Impact of Emerald Ash Borer (EAB) under Different Management Strategies in Downtown Toronto: Publicly and Privately Owned

by

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A thesis submitted in conformity with the requirements
for the degree of Master of Forest Conservation

Faculty of Forestry
University of Toronto

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2018

Abstract

Emerald ash borer, *Agrilus planipennis* Fairmaire (Coleoptera: Buprestidae) (EAB) was first introduced into North America during the late 1990s and has since caused devasting economic and ecological impacts. Inventory data in downtown core of Toronto of last ten years were used to quantify impact caused by EAB on urban forest and explore the ash mortality pattern under the management of Harbord Village Residents' Association (HVRA), University of Toronto St-George Campus (UoT-StGeorge) and the City of Toronto. The results indicate that HVRA lost 52.5%, UoT-StGeorge lost 39.2% and the city lost 44.7% of the ash trees respectively; HVRA lost over 40%, UoT-StGeorge lost over 20%and the city lost 35% of the associated values respectively. All the ash mortality patterns fit the exponential regression model and are predicted to reach 100% by 2019. Although different parties have their own decision criteria when treating ash trees, a comprehensive management strategy can be considered as a better way to reduce the impact caused by EAB.

Acknowledgments

The author would like to thank supervisor Professor Sandy M. Smith for guidance and support in the project, and Professor Danijela Puric-Mladenovic for providing tree inventory training and previous inventory data of UoT-StGeorge area. The author also thanks Stan Szwagiel from University of Toronto, Sue Dexter from HVRA, Jozef Ric and Josh McMeekin from the City of Toronto for providing information about the EAB management; John Caspersen for the help during the Capstone process; Amory Ngan and Nicholas Provart for being external examiners for the Capstone presentation; Leah Ritcey-Thorpe and Christian Rempe for cooperation in collecting the data during the summer internship; all the Master of Forest Conservation Program classmates for being nice and friendly, and helping a lot during the whole program.

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1 Introduction

Emerald ash borer (EAB), *Agrilus planipennis* Fairmaire (Coleoptera: Buprestidae), as a confirmed invasive species from Asia, was first detected in North America in May 2002 in various parts of southeastern Michigan (Haack et al., 2002; Cappaert et al., 2005). And in 2003, it was first detected in Canada near Windsor of Ontario, and in 2007, it was first detected in the City of Toronto near the area of Hwy 404 and Sheppard Avenue of North York (City of Toronto, 2017).

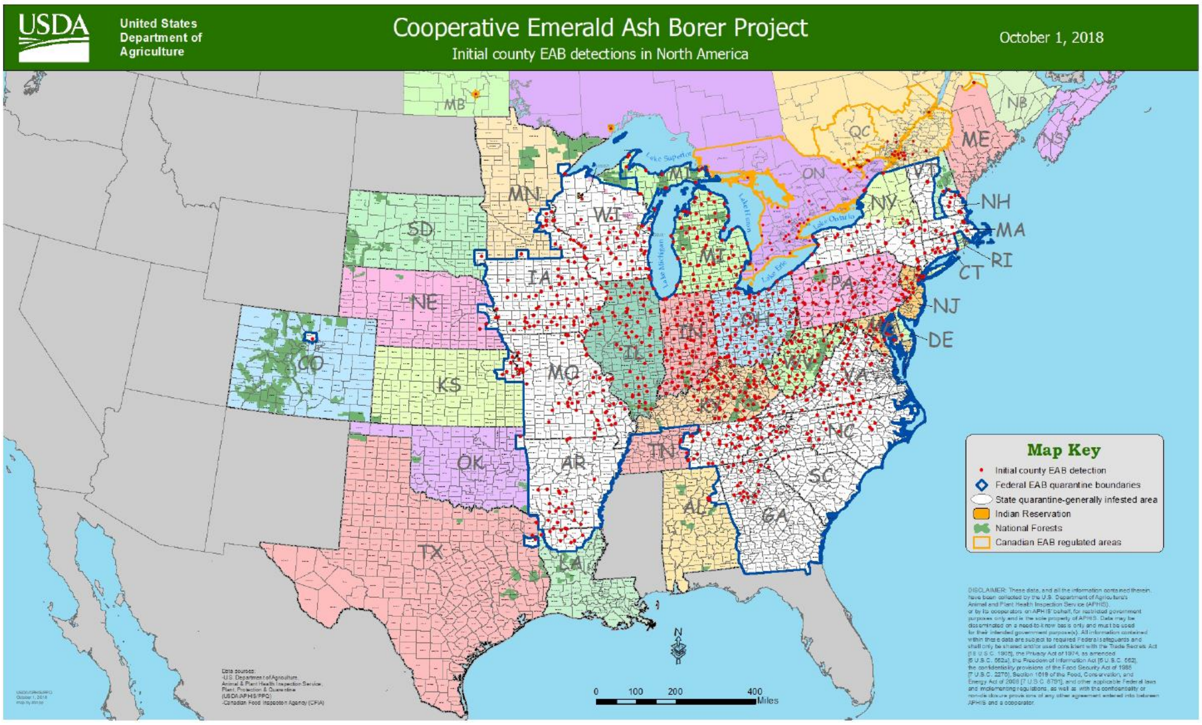

Figure 1. Current distribution (1 October 2018) of the emerald ash borer (EAB) in Canada and the USA. (USDA, 2018)

Due to the large amount and widely distribution of native ashes in North America, EAB spread continuously throughout the continent (Prasad et al., 2010). Natural spread of EAB could reach a few kilometers per year, but with anthropogenic movement, spread rate of EAB was greatly increased (Prasad et al., 2010; Siegert et al., 2015). As of October 2018, EAB has been found in five provinces of Canada, including Ontario, Quebec, New Brunswick, Nova Scotia and Manitoba, and 35 states in the USA (USDA, 2018; Fig.1). EAB was confirmed as an exotic species from Asia, probably transported along with baggage and cargo in the 1990s before Canadian Food Inspection Agency (CFIA) regulations (Haack et al., 2002; McCullough et al., 2006). Smith et al. (2004) did a genetic analysis of EAB collected from the Michigan infestations that indicated the source area was from Heilongjiang and Tianjin provinces in China.

Ash, as the only host reported for EAB, is one of the most common tree species planted in urban areas throughout North America and often accounts for 5-20% of all the street trees in many US midwestern and Canadian cities (Haack et al., 2002; Herms & McCullough, 2014). Since its introduction from Asia, it has killed more than 99% of ash trees having a DBH > 2.5cm (Klooster et al., 2014). EAB feeds more on green ash (*F. pennsylvanica* Marsh), white ash (*F. americana* L.), and black ash (*F. nigra* Marsh), compared to blue ash (*F. quadrangulata* Michx.), European ash (*F. excelsior* L), and Manchurian ash (*F. mandshurica* Rupr.); the former are the most widely distributed ash species in North America (Pureswaran and Poland, 2009). External symptoms of EAB infestation are not significant until trees show significant dieback and bark cracks over larval galleries, which results in anthropogenic spread without realization, such as movements of lightly infested nursery trees, logs, and firewood, forming satellite EAB populations and rapidly expanding the its geographical distribution (Cappaert et al., 2005; Kovacs et al., 2011; Siegert et al., 2014).

