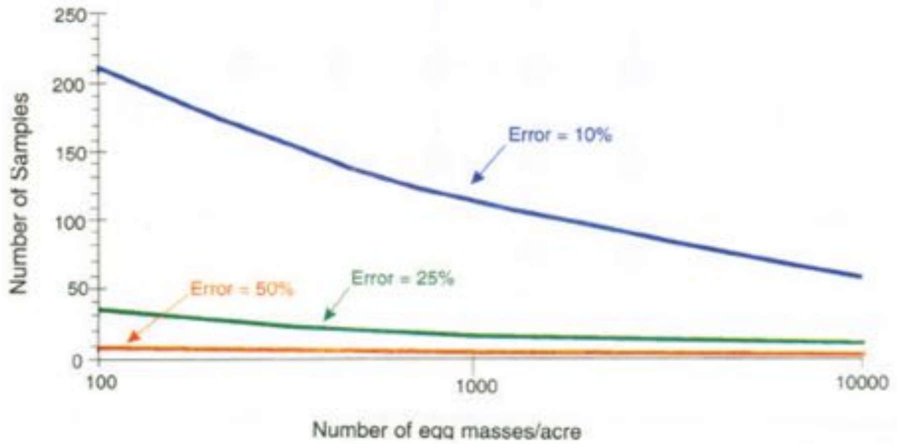


Figure 12: Error margins for egg mass sampling.
Source: Liebhold et al. 1994.



Appendix B: Tables

Table 4: Gypsy moth life cycle with photographic representation.
Source: BioForest, 2006

Egg mass → Larva→ Pupa→ Adult

Table 5: Host preference of the European gypsy moth.
Source: BioForest, 2006

Most Preferred Host	Preferred Host	Least Preferred Host
Oak (all)	Beech	Black ash
Largetooth aspen	Yellow birch	Green ash
Trembling aspen	Cherry (all)	White ash
White birch	Butternut	Black locust
Grey birch	Chestnut	Mountain maple
Tamarack	Eastern hemlock	White cedar
Alder	Ironwood	Easter red cedar
Apple (all species)	Maple (most species)	Sumac
Hawthorn	White spruce	Red mulberry
Willow	Norway spruce	Tulip-tree
Manitoba maple	Pine (all species)	Balsam fir
Mountain ash	Hickory	Sycamore
Larch	Sassafras	
	Serviceberry	

Table 6: Municipality size (km^2) and population (2016) in southern Ontario.
Source: StatsCan, 2018

	Norfolk County	Town of Oakville	City of Hamilton	City of Mississauga	City of Burlington	City of Toronto
Size	1,607 km^2	138.5 km^2	1,138 km^2	292.4 km^2	185.7 km^2	630.2 km^2
Population (2016)	64,044	193,832	536,915	721,600	183,315	2.732 million

Table 7: Justification of Criteria and Indicators for Urban Forestry and Gypsy Moth Management.

Theme	Criteria	Indicator	Objective/target (most specific/ambitious)	Type of Measurement
Maintenance	Pruning	Pruning cycle	2-5 years	Numeric
		Best management practices (BMPs)	encourage BMPs	Categorical
	Removal	Response time	Decrease	Categorical
		BMPs in removal specifications	Encourage BMPs	Categorical
		Identification	Enhance database	Categorical
	Tree Replacement	Replacement ratio (public and private trees)	1:1 ratio	Numeric
Management	Staffing	Hired consultancy firms	Specific projects	Categorical
		Highly educated staff	Training	Categorical
	Urban Forest Management Plan	GM control-specific management plan	Create, update every 10 years	Categorical
	Private subsidies	Homeowner resources	Lower homeowner maintenance costs for tree maintenance, pests	Numeric
		Permit system	create for tree care/removal	Categorical
		Private tree protection bylaw	create and undertake feasibility	Categorical
	Tree Inventory	GIS-based inventory	Adapt database to GIS, update regularly	Categorical
Environmental	Hazard trees	Risk reduction	Increase	Categorical
		BMPs in control specifications	Encourage BMPs	Categorical
		Response time	Decrease	Categorical
	Tree size	Large-stature trees	Favour in new plantings	Categorical
	Tree age	Representation of age class	Increase (e.g. max 10% for any age class)	Numeric
	Tree diversity	Family/genus/species %age representation of total forest	Increase (e.g. <10% for species, <20% for genus, <30% for family)	Numeric
	Climate	Resilience to climatic conditions that favor gypsy moth	Increase	Categorical
	Canopy cover	Percentage of total urban area	Increase (i.e. 20-40% over 20 years)	Numeric

Theme	Criteria	Indicator	Objective/target (most specific/ambitious)	Type of Measurement
Education (awareness)	Communication	Public information Centre (PIC)	Create or enhance	Categorical
		Site interpretation	Create or enhance for natural areas	Categorical
		Communications plan	Create	Categorical
		Communications role	Create	Categorical
Education (engagement)	Volunteering	Volunteer program	Create or enhance	Categorical
		Urban forest tours	Create or enhance	Categorical
	Plantings	Along recreational routes	Increase	Categorical
	Workshops	Information workshops	Create or enhance	Categorical
		Tree pest detection workshop	Create or enhance	Categorical
Monitoring	Sampling	Preventative or adaptive	Annually	Categorical
		Pest identification	Enhance monitoring and database	Categorical
		Permanent plot network	Create	Categorical
	Historical infestation	Tracking past infestations to inform current policy	Track annually (5+ year period)	Categorical
	Egg mass surveys, pheromone-baited traps	Aspect of sampling procedure	Enhance	Categorical
	Gypsy moth/Invasive species control	Procedure for addressing gypsy moth	Mention, outline objectives	Categorical
Treatment	Aerial Spray	Aspect of treatment procedure	Enhance and strategize	Categorical
		Outside hire	Create (including contractors)	Categorical
	Ground Spray	Aspect of treatment procedure	Strategize	Categorical
	Banding	Aspect of treatment procedure	Strategize	Categorical
	Threshold for treatment	Level above which treatment is necessary	BMP (1,000-2,500 egg masses detected)	Categorical