Ecological Impact: Like other introduced insects, EAB has significant ecological impacts on forests. Due to the wide distribution of ash, tree mortality induced by EAB is likely to cause a continental scale impact. In the USA, up to 15 million ash trees had been killed by 2006 and approximately 100 million trees six years later by 2012 (Poland and McCullough, 2006; Donovan et al., 2013). In mixed hardwood forests near the outbreak epicenter (Michigan), ash mortality exceeded 99% by 2009 and nearly 100% only three years later by 2012 (Klooster et al., 2014).

The ecological effects of tree mortality include not only a decrease in the number of trees, but also alteration of the understory environment, nutrient cycles, and seedling regeneration (Herms and McCullough, 2014). EAB kills ash trees directly and this leads to isolated canopy gaps widely distributed in the forest. Without competition from ash, other exotic trees or shrubs have the opportunity to establish and this can exert detrimental impacts on native ecosystems (Simberloff & Von Holle, 1999; Gandhi & Herms, 2010a). Increased ash mortality also greatly affects the seed bank in forest regeneration, including seedlings and saplings. As ash mortality approaches 100%, ash regeneration tends to cease (Klooster et al., 2014). Thus, the prognosis after the complete decline of ash trees suggests that stand composition and structure will be irreversible altered, leading to a completed extirpation of ash from these forests.

With the loss of ash as a key tree species in naturalized forest areas, many arthropod species that can only feed or breed on these species are also facing extirpation. In turn, this will indirectly affect those species affiliated with ash dependent species (i.e. parasitoids, pollinators, etc.) since they have an inextricably relationship with them (Gandhi & Herms, 2010b). Leaf litter arthropods, earthworms, and even bird communities will also be influenced by ash mortality induced (Ulyshen et al., 2011; Koenig et al., 2013; Gandhi et al., 2014).

Economic Impact: In order to prevent the human-mediated spread of EAB, industries such as nursery producers, sawmills, logging companies, and other ash-related producers, are subject to increasingly restrictive regulations (Herms and McCullough, 2014). This has resulted in potential economic impacts between $1.8 and $7.6 million in USA communities such as Ohio where EAB has resulted in the loss of ash landscapes, removal, and replacements (Sydnor et al., 2007). Kovacs et al. (2010) simulated EAB spread over a 10-year timeline for communities across 25 states in USA and estimated that by 2019 the discounted cost would be $10.7 billion for the treatment, removal, and replacement of more than 17 million ash trees.

Trees in urban areas increase property values by thousands of dollars through their ecosystem services including water capture, purification of air pollutants, and temperature cooling (Anderson & Cordell, 1985). Thus, the loss of ash trees in cities influences human recreation as well ecosystem values. Arnberger et al. (2017) found that citizens dislike views showing city buildings and the removal of most ash trees.

Slowing expansion of existing EAB populations to prevent the establishment of new satellite epicenters is thought to be a reasonable, cost-effective management strategy even though the initial costs are high for insecticide and harvesting interventions (Kovacs et al., 2011). Unfortunately, recent analysis by Cuddington et al. (2018) suggests that the spread of EAB is unlikely to be slowed by extreme cold events in most of North America even though EAB has poor survival below about -35.3°C, its lower lethal temperature (Wu et al. 2007; Crosthwaite et al., 2011). Their mechanistic model shows that such events are not frequent enough to cause complete (99%) or partial (75%) EAB mortality, and thus cannot prevent tree mortality and economic loss.

Management & Treatment: Smith et al. (2015) found that ash tree mortality increased steadily following EAB arrival Michigan, USA, reaching 93% by 2007, however they saw no evidence that it had any relationship with forest composition, including species diversity, tree density, and total basal area. This suggests that silviculture practices to reduce EAB impacts might be limited, but different management practices and environmental conditions can significantly affect the regrowth of ash and other species (Peper et al., 2014). Knight et al. (2013) found that stands with lower ash densities tended to have more rapid tree mortality. EAB attack was concentrated on a few trees and that this accelerated tree deterioration suggesting that management to reduce ash density has little positive effect on protecting the remaining ash trees.

The annual treatment of infested trees with a highly effective systemic insecticide was found to be more effective in protecting remaining trees and slowing EAB growth compared to the removal of ash trees (i.e. to reduce phloem-feeding alone). Economic analysis showed that the costs associated with insecticide treatment were also substantially lower that tree removal (Cappaert et al., 2007; McCullough et al., 2015; McCullough and Mercader, 2012). TreeAzin™ is currently one of the widely used systematic insecticides against EAB. It was injected under trees' bark, killing insect larvae and reduce fertility and egg viability of adult females. It can provide up to 2 years' control of EAB infestation (BioForest Technologies Inc., 2018).

Biological control is another strategy considered for the reduction of EAB populations, although this approach is viewed as long-term. Exotic biological agents have been released for EAB control in the USA since 2008, including *T. planipennisi*, which was introduced from China and has become established 4-5 years after release (Duan et al., 2017). Most North American EAB populations are also heavily attacked by native woodpeckers and a group of native hymenopteran parasitoids (Duan et al., 2017); all show a significant effect on EAB populations.

Urban Ecosystem: Urban forests consist of planted or naturally regenerated trees in forested stands, city parks, residential areas as well as trees along the streets and in other land use in the city (Nowak, 2016). Trees growing in urban environment provide human beings with large amount of ecosystem services. Many studies have verified that urban trees have significant contribution in removing carbon dioxide from the atmosphere by storing carbon as biomass in their roots, stems and branches through photosynthesis process (Brack, 2002; Nowak & Crane, 2002; Davies et al., 2011; Russo et al., 2014). Urban trees can modify the temperature and microclimate in the city environment by shading surfaces, transpiring water, storing and exchanging the heat, as well as altering wind speed and direction (Heisler et al., 1995; Nowak & Dwyer, 2007). With healthy leaf-surface area, urban trees can produce oxygen and remove air pollution at the same time, including ozone, 10 microns, nitrogen dioxide, sulfur dioxide, carbon dioxide , carbon monoxide, dust and smog (Nowak & Dwyer, 2007; Roy et al. 2012). Urban trees can also contribute to urban hydrology processes by intercepting, retaining, slowing the precipitation reaching the ground and reducing the rate and volume of storm water runoff (Nowak & Dwyer, 2007; Roy et al. 2012). Moreover, trees planted in a row can also absorb, deviate reflect and refract sound waves which is another major pollution in city areas (Gómez-Baggethun et al., 2013). Therefore, loss of plenty ash trees in the urban ecosystem could result in massive loss of ecological benefits.

Public Management: When facing severe threats brought by EAB, municipalities across Canada are putting lots of efforts to save ash trees and prevent further damage because of the EAB infestation. A pilot project, known as Slow Ash Mortality (SLAM), has been implemented in infested areas. McCullough and Mercader (2012) found that the outcome of Slow Ash Mortality (SLAM) was influenced by how soon the insecticide treatment got implement after EAB infestation and the proportion of trees that got the insecticide treatment. The results showed that in a 10-year horizon, 20% of the ash trees got annual treatment could protect 99% of the trees and reduce a substantial cost compared with removing them.

In 2008, the City of Ottawa approved an EAB strategy, including selective tree injections with TreeAzin™, tree removal, proactive tree planting, replacement tree planting, wood movement and disposal, and public education to raise awareness about EAB (City of Ottawa, 2018).

The City of Montreal, Quebec, has a by-law to help mitigate the spread of EAB, including how to identify an ash tree and the emerald ash borer, how to treat or removal an ash tree, how to properly handle an ash wood, as well as some financial support to reduce the costs for removal and replacing an ash tree (City of Montreal, 2018).

In the City of Toronto, Ontario, it was estimated in 2010 that there were 860,000 ash trees across the whole city, among which 32,000 were city owned street ash trees. It is already known that it is impossible to eradicate the EAB, so the city is trying to slow the spread of EAB. Canadian Food Inspection Agency (CFIA) restricted to movement of potentially infested wood materials in the infested area. The City of Toronto has banned any planting of new ash trees since 2003. And criteria have been used to identify ash trees for TreeAzin™ injection. An ash tree that is over 15cm DBH, shows low-level signs of infestation, with less than 30% loss of the canopy and is in fair or good health will be injected in the main stem with a full dosage of insecticide every second year. EAB traps were also installed on healthy ash trees to reduce the EAB infestation. The city also removed and replaced the dead ash trees (City of Toronto, 2017; 2018a; 2018b; 2018c).

Private Management: Among all the 860,000 ash trees across the Greater Toronto Area, only 32,000 belongs to the city while other ash trees situated on private property, road allowance and in parks (City of Toronto, 2017). Therefore, the actions taken by the private land owner are more essential to reduce the impact caused by EAB in urban areas. Privately owned trees will not be treated by the City of Toronto, so the city encourages private property owners to actively treat and maintain the health ash trees on private land (City of Toronto, 2018b).

Private land owners are supposed to consult some tree care and management experts, such as an arborist or a Registered Professional Forester (RPF) before undertaking any management of ash trees on the property. There are several options that private property owners can select. The first is to remove and replace the ash trees. In general, a small DBH tree or a tree in poor health condition will be recommended to be replaced, considering the cost-effectiveness. The second is to treat the ash trees, which is a long-term commitment. A tree in overall a good health condition with small percent of branch dieback and having a significant value will be recommended to inject with TreeAzin^{TM}. The last one is to do nothing, which is not an advisable option, since the dead or dying trees is considered as a hazard to the people as well as the property (Ontario Ministry of Natural Resources, 2018; Village of Bloomingdale, 2018).

Problem Definition: There is currently a knowledge gap about the impact of EAB on ash trees within cities across Canada. It is becoming increasingly clear that most ash trees in Canadian cities will be impacted by EAB. McCullough & Mercader (2012) found that ash survival varied depending on management strategies, including how soon insecticide treatment began after EAB introduction, the proportion and distribution of treated trees. Therefore, public and private management strategies are expected to be different in reducing the impact brought by EAB. Although many researchers have estimated the potential loss of these trees and the forest canopy in municipalities across North America, the true annual ecological and economic impact under varying management scenarios remains unclear due to the expense of annual tree inventories.

2 Objectives

The current study was initiated to assess the ecological and economic loss due to EAB in response to different management strategies by taking advantage of two existing public-private tree inventory databases, one derived from a large downtown institution (University of Toronto-St. George campus; UoT-StGeorge) and one in an adjacent neighbourhood community (Harbord Village Resident's Association; HVRA) over a 10-year horizon (2008-2017). Both areas have trees owned and managed by the City of Toronto, which is considered as public management. Specific objectives are to:

1. Quantify the impact caused by EAB, including the tree number, ecological and economic loss.

2. Based on the number of tree loss, compare the difference between public management (city) and private management (private individual and private institution).

3. Explore the ash mortality pattern under different management strategies and predict the potential time of the mortality reaching 100%.

This research will provide a deeper understanding about the influence of EAB on the urban forest in the downtown of a large metropolitan city and provide information on the impact of landowners for the future management of invasive pests such as EAB.

3 Methods

3.1 Study Area

The study was located in the downtown core of Toronto; one site is Harbord Village Residents' Association (HVRA) neighbourhood and the other is the University of Toronto St-George Campus (UoT-StGeorge) (Fig. 2).

Harbord Village Residents' Association (HVRA): The HVRA neighbourhood is located south of Bloor Street, west of Spadina Avenue, north of College Street, and east of Bathurst Street in Toronto (Fig. 2). According to Census Profile of Canada, the neighbourhood has 3955 residents (Statistics Canada, 2012). As one of the densest urban neighbourhoods in downtown Toronto, HVRA neighbourhood contributes over 4000 trees to the tree canopy of Toronto. In 2007, HVRA initiated a formal inventory of all trees in the area; they completed a re-inventory of ash trees in 2016 and 2017. A final tree inventory was carried out in 2018, which completed a 10-year horizon study of all trees in HVRA neighbourhood (2007, 2008, 2016, 2017, 2018). HVRA has attempted to manage for EAB since it was first found in the Toronto area in 2007 by providing information and financial support to homeowners to actively inject and protect trees on their private land (TRCA, 2018; Melamed & Zhou, 2012). At the same time, the City of Toronto has maintained an active EAB management program in the area along city-owned streets, boulevards, and parkettes (City of Toronto, 2012).