Theme	Criteria	Indicator	Objective/target (most specific/ambitious)	Type of Measurement
Cultural Identity	Heritage trees	Historic/heritage tree program	Create	Categorical
		Identification	Identify 5 new/year	Numeric
		Protection	Enhance	Categorical
	Municipal documentation	Bylaw update and amendment	Change municipal documentation annually	Categorical
Legislative	Practitioners	Staff openings, RPF or FTE on staff	Create, add	Categorical
		Staff training requirements	Create (including contractors)	Categorical
	Municipal continuity	Recognition of landscape-level effects across districts	Collaboration	Categorical
		Co-ordination efforts	Inter-municipal (i.e. RPF representative across several districts)	Categorical
	Climate change strategy	Public information	Increase	Categorical
		Specific plan implementation	Create and maintain	Categorical
Economic	Finances	Identification of costs, tree benefits	Identify implementation costs, seek financial support, create monitoring incentives	Numerical
Temporal-spatial	Scale of treatment	Multi-scale specifications	Create targets and objectives	Categorical
	Resource continuity (across ownership)	One ecosystem across ownership	Recognize public and private patterns	Categorical

Table 8: A Comparative Matrix of Criteria and Indicators for Oakville, Hamilton, Burlington, Norfolk, Mississauga and Toronto.

Theme	Criteria	Norfolk County	City of Burlington	Town of Oakville	City of Hamilton	City of Mississauga	City of Toronto
Maintenance	Pruning						
	Removal						
Management	Tree Replacement						
	Staffing						
	Urban Forest Management Plan						
	Private subsidies						
	Tree Inventory						
Environmental	Hazard trees						
	Tree size						
	Tree age						
	Tree diversity						
	Climate						
	Canopy cover						
Education (awareness)	Communication						
Education (engagement)	Volunteering						
	Plantings						
	Workshops						