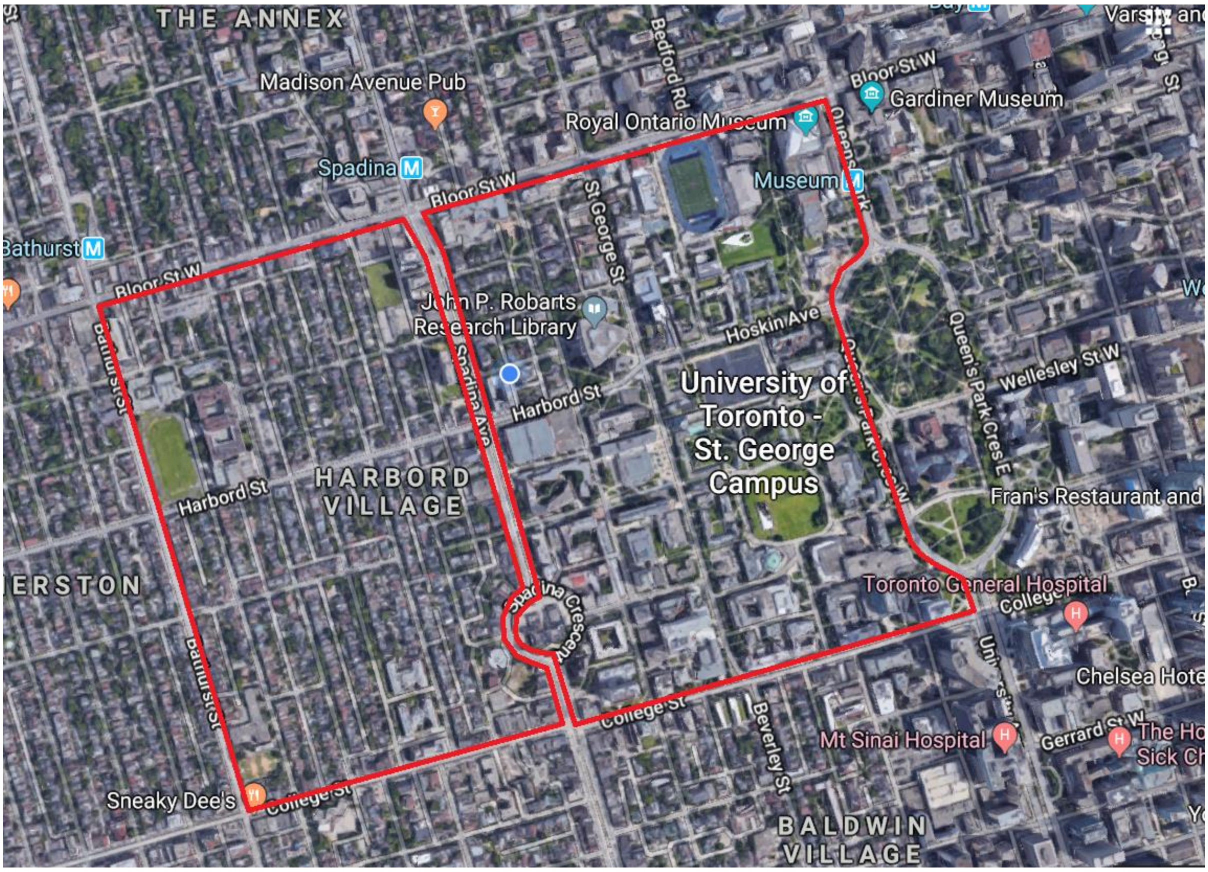

Figure 2. Map of adjacent study areas in the downtown City of Toronto core; HVRA (Harbord Village Residents' Association) and UoT-StGeorge (University of Toronto) St. George campus. (Google Maps, 2018)

University of Toronto St-George Campus (UoT-StGeorge): The second study area, the downtown St. George campus owned by the University of Toronto, is 71 hectares and located immediately adjacent to the HVRA neighbourhood. It is located on the south side of Bloor Street, west side of Queens Park, north of College Street and east to Spadina Avenue in Toronto (Fig. 2). It has been Canada's leading institution of learning, discovery, and knowledge since it was created in 1827. Most of the private land in the bounded area is owned and managed by the university, with street corridors owned and managed by the City of Toronto the same as with HVRA. UoT-StGeorge is responsible for all the trees on its property. Regarding EAB, UoT-StGeorge has implemented tree injections of insecticide for the management of EAB since it was first discovered on campus. An arborist was hired to treat the ash trees on the property. All the infested ash trees were injected with TreeAzin ™ annually or every 2-3 years depending on the tree health condition. All the ash trees are fertilized and irrigated regularly. Dead wood is pruned when the tree is dormant.

3.2 Data Collection

Both HVRA and UoTSt-George sites have had irregular tree inventory data collected over the past 10 years between 2008 and 2018. Available inventory data in HVRA were from 2008, 2016, 2017 and 2018 and available inventory data in UoT-StGeorge were from 2008, 2012 and 2017. All inventory data were collected according to the Neighbourwoods© Protocol developed by Drs. Andy Kenney and Danijela Puric-Mladenovic (Kenney & Puric-Mladenovic, 2018). 12 attributes recorded for each tree were used in this study, including tree location, tree species, diameter-at-breast-height (DBH), total tree height, height to crown base, average canopy width, reduced crown, crown defoliation, conflict with sidewalk and structure, land use, and owner of trees. The attribute, owner of trees, was used to distinguish trees that are under the management of HVRA, UoT-StGeorge or the City of Toronto. Trees owned by HVRA were considered as being managed by private individuals; trees owned by UoT-StGeorge were considered as being managed by the private institution; and trees owned by the City of Toronto were considered as being publicly managed by the city.

3.3 iTree Eco (v6.0) Analysis

Software iTree Eco (v6.0) was used to estimate ecosystem services and associated economic values provided by ash trees under the management of HVRA, UoT-StGeorge and the City of Toronto. Estimation provided included tree cover, leaf area, carbon storage, carbon sequestration, pollution removal, oxygen production, avoided runoff, structural values, and annual functional values. According to iTree Eco User's Manual (2018) and iTree Ecosystem Analysis Written Report : (1) carbon storage was the amount of carbon that tree hold in its accumulated tissue, which also indicates the amount of carbon that will be released if the tree dies and decomposes; (2) carbon sequestration was the annual amount of atmospheric carbon that can be removed and stored in the tree; (3) pollution removal was an estimation of annual amount of air pollution removed by trees, including ozone (O_3), carbon monoxide (CO), nitrogen dioxide (NO_2), particulate matter less than 2.5 microns (PM2.5)[2] and sulfur dioxide (SO_2); (4) annual oxygen production is the amount of oxygen trees can produce, which is directly related to the amount of annual carbon sequestration; (5) avoided runoff was the volume of precipitation which trees intercept and promote infiltration and storage in the soil; (6) urban forest structural values were base on tree themselves, including structural value and carbon storage value; (7) annual functional values was based on the functions that trees perform, including carbon sequestration value, avoided runoff value and pollution removal value. iTree Eco (v6.0) used a combination of field data, weather and pollution data from Toronto City Center Weather Station (2010) and currency exchange rate between US dollar and Canadian dollar to estimate above ecosystem services and the corresponding monetary values.

3.4 Data Analysis

Since the inventory data were no available for every single year over the past ten years, annual loss of the ash trees was calculated by dividing the total loss number of several years by the number of years. The annual mortality rate was calculated by the same method.

The data didn’t satisfy a normal distribution. Therefore, Wilcoxon rank sum test was used to test the difference of the annual loss as well as the annual mortality rate under different management strategies.

Exponential regression model was used to fit the ash tree accumulative mortality rate as a function of years since the first available inventory year (Klooster et al., 2014; Morin et al., 2017) to explore patterns of ash tree mortality under different management strategies over the past 10 years.