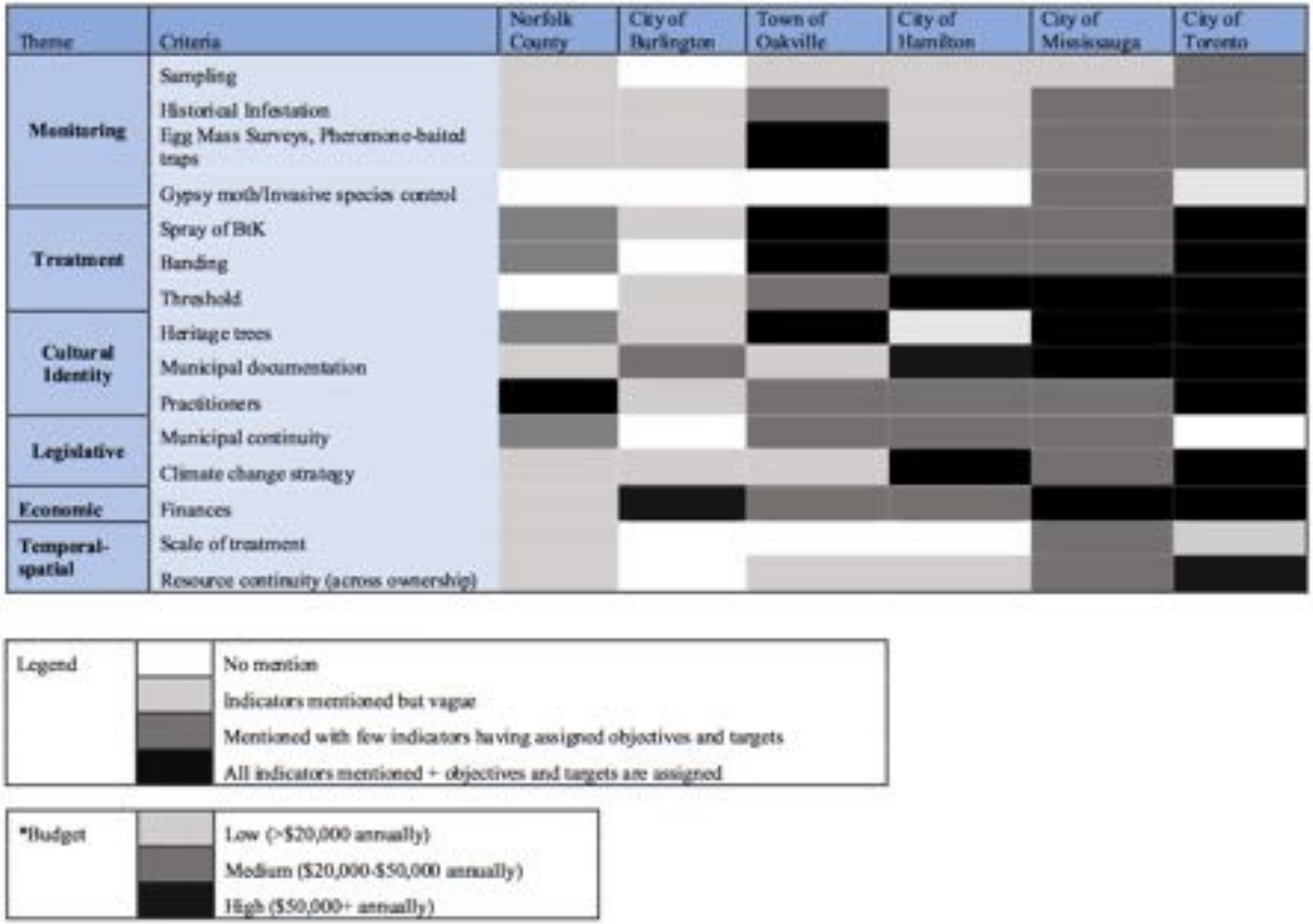

Theme
Criteria
Norfolk County
City of Burlington
Town of Oakville
City of Hamilton
City of Mississauga
City of Toronto
Monitoring
Sampling
Historical Infestation
Egg Mass Surveys, Pheromone-baited traps
Gypsy moth/Invasive species control
Treatment
Spray of BtK
Banding
Threshold
Cultural Identity
Heritage trees
Municipal documentation
Practitioners
Legislative
Municipal continuity
Climate change strategy
Economic
Finances
Temporal-spatial
Scale of treatment
Resource continuity (across ownership)
Legend
No mention
Indicators mentioned but vague
Mentioned with few indicators having assigned objectives and targets
All indicators mentioned + objectives and targets are assigned
*Budget
Low (>$20,000 annually)
Medium ($20,000-$50,000 annually)
High ($50,000+ annually)

Table 9: Climate data for the Town of Oakville, Ontario (October 2016-October 2018).
Source: *Global Summary of the Month for 2018. U.S. Department of Commerce. National Centers for Environmental Information National Oceanic & Atmospheric Administration. National Environmental Satellite, Data, and Information Service. Generated on 11/29/2018.*

Current Location: Elev: 551 ft. Lat: 43.5167° N Lon: -79.6833° W
Station: **OAKVILLE TWN, ON CA CA006155750**

Date	Temperature (F)													Precipitation (Inches)								
Elem ->	TAVG	TMAX	TMIN	HTDD	CLDD	EMXT		EMNT		DX90	DX32	DT32	DT00	PRCP	EMXP		SNOW	EMSD		DP01	DP10	DP1X
										Number of Days					Greatest Observed		Snow, Sleet			Number of Days		
Month	Mean	Mean Max.	Mean Min	Heating Degree Days	Cooling Degree Days	Highest	High Date	Lowest	Low Date	Max >= 90	Max <= 32	Min <= 32	Min <= 0	Total	Amount	Date	Total Fall	Max Depth	Max Date	>=.01	>=.10	>=1.0
Oct	54.3	61.9	46.7	344	12	79	18	30	26	0	0	3	0	1.89	0.60	01	0.0	0	31	11	7	0
Nov	45.1	53.1	37.2	597	0	67	01	25	23	0	0	8	0	2.24	0.98	02	0.0	0	30	11	6	0
Dec	29.9	35.2	24.7	1086	0	52	26	8	16	0	9	25	0	3.27	0.83	11	16.9	9	17	13	9	0

Current Location: Elev: 551 ft. Lat: 43.5167° N Lon: -79.6833° W
Station: **OAKVILLE TWN, ON CA CA006155750**

Date	Temperature (F)													Precipitation (Inches)								
Elem ->	TAVG	TMAX	TMIN	HTDD	CLDD	EMXT		EMNT		DX90	DX32	DT32	DT00	PRCP	EMXP		SNOW	EMSD		DP01	DP10	DP1X
										Number of Days					Greatest Observed		Snow, Sleet			Number of Days		
Month	Mean	Mean Max.	Mean Min	Heating Degree Days	Cooling Degree Days	Highest	High Date	Lowest	Low Date	Max >= 90	Max <= 32	Min <= 32	Min <= 0	Total	Amount	Date	Total Fall	Max Depth	Max Date	>=.01	>=.10	>=1.0
Jan	30.1	35.3	24.9	1048	0	53	11	6	07	0	11	22	0	3.13	0.78	11	2.8	2	10	13	8	0
Feb	32.4	39.7	25.1	815	0	65	23	11	09	0	8	20	0	2.56	0.72	07	6.9	5	14	7	6	0
Mar	32.4	40.0	24.7	913	0	63	27	9	12	0	8	19	0	2.48	0.51	30	5.9	4	14	11	8	0
Apr	49.3	58.2	40.3	472	0	76	10	31	07	0	0	2	0	4.81	1.20	20	0.0	0	07	12	7	2
May	55.1	63.2	47.0	328	20	88	18	34	08	0	0	0	0	5.53	1.38	25	0.0	0	31	15	9	2
Jun	67.6	77.1	58.1	47	125	91	12	48	07	1	0	0	0	3.03	0.63	29	0.0	0	30	17	10	0
Jul	71.8	80.8	62.8	3	214	90	31	57	26	0	0	0	0	2.33	0.47	20	0.0	0	31	14	7	0
Aug	69.2	78.2	60.3	17	149	88	21	50	26	0	0	0	0	3.54	0.63	04	0.0	0	31	14	10	0
Sep	66.3	76.1	56.5	87	126	91	24	45	30	2	0	0	0	0.97	0.43	02	0.0	0	30	7	2	0
Oct	57.2	66.0	48.5	259	19	82	04	36	27	0	0	0	0	2.30	0.69	08	0.0	0	31	11	9	0
Nov	39.7	46.5	32.9	759	0	63	28	15	10	0	1	14	0	2.50	0.80	18	0.0	0	11	13	7	0
Dec	24.2	30.6	17.7	1264	0	53	05	-13	31	0	18	29	4	2.14	0.51	24	17.2	9	28	12	5	0

Current Location: Elev: 551 ft. Lat: 43.5167° N Lon: -79.6833° W
Station: **OAKVILLE TWN, ON CA CA006155750**

Date	Temperature (F)													Precipitation (Inches)								
Elem ->	TAVG	TMAX	TMIN	HTDD	CLDD	EMXT		EMNT		DX90	DX32	DT32	DT00	PRCP	EMXP		SNOW	EMSD		DP01	DP10	DP1X
										Number of Days					Greatest Observed		Snow, Sleet			Number of Days		
Month	Mean	Mean Max.	Mean Min	Heating Degree Days	Cooling Degree Days	Highest	High Date	Lowest	Low Date	Max >= 90	Max <= 32	Min <= 32	Min <= 0	Total	Amount	Date	Total Fall	Max Depth	Max Date	>=.01	>=.10	>=1.0
Jan	22.6	31.4	13.9	1279	0	55	11	-9	06	0	17	28	4	3.02	0.67	22	10.3	9	06	10	8	0
Feb	30.0	38.0	22.0	980	0	63	20	4	05	0	10	21	0	3.05	0.96	19	9.2	9	11	12	9	0
Mar	32.8	39.8	25.8	998	0	54	18	18	25	0	1	27	0	1.44	0.68	29	2.3	2	02	5	4	0
Apr	39.1	47.1	31.1	777	0	70	30	21	07	0	0	20	0	8.10	3.43	15	3.2	2	16	12	10	3
May	63.2	73.8	52.7	132	75	90	28	41	11	1	0	0	0	2.57	0.83	14	0.0	0	31	15	8	0
Jun	67.5	75.7	59.3	35	98	95	30	50	07	3	0	0	0	3.55	1.04	24	0.0	0	30	9	6	1
Jul	74.9	84.5	65.3	0	308	95	18	56	19	5	0	0	0	2.63	1.01	05	0.0	0	31	8	4	1
Aug	75.0	83.5	66.5	0	310	95	06	58	23	3	0	0	0	4.77	1.89	06	0.0	0	31	10	8	1
Sep	67.5	75.8	59.2	79	154	94	05	43	23	2	0	0	0	2.89	0.83	09	0.0	0	30	9	6	0
Oct	50.1	57.6	42.5	481	18	83	10	30	18	0	0	2	0	2.68	0.94	01	0.0	0	31	15	9	0

Appendix C: Results of criteria and indicators matrix of southern Ontario municipalities

Norfolk County

Norfolk County does not currently have a UFMP in place. There are three foresters on staff in Norfolk that respond mostly to calls for forest health issues. The majority of the land is private in Norfolk County (Biddle 2017). There are over 25,045 private households in Norfolk, which has increased 3.3% since 2007. Forest health monitoring is often is performed by the Norfolk County Woodlot Owners Association (NWOA), which has over 300 members. Public forestry staff in Norfolk monitor for gypsy moth and other pests on public land every 2-3 years by performing walk-throughs to get an idea of general threat levels (Adam Biddle, *personal communication* 2018). Monitoring is usually done by summer students, while the OMNRF also maps gypsy moth hot spots in the area and the Norfolk environmental stewardship team maps defoliation (Adam Biddle, *personal communication* 2018).

In 2006, when the last aerial spray program was performed, it was dictated 100% by expression of interest and all public landowners were billed accordingly (Adam Biddle, *personal communication* 2018). Installation of 10x10m MPK plots and egg mass counts are done in the Fall annually (Adam Biddle, *personal communication* 2018). The last treatment program in 2006 was conducted in conjunction between the county forest bylaw officer, in house forest tech, the Long Point conservation forester staff and the Canadian forester staff from St. Williams (Adam Biddle *personal communication* 2018).

Norfolk county has 25% landscape forest cover, which is the highest percentage of forested land in south-western Ontario (Biddle 2017). Norfolk currently has a publicly available inventory of a small portion of park and major trees which currently needs an update post-infestation of emerald ash borer (EAB). Norfolk county staff are interested in protecting heritage trees such as those in Lynnwood park (Norfolk County 2018). Norfolk county, as a smaller area, has a lower budget, yet they are supported by council and the private landowner association. They have a singular level of spray treatment, although some individual banding or scraping takes place on trees. Norfolk plants on a 1:3 ratio and takes requests for planting trees along County owned roadways to enhance canopy cover in areas where trees have been removed for maintenance (Adam Biddle, *personal communication* 2018).