4 Results

4.1 Loss caused by EAB over past 10 years

The change of number and average characteristics of ash trees under the management of HVRA, UoT-StGeorge and the city in available inventory years are described in Table 1. Over the past 10 years, the city has always had the greatest number of trees, but all the three average tree attributes (DBH, canopy width, and tree height) are the smallest among the three management strategies. Trees under UoT-StGeorge management are the second most and exhibit the largest average DBH all the time, whereas HVRA contains the least number of ash trees. Except that the average tree height of city ash trees stays the same from 2008 to 2017, all the average attributes (DBH, canopy width and tree height) are increasing over the past ten years.

Table 1. Main ash tree characteristics under the management of HVRA, UoT-StGeorge and the city in Toronto in available inventory years.

	HVRA			UoT-StGeorge			City	
	2008	**2016**	**2017**	**2008**	**2012**	**2017**	**2008**	**2017**
Trees	61	35	29	143	142	87	197	109
Avg. DBH (cm)	29.4	33.9	36.8	32.1	36.0	40.6	16.8	20.5
Avg. canopy width (m)	9.0	10.1	11.1	8.5	10.0	10.4	5.6	6.8
Avg. tree height (m)	13.9	14.3	15.0	13.8	16.1	16.3	9.5	9.5

Because of the loss of ash trees, multiple ecological benefits provided by ash trees are lost as well (Table 2.). HVRA lost most carbon storage although it lost the least number of ash trees at 32. UoT-StGeorge lost the most tree cover and leaf area, as well as avoided runoff and pollution removal which is directly influenced by the tree canopy. And the city lost the greatest number of ash trees at 88 and lost the greatest annual carbon sequestration and oxygen production.

Considering the difference in the number of trees and the ecological services they provided under three management strategies in the first inventory year, the percentage of loss is also calculated in Table2. HVRA lost the 52.5% of its original ash trees in 2008, ranking first among the three management strategies. The city lost the greatest number of ash trees at 88, whereas the percentage ranked second at 44.7%. UoT-StGeorge lost 56 ash trees, which accounts for 39.2% of its ash trees in 2008. Due to the large percentage of lost ash trees, HVRA also has the greatest loss percentage in all the seven ecological values. Averagely, HVRA lost 41.7%, UoT-St-George lost 25%, and city lost 35.2% of their original ecological values in 2008.

Table 2. The loss of ecological values and percentage under the management of HVRA, UoT-StGeorge and the city, Toronto, 2008 to 2017.

	HVRA		UoT-StGeorge		City	
	Value	**%**	**Value**	**%**	**Value**	**%**
Trees	32	52.5	56	39.2	88	44.7
Tree Cover (m^2)	1,627	33.5	1,804	17.6	1,560	25.5
Leaf Area (m^2)	5,789	42.7	12,090	32.5	6,770	33.2
Carbon Storage (ton)	7.4	37.0	2.9	6.4	7.2	35.4
Gross Carbon Sequestration (kg/yr)	151.5	51.9	215.3	27.8	225.8	47.1
Avoided Runoff (m^3/yr)	13.9	38.1	22.4	25.6	14.8	29.5
Pollution Removal (kg/yr)	6.5	37.0	9.4	23.0	6.7	28.3
Oxygen Production (kg/yr)	403.7	51.9	574.0	27.8	602.4	47.1

The economic loss due to the loss of ecological services is shown in Table 3, which corresponds to Table 2. More ecological values are lost, more corresponding economic values are lost. Therefore, HVRA lost the most percentage of economic values as well. Structural value in Table 3 represents the cost replacing a tree with a similar tree, which can only be measured by economic values. Although UoT-StGeorge lost Can$98,000 of structural value, it only accounts for 24% of its original structural value in 2008. Averagely, HVRA lost 43.1%, UoT-StGeorge lost 22%, and city lost 34.5% of their original economic values in 2008.

Table 3. The loss of economic values and percentage under the management of HVRA, UoT-StGeorge and the city, Toronto, 2008 to 2017.

	HVRA		UoT-StGeorge		City	
	Can$	**%**	**Can$**	**%**	**Can$**	**%**
Carbon Storage	850	37.0	330	6.4	830	35.6
Structural Value	46,300	49.1	98,000	24.0	35,900	29.7
Gross Carbon Sequestration ($/yr)	17	51.9	25	27.8	26	47.1
Avoided Runoff ($/yr)	32	38.1	52	25.5	34	29.2
Pollution Removal ($/yr)	197	39.6	318	26.1	219	30.9

4.2 Compare the annual loss and annual mortality rate under different management strategies

In the past ten years, the city lost 10 ash trees per year under its management, which is significantly higher than the loss of HVRA (4 ash trees per year) and UoT-StGeorge (7 ash trees per year) (Table 4.and Table 5.). However, there is no significant difference between the loss of HVRA and UoT-StGeorge.

Table 4. Average annual loss and standard deviation of ash trees under the management of HVRA, UoT-StGeorge and the city, Toronto.

HVRA	UoT-StGeorge	City
3.56 ± 1.01	6.22 ± 10.72	9.78 ± 7.85

Table 5. P value from Wilcoxon rank sum test of annual loss under the management of HVRA, UoT-StGeorge and the city, Toronto.

	HVRA	UoT-StGeorge	City
HVRA	\	0.890	<0.001
UoT-StGeorge	\	\	0.041
City	\	\	\

Although the city has the largest number of ash tree lost, it also has the most trees under its management. Annual mortality rate is a better way to compare whether there is a difference among three different management strategies. HVRA loses an average of 5.83% of its trees per year. The city lost an average of 4.96% per year and UoT-StGeorge lost 4.35% of trees per year, which is the least among the three management strategies (Table 6.). However, according to the results of the Wilcoxon rank sum test, none of them has any significant difference from each other (Table 7.).

Table 6. Average annual mortality rate and standard deviation of ash trees under the management of HVRA, UoT-StGeorge and the city, Toronto.

HVRA	UoT-StGeorge	City
5.83 ±1.66	4.35 ± 7.50	4.96 ± 3.85

Table 7. P value from Wilcoxon rank sum test of annual mortality rate under the management of HVRA, UoT-StGeorge and the city, Toronto.