Norfolk County loosely addresses canopy cover goals although there is no set goal in this respect. Their aim is to strengthen natural heritage plans and to improve the existing tree cover (Biddle 2017). In 2018, a landscape plan was proposed to council which has yet to be approved. Private landowners are encouraged to view forestry and agriculture as mutually compatible through pamphlets and the public information centre (Norfolk County 2018). Because of the amount of private land, resource continuity on major endeavors such as aerial spray of gypsy moth in Norfolk has been positive because it does not fall solely upon the small budget of the forestry department.

City of Burlington

The City of Burlington has a UFMP currently in place (City of Burlington 2010), the purpose of which is to increase urban forest management's effectiveness and efficiency, improve tree health and diversity, minimize public risk and maximize the benefits provided by a healthy and sustainable forest. A key issue concerning utility pruning in Burlington is a lack of co-ordination between municipal and utility pruning activities (City of Burlington 2010). A review of tree planting standards is recommended in municipal documentation. Burlington implements a 7-year grid pruning cycle that is comparable with many municipal cycles. The UFMP identified the need to improve this cycle, yet no specific targets are outlined toward this objective (City of Burlington 2010). No replacement ratio is mentioned. Approximately 1,000 trees are planted annually as replacements through capital projects and in response to resident requests, through either the Roads and Parks Maintenance, engineering, and Parks and Recreation (City of Burlington 2010). The City does not actively plant in naturalized areas (City of Burlington 2010). Tree removal is also mentioned with no specific targets outlined (City of Burlington 2010). Diversity of trees is also mentioned, with 25% of canopy comprised of Norway maple and Ash (*Fraxinus* sp.) trees. Risk minimization of hazard trees is mentioned with no targets defined (City of Burlington 2010). Diversifying planting is an important consideration outlined as it builds resilience to stressors. The Town's Official Plan (2017) outlines protection of natural heritage features and the inclusion of landmark trees, and updates to tree protection by-laws are outlined in targets and objectives (City of Burlington 2017).

Burlington has a basic inventory of its street trees, primarily in the urban areas south of Highway 5 (City of Burlington 2010). It is not currently linked with cyclical tree inspections. Therefore, there is no process for updating the inventory information. There are no records of trees removed or planted as part of the Site Plan Approval process on private lands. Canopy cover increase is ranked as medium priority (City of Burlington 2010). This includes a recommendation to utilize a suite of criteria and indicators for monitoring the state of Burlington's urban forest rather than setting a target for canopy cover. Halton region conducts some workshops for community engagement in forestry, and the UFMP (2011-2030) mentions promoting the value of SFM by providing more information to the public and hosting seminars, as well as using local media to advertise stewardship events (Gartner Lee Ltd. 2005).

The Town of Burlington conducted a ground spray of Mountainside Park this year with truck-mounted ground spray application. Lallemand Inc./BioForest conducted sampling in 2008 for the City of Burlington, and the last spray was conducted in 2008 (City of Burlington 2009). A threshold for IPM implementation is mentioned yet not outlined in the plan. the Roads and Parks Department have coordinated with residents to keep pest populations under control through IPM methods (i.e. scraping, stick trap installation, etc.). the Town of Burlington has a relatively higher budget through private funding (City of Burlington 2017). Public communication need be stronger in the area to properly address gypsy moth and pest issues.

Town of Oakville

Oakville published a publicly-available 20-year Urban Forest Strategic Management Plan that is reviewed and updated periodically (Kenney et al. 2008). Pruning of publicly-owned trees in Oakville is done on a request basis. The UFSMP recommends adopting a 5-year pruning cycle for mature trees and a 3-year cycle for juvenile trees (Kenney et al. 2008). Oakville provides gypsy moth banding kits at workshops and public events, yet do not explicitly subsidize homeowner tree care. To ensure that the town of Oakville's forests do not decrease below 29.1%, there is a replacement policy of 1:1/m^2 of leaf area removed (Kenney et al. 2008). The UFSMP outlines that space identified for planting should be filled immediately in the future.

Most of the dominant species in Oakville are maples (*Acer* sp.), comprising 28% of leaf area (Kenney et al. 2008). Oakville is losing ash trees that represent some of the largest DBH trees out of all species in Oakville (Kenney et al. 2008). The plan outlines that future plantings should keep composition in mind with 10% of the forest being one species, 20% of one genus, and 30% of one family (Kenney et al. 2008). Age class in Oakville is only 0.5% large-stature trees. The UFSMP outlines that 10% of each tree age should be represented.

Oakville currently has regularly updated Municipal Street Tree and Open Space Inventory which is referenced which is based on compliance with the Forest Management Policy Manual of the Town's Forest Stewardship Council (FSC) partner, the Eastern Ontario Model Forest (Kenney et al., 2008). The project started in 2008, with a capital budget valued at $500,000. Volunteer pest monitory workshops are conducted yearly to inform the public of tree health issues in the area. The UFSMP outlines that the town's forestry staff and ITTAC should host a workshop on the use of enhanced rooting environment techniques, which would bring together forestry and engineer staff (Kenney et al. 2008).

Heritage trees are identified in the inventory as defined by the OUFC and Ontario Heritage Tree Alliance (Kenney et al. 2008). The town of Oakville conducted a gypsy moth aerial spray program in 2017 which cost $205,000 (Hashemi 2017). The report to council outlines reductions in costs by coordination with bordering municipalities such as Mississauga (Kenney et al. 2008). Oakville regularly monitors for gypsy moth pests in woodlots and on public street trees. The forestry department hires consultants such as Lallemand Inc./BioForest (BioForest 2017). Egg-mass survey plots are completed by Lallemand Inc./BioForest are based off of history of infestation, the size of each woodlot, and oak concentration (Allison Craig, *personal communication* 2018). Oakville's UFSMP mentions but does not create specific objectives for climate change mitigation. The threshold for action of spray implementation is 2,500 egg masses per hectare (Kenney et al. 2008). There is currently no public information centre in Oakville but many resources are available online.