	HVRA	UoT-StGeorge	City
HVRA	\	0.988	0.799
UoT-StGeorge	\	\	0.949
City	\	\	\

4.3 Ash Mortality Pattern Under Different Management Strategies

Based on the annual mortality rate, the exponential regression model was used to fit the accumulative mortality rate. Various management strategies lead to different ash mortality patterns (Figure 3). According to the results of exponential regression, trees under different management showed different mortality pattern as following equations presenting:

Ash trees under HVRA management:

$$y = 5.8178e^{0.2652x} \qquad R^2 = 0.9146,\ p<0.05 \tag{1}$$

Ash trees under UoT-StGeorge management:

$$y = 0.1617e^{0.6345x} \qquad R^2 = 0.7269,\ p<0.05 \tag{2}$$

Ash trees under the City of Toronto management:

$$y = 2.7509e^{0.3332x} \qquad R^2 = 0.9361,\ p<0.05 \tag{3}$$

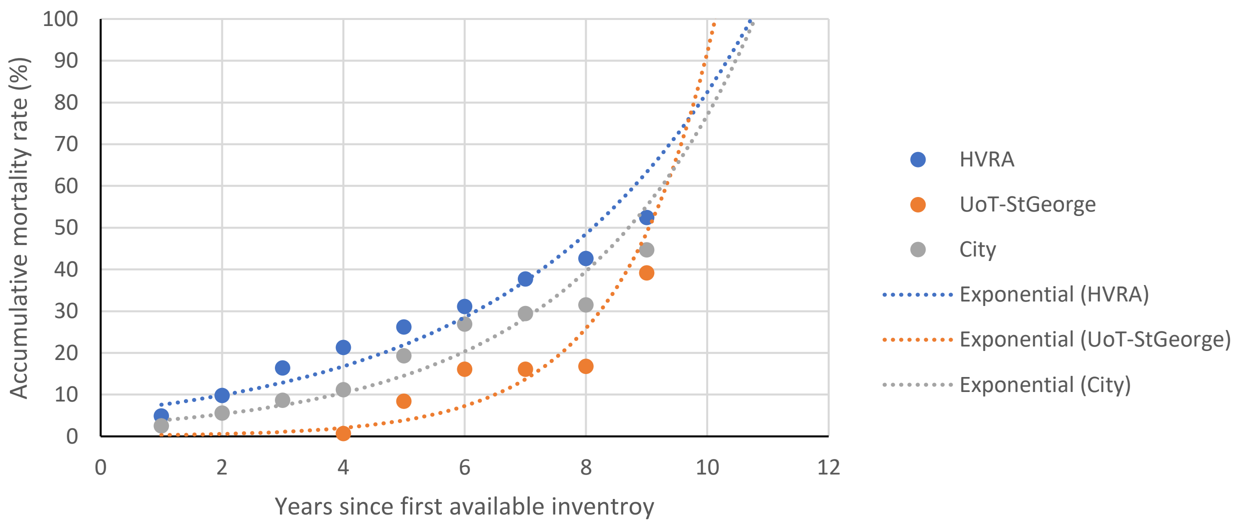

Figure 3. Accumulated ash mortality as a function of years since first available inventory with exponential regression line, Toronto, 2008 to 2017.

All the three regression equations can explain more than 70% of the variance with p values less than 0.05, indicating the reliability of the equations. According to the equation from exponential regression, prediction can be made to explore the potential time for the existing ash reaching entirely dead. The accumulative mortality rate of all the three curves will exceed 100% at the 11^{th} years, which is 2019.

4.4 New Ash Trees

Although the original trees from 2008 were dying, inventory data from 2018 showed ash regeneration trend in HVRA area. All the ash regeneration was found to be not purposefully planted, which were usually growing in the alleyways, parking lot or front yards of local residence in the HVRA neighbourhood. 15 green ash and 1 white ash were recorded, with an averaged DBH of 1.5cm, average canopy width of 1.5m and average total height of 2m. Most of these new ashes were found to be epicormics from old ash stumps. Such not purposefully planted ash regeneration was not recorded in the UoT-StGeorge inventory data over the years.

5 Discussion

5.1 Impact of EAB

Urban forest has high ecological and economic value has been demonstrated by many studies (Bolund & Hunhammar, 1999; Nowak et al., 2008). Since ash trees represent 5-20% of all the street trees in many North America cities (Haack et al., 2002; Herms & McCullough, 2014), large percentage of ash trees loss could reduce regional forest productivity (Flower et al., 2012). All the ash species were susceptible to EAB (Herms and McCullough, 2014), while black ash, green ash and white ash were the top three ash species that have more significant decline trend than other species in the genus (Smith, 2006; Gandhi et al., 2008). Green ash, as the major species in the study area, showed a significant decline trend, which could be considered as the main part of the lost ash within both areas.

Over the past 10 years, the city lost 88 ash trees, UoT-StGeorge lost 56 ash trees and HVRA lost 32 ash trees. Considering the number of original ash trees they have in 2008, HVRA lost the most ash trees that accounts for 52.5% of the number in 2008, which lead to over 40% of the ecosystem services. In this study, HVRA has the greatest loss percentage. However, compare to some research in the U.S. forest that most ash trees died over a five-year period, leading to a huge disturbance on the forest ecosystem (Klooster et al., 2018). And according to the prediction of the City of Toronto that most ash trees will be killed by 2017 (City of Toronto, 2017), while the results of this study show a more optimistic status than the prediction. Therefore, the management strategies of the three parties in this study did contribute to reducing the EAB impact and maintaining the stability of urban forest.

An important factor that is not taken into consideration in this study is the stresses from the urban environment. Most city trees are planted along the street. Since the study area is located in the downtown core of Toronto, which is a busy and crowded area. Most city ash trees in the area were planted in an open bed surrounded by a barrier curb made of granite, precast concrete or other materials that the city approved (City of Toronto, 2010). In contrast, ash trees owned by private owners or private institutions were mostly planted in an open area without the constraints of the root space. Therefore, city trees suffer more stresses from the urban environment than private trees, such as restrictive soil volume, soil compaction, soil and air pollution (Sæbø et al., 2003). Thus, the city lost their ash trees, not only because of their management strategy, but also because the trees are under more pressure from the urban environment.

Although EAB caused very high mortality of ash trees and huge loss of ecological and economic values, it can enhance the growth of other species in the EAB infestation area, among which *Acer spp.* and *Ulmus spp.* responded most positively (Flower et al., 2013). This potential ecological impact brought by EAB was not considered in this study due to the limitation of inventory data, and this could be a potential topic for further research.

The invasion of EAB is now one of the hottest ecological issues in North America. The huge negative impact brought by this invasive species also gave us alert and enlightenment to prevent damage of any other potential eco-catastrophe. Investing in municipal forest management, such as ecological infrastructure, is considered to be desirable in ecological, social and economic aspects (McPherson et al., 2005; Elmqvist et al., 2015). Therefore, no matter public communities, private institutions or the government are supposed to actively engage in maintaining the stability and integrity of the urban ecosystem.

5.2 The difference between public and private management

The city lost the greatest number of ash trees at 88. Considering the City of Toronto's insecticide injection criteria that a tree will get injected only if it is bigger than 15 cm DBH, showing low-level of infestation, having less than 30% loss of canopy and in fair or good health condition, as well as both average DBH in 2008 and 2017 are a little bigger than 15 cm, we can indicate that there is a certain number of small DBH ash trees did not get injected under the city's management. Without any treatment, ash trees are more susceptible to the EAB infestation. The city made the injection criteria considering the cost-effectiveness. Since there are 32,000 city owned ash tree across Toronto, the city intended to reduce the EAB impact as much as possible with the limited budget.

The average tree height of city ash trees stays the same from 2008 to 2017, indicating that the ash trees under the city's management didn't show any significant growth during the past 10 years. Or we can consider that the growth of ash trees is equal to the loss of ash trees, resulting in no rise in the average height in past 10 years. We can infer that the growth of other ash trees in the area is not significant, either, due to the infestation of EAB. However, except for the average tree height of city trees, other average attributes all showing an increasing trend. Excluding the influence of tree growth, we can infer that the increase of the average attributes is because of the loss of small DBH trees. Therefore, not only the city is losing small ash trees, HVRA and UoT-StGeorge are losing them too. This indicates a consensus among the three parties on the treatment of ash, which is to optimize the protection on large diameter ash trees while minimizing the ecological and economic impacts.

UoT-StGeorge has the least loss of ash trees and its associated ecological and economic values. It is mainly due to its comprehensive management strategy. The university is responsible for all the trees on its property, and all the infested ash trees were injected to prolong their lives as long as possible. As a private institution, the primary objective of UoT-StGeorge is to maintain a beautiful landscape. And regarding 143 ash trees in 2008, it wasn't a big financial problem to inject all the trees for such a big institution. Therefore, UoT-StGeorge ash management strategy can be considered as a relatively successful approach to reduce the impact of EAB infestation.

In contrast to the UoT-StGeorge comprehensive management strategy, ash management against EAB in HVRA is more depending on private individuals. Although this study can't trace the treatment of every single ash tree in the area, it was found that some residents did not well-manage the ash in their yards, and some residents in the neighbourhood didn't recognize the severity of EAB until the trees showed a significant dieback. Financial problem is a main constraint of the EAB management in a neighborhood like HVRA. The cost of TreeAzin™ depends on many factors, such as tree size, tree health, tree location and the degree of infestation (BioForest Technologies Inc., 2018). As of 2013, the cost of TreeAzin™ was approximately $5 per cm DBH per treatment (Ryan, 2018). And the injections need to be operated every two years for at least two cycles. Except for the cost of insecticide, the private owners need to consult a tree management expert before undertaking any steps and pay for a treatment visit before the injection (Ryan, 2018). Tree removal cost in Toronto could range from $170 to $960 depending on the tree size and the tree location (Tree Removal, 2018). Although injection can bring more ecological benefits, the actual cost of removing an ash tree might be equal or even less than injecting one. Therefore, some residents in HVRA chose to remove their ash trees instead of a long-term injection. But there are still some residents decided to inject their ash trees to maintain multiple benefits brought by the trees. Therefore, the management strategy in HVRA is highly depending on the individual choice of the land owner.

Overall, each party has their own primary objective and decision criteria. We can't consider generally that one management strategy is suitable everyone. However, in terms of the effectiveness, a comprehensive management strategy against EAB can be considered as a better way to reduce the impact caused by EAB.

5.3 Ash Mortality Pattern

Many studies have already demonstrated the ash mortality of regional forests. Morin et al. (2017) found an annual increase of ash mortality at 2.7% per year after the first detection of EAB in a county. Gandhi et al. (2008) and Klooster et al. (2014) found that within forested stands in the Michigan Upper Huron River Watershed, ash percentage mortality increased over 30% in three years and increased more than double in four years. Pugh et al. (2011) found ash volume was significantly decreased in 5 years due to de high mortality rate in the Grate Lakes States regional forests in US. In this study, ash mortality showed a similar increasing trend over the ten years. The ash mortality rate under all three management strategies (HVRA, UoT-StGeorge and city) fitted the exponential regression model, showing an increasing annual mortality rate over the years. The same ash mortality pattern was also verified by Klooster et al. (2014), Herms (2014), and Morin et al. (2017).

In the Figure 3, the curve of UoT-StGeorge is the first to reach 100%. The trend of this curve is beyond expectation. According to the previous analysis, UoT-StGeorge has the least loss of ash trees and its associated ecological and economic values, and it was expected to take more time to reach 100% mortality rate. Therefore, it is inferred that the trend of the curve is influenced by the last point, which is the loss in 2017. Based on the current available inventory data, we can only get a curve showed in Figure 3. But if there are further data in the future, it can be tested that if the last point is an outlier or the mortality rate in UoT-StGeorge is really rising rapidly.

The curve of ash cumulative mortality percentage in the Huron River Watershed in southeastern Michigan was showed in Figure 4 (Klooster et al., 2014). Data in the research were collected by annual direct measurements from 2005 to 2010. Although the research didn't include the data of first several years after infestation, the curve still fits the exponential regression model. A phenomenon presented by Figure 4 is that the curve tends to be flat when the mortality approaching 100% and even shows a little decline in 2010 due to the ash regeneration. Therefore, even though the prediction by the curve in this study indicates that all the ash trees will die by next year, it will actually take more time for the rest of ash trees to die.

Furthermore, as the regeneration happens and grows, the ash mortality rate will not really reach 100%.

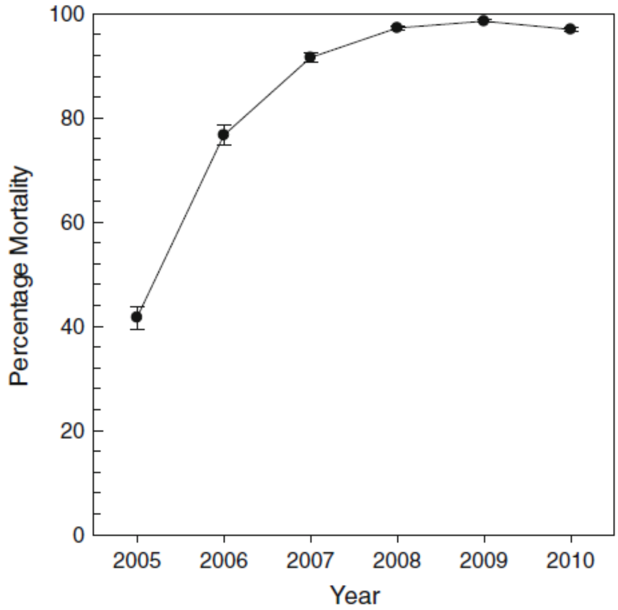

Figure 4. Percentage ash mortality of trees from 2005 to 2010 in 38 forested stands within the Huron River Watershed in southeastern Michigan. Adapted from " Ash (*Fraxinus spp.*) mortality, regeneration, and seed bank dynamics in mixed hardwood forests following invasion by emerald ash borer (*Agrilus planipennis*)." by W.S. Klooster et al., 2014, Biological Invasions, 16(4), 859-873.

Actually, a small percent of the ash tree has the possibility to survive, although EAB has been confirmed causing high mortality rate of ash trees (Poland and McCullough, 2006; Donovan et al., 2013; Klooster et al., 2014). Knight et al. (2012) found that 2.6% of the ash tree with a DBH of 10cm or more survived from the massive ash mortality in 2008 and even 1% of them still were at a healthy condition. Therefore, ash trees within the study area and even in the entire City of Toronto still have a chance to survive EAB infestation, in spite of the prediction in this study that ash mortality rate will reach 100% in the next few years.