City of Hamilton

The City of Hamilton does not currently have an UFMP in place, yet they hope to have an urban forest strategy (UFS) implemented by December 2019 (Plosz 2017). In May 2018, Lallemand Inc./BioForest and Dillon consultants were asked to help develop an UFS for the city in order to reach its target of 30-35% tree cover and to identify challenges and opportunities for urban forestry. Their budget for this plan is $150,000 (Plosz 2017).

The city has a publicly updated working inventory that is accessible online. Because this is not a comprehensive inventory, the tree age and dominant species and age composition of the urban canopy is unknown, with no set goals in place (City of Hamilton 2015). Lallemand Inc./BioForest conducted an egg mass survey in the Fall of 2016 and sprayed for gypsy moth in the Spring of 2018. The 2018 spray areas are mapped online on the City of Hamilton website. The City's threshold for treatment of gypsy moth is 2,500 egg masses/ha (City of Hamilton 2015). Pruning cycles in Hamilton are based on call response. The City has a public information centre (City of Hamilton 2015). The city maintains a historical timeline of gypsy moth infestation since 2004, and updates its tree bylaws frequently. Rural heritage trees are not protected in the bylaw and require better protection (City of Hamilton 2015).

There is no planting standard ratio, although for pests such as EAB it is assumed to be a 1:1 tree replacement ratio on private property (City of Hamilton 2015). The City provides removal services to trees accessible by road access, and will provide $30/treatment for private homeowner TreeAzin injections (City of Hamilton 2015). The City of Hamilton also has a community climate change action plan in place, written in 2015, which outlines long-term goals and directions for mitigation and adaptation (City of Hamilton 2015).

City of Mississauga

The City of Mississauga maintains a UFMP as part of their Natural Heritage and an Urban Tree Health Strategy (Wassenaer et al. 2014). Tree replacement occurs on a 1:1 replacement ratio for trees 15-29cm DBH and 2:1 for trees 50cm or higher (Wassenaer et al. 2014). Pruning is conducted on an 8-year cycle. By-laws regulate tree injury and removal of private property trees. Mississauga's tree inventory is sample-based and contains general risk information. Their management plan defines BMP as a complete and detailed tree inventory which would include detailing of tree failure risks with a maximum of one week's confirmation of hazard potential (Wassenaer et al. 2014). Their target is to achieve "good" or "optimal" status in risk management by 2033 (Wassenaer et al. 2014). Mississauga's current Private Tree Protection By-law was updated in 2012 and regulates the removal of three or more healthy trees greater than 15cm diameter annually on private properties (TRCA 2011). Best practices for planting and replacement is defined as having a strong tree protection by-law to regulate tree removal that are widely promoted and enforced (Wassenaer et al., 2014).

The 'One Million Trees' Mississauga program is a program to plant one million trees on private and public land over the next 20 years as of 2012 (Wassenaer et al. 2014). This is an action item from the City's *Living Green Master Plan* (2012) and *Strategic Plan* (2012) (Wassenaer et al. 2014). The trees will be planted by City staff and support will be given to volunteer and community groups (Wassenaer et al. 2014). The city has a *Significant Trees* Program which gets residents to think about the value of trees by nominating unique trees for designation. There is no climate change strategy although they have a 5-year energy conservation plan, and Peel region municipality outlines Mississauga in their climate change strategy (TRCA 2011; Peel Region 2011). The City of Mississauga's UFMP mentions planting tree species that are adapted to warmer conditions (Wassenaer et al. 2014). Their canopy goal is to increase from 15-25% over the next 20 years and to change the distribution of canopy cover. There are more than 60% trees that are less than 15.3cm DBH in 2011 and the canopy is ~22% Norway maple (*Acer platanoides* L.) (Wassenaer et al. 2014). The City adopts a positive approach rather than punitive for tree regulation by proactively hosting workshops and formation sessions for communities (Wassenaer et al. 2014). The City encourages tree owners to conduct sampling and tree treatment through online tutorials (Wassenaer 2014).

The City of Mississauga is the only municipality reviewed that has an Invasive Species Management Strategy underway (Ferguson and Piett 2017). The objectives of this plan are to provide an approach to managing invasive species in an economically efficient manner (Ferguson and Piett 2017). The total cost of the 2018 aerial spray program for gypsy moth was $600,000. Private properties that were sprayed were charged $200 per property, which is compared with ~$1,200 to cut down a dead tree (Wassenaer et al. 2014). The City was responsible for charges to City parks and woodlands. The City of Mississauga approaches pest management proactively (monitoring, inspection, pruning), and reactively (tree removal, pesticide treatment) (Wassenaer et al. 2014). The City maintains an IPM approach (Wassenaer et al. 2014). They install tree bands and burlap to selected City oaks based on egg mass counts and location. The City has a Landscape Scale Analysis (LSA) to be implemented by 2020 (Wassenaer et al. 2014).

City of Toronto

The City of Toronto has a 10-year Strategic Forest Management Plan (SFMP) in place (City of Toronto 2013). Their canopy goal is to increase from 27%-40% by 2020. 68% of trees in Toronto are less than 15.2cm diameter. There is a predominance of native species in Toronto, with 64% native species (City of Toronto 2013). The City supports subsidized tree planting through organizations like Gord Trees and LEAF. There is a 7-year pruning cycle in Toronto with no mention of increase (City of Toronto 2013). The City has proposed a climate change action plan to council, yet the plan has not been implemented (Butts 2007). The goal of Toronto's urban forestry programming is to promote natural regeneration and fill in the gaps where it fails.

There are by-laws in place to remove, cut or injure trees over 30cm DBH at a height of 1.4m above ground level. Maintenance pruning of street and park trees is performed to eliminate hazardous limbs or branches and encourage good form and healthy growth. Tree risk assessments are performed to examine trees for structural defects. The removal of ravine trees is mentioned followed by a dense combination of native, large-growing tree species, understory trees, shrubs and ground level grasses and herbs (City of Toronto 2013). The City will provide treatment for City-owned trees; however, homeowners are responsible for treatment of private trees. There are several highly-trained foresters on the City of Toronto staff, including many Registered Professionals. They also hire outside consultants to assist in specified projects. The SFMP mentions management at a landscape scale with no targets outlined (City of Toronto 2013).

In 2010, a pilot program was launched to develop a method to identify hazardous trees and map their locations so hazards could be eliminated (City of Toronto 2013). The city takes a proactive maintenance approach since 2009 which utilities city sub-grids to systematically assess and maintain trees in a regular cycle. This has been shown to be more efficient (City of Toronto 2013). Currently, there is a sample-plot based inventory being developed for the City of Toronto (BioForest 2017). The SFMP outlines the City's commitment to enhancing inventory practices and improving data management systems used to store information about the urban forest. The SFMP outlines increasing biodiversity as a goal to improve urban forest resiliency and respond to climate change (City of Toronto 2013). Shifting toward larger trees is outlined as a goal with no percentages mentioned (City of Toronto 2013).

Initiatives are being undertaken to expand current levels of awareness of pest issues through the City's website, various public outreach and educational events, and tours and workshops in communities (City of Toronto 2013). The *parkland naturalization program* and the *community stewardship program* are initiatives that play a part in increasing awareness (City of Toronto 2013). Urban Forestry staff encourage citizens to report signs of gypsy moth to 311 (City of Toronto 2018). Invasive species management and gypsy moth control are mentioned in objectives yet not explicitly targeted (City of Toronto 2013).

The threshold for action on gypsy moth is 2,000 egg masses/ha (City of Toronto 2018). A lot of oak trees in Toronto are quite old and are currently in decline. The City of Toronto mostly responds to call volumes for targeting areas for gypsy moth survey, which tends to create a bias toward wealthier pockets of the city (Joel Harrison-Off, *personal communication* 2018). The City of Toronto recognizes that gypsy moth will always be present on the landscape. The Urban Forestry Department regularly monitors the effectiveness of the gypsy moth program as well as controlling populations of the insect through Btk administration (City of Toronto 2013).

Appendix D: Sampling methods for gypsy moth

- *Burlap banding*
  For caterpillars and pupae, tar paper bands are placed around the stem of the tree. Gypsy moth caterpillars seek shelter under bands and pupate under them. Densities can vary greatly from day-to-day and time of day and are dependent on host species, density of caterpillars and larval development, and weather. Caterpillars can also be collected from tree canopy foliage. This method has not yet been assessed for accuracy. However, it can be useful in determining the presence of caterpillars.
- *Frass collection*
  Larval populations can also be assessed by frass collection (Liebhold and Elkinton 1988). Frass collection is extremely time-consuming and requires a great of expertise, so is not often implemented.
- *Pheromone trapping*
  For adult gypsy moths, pheromone trapping is the most common method. Pheromone is synthetically reproduced and used to lure male moths to sticky or bucket traps. This method can be effective for detecting low gypsy moth populations (Gage et al. 1990). Pheromone traps are less effective during high population periods, largely due to their efficiency. When they are saturated with moths, it is difficult to develop relationships between trap catches and gypsy moth damage (BioForest 2006). Evaluation and action zones are sometimes utilized in the United States whereby spacing in each zone differs based on threshold levels (Ravlin et al. 1990).
- *Egg mass counts*
  Egg masses are very easy to count, especially after foliage falls in the Autumn, and old egg masses are generally easy to distinguish from new egg masses (BioForest 2006). Gypsy moths lay eggs in masses that remain on the tree from July until April or May of the following year (BioForest 2006). Because of this long period, egg mass surveys are generally the most reliable method of tracking gypsy moth populations and forecasting future levels (Appendix A; Figure 4). The high cost of egg mass surveys, however, often leads to inadequate replication which can lead to measurement error. There is also considerable variation between egg mass density and actual defoliation observed (BioForest 2006). Thresholds for action have been developed which can help to guide in the collection of egg mass data.
- *Windshield surveys*
  Windshield surveys are often used to identify hazard trees in areas with budget concerns. Many municipalities desire accurate methods of inspecting tree populations. Because gypsy moth defoliation is

highly visible, trees can be inspected with some accuracy from afar. Windshield surveys can be utilized in finding hazardous conditions in roadside trees, using a simple system (Rooney et al. 2005). Windshield surveys can save time over walking because a trained professional such an arborist or consultant is driven along community roads while keeping a few characteristics in mind, such as defoliation (Rooney et al. 2005). These areas can then be prioritized for surveying or treatment.