In addition, ash regeneration was found in HVRA area, indicating a trend of natural recovery of ash species. However, regeneration was not found in the UoT-StGeorge area. The reason might be the different management strategies. The University of Toronto has a much more systematic method in maintaining the ash trees within the property, preventing the growth of any not purposefully planted plants to keep the aesthetic of the landscape. In Contrast, some areas in HVRA, such as alleyways and parking lot, are sometimes neglected to manage, or some local residents allow plants to grow freely in their yards, which gives the ash species a chance to regenerate spontaneously.

5.4 Limitations and Uncertainties

As the EAB continues to damage the ash species in most area of North America, regular inventory data can be used to monitor and quantify the ash mortality and the loss brought by loss of ash trees. Inventory data used in this study were from irregular tree inventory over the past 10 years between 2008 and 2018. Available inventory data were not annually, which made the calculation process and the results less convincing. For example, the method of fitting annual ash mortality by linear regression used by Morin et al. (2017) was not suitable for this study. Because the annual ash mortality was obtained by averaging rather than actual measuring, making the R-square value and p value insufficient to prove the reliability of the regression equation

Furthermore, staff who did the inventory at two sites were different and even within the same site people who did the inventory over the years were different, resulting in deficiency of continuity and consistency. For example, HVRA 2008 inventory data used in this study were collected by a group of volunteers who trained by Dr. Andy Kenney of the University of Toronto, 2017 and 2018 inventory data were collected by students (HVRA, 2018). And UoT-StGeorge 2012 inventory data were collected for a management plan making, which might be more accurate than other years. All these uncertainties might cause the inaccuracy of the results. Moreover, there were some missing values in the inventory data, which were filled by the data from last available inventory data (for example, missing DBH value in UoT-StGeorge 2012 was filled by DBH value of the same tree in UoT-StGeorge 2008). Therefore, the ecological and economic values calculated in this study are supposed to be the minimum values.

6 Conclusion

Over the past 10 years, HVRA, UoT-StGeorge and the city lost 52.5%, 39.2% and 44.7% of their ash tree respectively; 41.7%, 25% and 35.2% of their ecological values respectively; and 43.1%, 22%, and 34.5 of their economic values respectively.

Regarding the loss number of ash trees, the city lost significantly more than HVRA and UoT-StGeorge. However, regarding the mortality rate, there is no significant difference among three management strategies.

UoT-StGeorge has the lowest loss rate and associated values, because of its comprehensive management on infested ash trees.

Ash mortality patterns under three management strategies fit the exponential regression model and are predicted to reach 100% by 2019.

7 Recommendations

Since EAB has caused huge loss to the urban forest, recommendations were made for various management parties to reduce the impact of EAB:

1) For private institution like UoT-StGeorge, the comprehensive management strategy can be kept maintaining every single tree on its property to keep a good health condition of the urban forest.

2) For local community like HVRA, awareness of local residents needs to be increased, so that they will actively maintain the health condition of trees on their property as possible as they can. Furthermore, community board can provide some financial support to the local residents since the main criteria for private owner whether to inject an ash or not is the financial problem. Financial support could be within the neighbourhood, for example, some neighbors could contribute to help defray the costs for individual trees where the owner is unable to afford it. Financial support could also be achieved through cooperation with some organizations. Some non-profit organizations are working on helping to mitigate the

impacts of EAB. In 2016, Tree Canada offered private ash owners a lower price of TreeAzin™ at $3 per centimeter compared with a regular price of $5 per centimeter (Tree Canada, 2018). LEAF (Local Enhancement and Appreciation of Forests) has a Youth EAB Ambassador program, which is a workshop to educate Childs in the importance of urban forest and the impact brought by EAB.

3) For public management like the City of Toronto, the injection criteria are necessary to keep the cost-effectiveness of the ash tree treatment. At the same time, it is important as well to educate and increase citizens' knowledge and awareness to protect and maintain the ash trees, so that it will be easier for the city to save the ash trees across the whole city.

A regular tree inventory by trained individuals could be helpful for future research. With a continuous and consistent inventory data, the estimation and the prediction would be more accurate.

The management of other existing or potential future invasive pests could use this study as a reference for a better management strategy.

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Appendices

Appendix I: Ecological values and economic values under three management strategies (HVRA, UoT-StGeorge, city) in Toronto in available inventory years.

	Year	Trees	Tree Cover	Leaf Area	Carbon Storage		Gross Carbon Sequestration		Avoided Runoff		Pollution Removal		Structural Value	Oxygen Production
		Number	m^2	ha	(ton)	(Can$)	(kg/yr)	(Can$/yr)	(m^3/yr)	(Can$/yr)	(kg/yr)	(Can$/yr)	(Can$)	(kg/year)
City	2008	197	6,113	2.04	20.3	2,330	479.1	55.0	50.1	116	23.6	708	121,000	1,278.0
City	2017	109	4,553	1.36	13.1	1,500	253.3	29.1	35.3	82	17.0	489	85,100	675.6
HVRA	2008	61	4,855	1.36	20.0	2,300	291.8	33.5	36.4	85	17.6	498	94,300	778.0
HVRA	2016	35	3,384	0.83	13.1	1,510	156.6	18.0	23.8	55	11.7	320	51,900	417.6
HVRA	2017	29	3,228	0.78	12.6	1,450	140.3	16.1	22.5	52	11.1	301	48,000	374.3
UoT-StGeorge	2008	143	10,250	3.72	45.0	5,170	773.3	88.8	87.7	204	40.7	1,220	408,000	2,062.0
UoT-StGeorge	2012	142	13,050	3.93	56.6	6,510	747.6	85.9	101.5	236	48.7	1,410	405,000	1,994.0
UoT-StGeorge	2017	87	8,446	2.51	42.1	4,840	558.0	64.1	65.3	152	31.4	902	310,000	1,488.0

Appendix II. Annul loss rate under the management of HVRA, UoT-StGeorge and the city, Toronto.

Year	HVRA	UoT-StGeorge	City
2008	0	0	0
2009	4.9%	0.0%	2.5%
2010	4.9%	0.0%	3.0%
2011	6.6%	0.0%	3.0%
2012	4.9%	0.7%	2.5%
2013	4.9%	7.7%	8.1%
2014	4.9%	7.7%	7.6%
2015	6.6%	0.0%	2.5%
2016	4.9%	0.7%	2.0%
2017	9.8%	22.4%	13.2%

Appendix III. Accumulative ash mortality rate under the management of HVRA, UoT-StGeorge and the city, Toronto.

Year	HVRA	UoT-StGeorge	City
2008	0	0	0
2009	4.9%	0.0%	2.5%
2010	9.8%	0.0%	5.6%
2011	16.4%	0.0%	8.6%
2012	21.3%	0.7%	11.2%
2013	26.2%	8.4%	19.3%
2014	31.1%	16.1%	26.9%
2015	37.7%	16.1%	29.4%
2016	42.6%	16.8%	31.5%
2017	52.5%	39.2%	44.7%