- *Timed-walk method*
  Observers count all the egg masses visible during a typically five- minute walk through an area. These counts are used to estimate egg masses per unit area (Liebhold et al. 1991). When compared to fixed-radius egg mass plots, fixed-radius plots were more correlated with true density (Liebhold et al. 1991). Lack of precision and observer effects indicate that fixed-time and fixed-distance methods are less accurate than fixed-radius plots (Liebhold et al. 1991). This method, however, can be used as a quick or low-budget survey tool but is imprecise and is usually followed up with a more detailed survey.

Appendix E: Treatment methods for gypsy moth

- *Low population strategies*
  The effects of gypsy moth defoliation can be minimized during low population periods in a number of ways. For example, cleaning yards of objects that provide habitat for larvae and pupae such as dead branches and can control populations (BioForest 2006). As well, tree diversification in urban areas can reduce the proportion of preferred species. Selection of species that are locally-adapted to climate conditions encourages tree vigor (BioForest 2006).
- *Egg mass scraping*
  Destroying egg masses is a technique that homeowners can utilize to reduce property damage from gypsy moth. Locating egg masses is easiest from Fall until early Spring when there are no leaves on trees. They can be found on tree trunks and many other surfaces. They can be scraped off into soapy water or detergent and left to sit for a full week (BioForest 2006). Old egg masses are not necessary to remove yet can be destroyed as well if there is any doubt.
- *Burlap bands*
  As aforementioned, burlap bands are often used to count gypsy moth populations. They intercept larval movement and larvae will seek shelter in the bands (BioForest 2006). They can then be removed from the bands and destroyed. Bands can be made of burlap or cloth. They should be 30-45cm wide and fastened to the tree at 1.3m above the ground. They must be checked daily to remove larvae (BioForest 2006). Again, larvae should be left in soapy water for a week in order to ensure mortality. Aluminum foil and plastic wrap can cause searing or mortality to trees so should not be used.
- *Barrier bands*
  Barrier bands also intercept larvae crawling up or down a host tree trunk. They can be created using sticky material applied to bands on the trunk. Tar paper or duct tape can be wrapped around the tree 1.5m above ground level (BioForest 2006). The total width of the band should be at least 12.5cm. the band should be pressed into bark crevices so that larvae cannot crawl underneath it. Small insects will get caught on the band as they crawl on the trunk surface (BioForest 2006). Larvae should again be left in soapy water for a week to ensure mortality. Avoid using petroleum-based products as they can cause swelling and cankering on trees with thin bark (BioForest 2006).
- *Insecticide administration*
  Homeowners can use insecticides for small-scale shrub and tree treatments on private property. *Bacillus thuringiensis* (Btk), *carbaryl, pyrethrin, phosmet,* and *permethrin* are all registered insecticides in Canada and should be used strategically (BioForest 2006).
- *Application of Btk*
  Btk application can either be done via ground or aerial spray administration. Btk is a common bacterium that causes disease to gypsy moths and other insects from the order *Lepidoptera.* In order for aerial spray of Btk to be successful, spray timing, number of applications, and weather parameters must be correct (BioForest 2006). Efficacy is assessed by measuring population reductions and defoliation in sprayed and unsprayed areas. If defoliation goals are met (i.e. below 50% in treated areas), the aerial spray is deemed successful.
- *Natural Controls*
  In Europe and Asia, gypsy moth outbreaks are cyclical. However, a clear outbreak pattern in North America has not yet been established (USDA 2012). Gypsy moth populations appear to exist in high and

low densities. Natural mechanisms such as weather, predators, parasites and diseases significantly influence their populations.

Low density populations are normally kept in check by natural enemies such as predators and parasites (Brooks and Hall 2005). Predators that feed on gypsy moth larvae include about 40 species of birds such as vireos, chickadees, tanagers, orioles, robins, blue jays, grackles, starlings, blackbirds, and cuckoos (OMNR undated), other insects, and small mammals such as skunks, white-footed mice, squirrels, and raccoons. Insect parasitoids kill gypsy moth by laying their eggs in gypsy moth eggs, larvae, and pupae (Alalouni et al. 2014).

Pathogens can cause infestations to collapse, with decreases in population tending to occur in cooler, wetter conditions. Gypsy moth is susceptible to bacteria, fungi, and nucleopolyhedrosis virus (NPV) (Campbell and Podgwaite 1971). *Entomophaga maimaiga* and NPV can kill large numbers of gypsy moth. *E. maimaiga* was first noticed for its effects on gypsy moth populations in 1989, and was recovered from gypsy moth in Ontario in 1990.

NPV was introduced in North America with the gypsy moth. It is host-specific to the gypsy moth. It is often referred to as "wilt" due to the soft, limp appearance of infected hosts (Nealis and Erb 1993). There are also several parasitic wasps that are host specific to gypsy moth, such as *Cotesia melanoscelus* and *Ooencyrtus kuvanae,* as well as the fly *Compsilura coccinnata* (McCullough et al. 2001). Their introduction, however, has not been successful in controlling gypsy moth populations. There is no single natural enemy or combination of control agents that can eliminate gypsy moth populations. They can, however, help to keep populations low. Under outbreak conditions, other control measures are necessary to control gypsy moth populations (OMNR undated).