UNIVERSITÉ DU QUÉBEC EN OUTAOUAIS

ÉVOLUTION DES SERVICES ÉCOSYSTÉMIQUES SELON DIFFÉRENTES STRATÉGIES DE GESTION DE L'INFESTATION D'AGRILE DU FRÊNE DANS UN ARRONDISSEMENT DE MONTRÉAL, QUÉBEC

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AVANT-PROPOS

Mon mémoire de maîtrise sera présenté sous la forme d'un article scientifique. Dans le chapitre II (l'étude de cas), les résultats de mon inventaire des arbres urbains de l'arrondissement montréalais d'Ahuntsic-Cartierville sont présentés. J'ai aussi élaboré et analysé des scénarios de gestion de l'infestation d'agrile du frêne entre 2011 (l'année avant la découverte de l'insecte à Montréal) et 2017. J'ai réalisé l'inventaire terrain, le traitement des données, les analyses et l'écriture de l'étude de cas sous la supervision de mon directeur, le Pr Jérôme Dupras (UQO), et de mon codirecteur, le Pr Sylvain Delagrange (UQO). Ce fut un réel privilège et un grand plaisir d'avoir côtoyé ces chercheurs lors des deux dernières années. Je me compte très chanceux d'avoir réalisé mes études de deuxième cycle à l'Institut des Sciences de la Forêt tempérée (ISFORT) avec des gens merveilleux.

J'aimerais aussi remercier l'ISFORT et ses partenaires pour leurs soutiens financiers.

Cette maîtrise m'a permis de me spécialiser dans le domaine extraordinaire de la foresterie urbaine. Lors de mon échantillonnage de l'été 2016, plusieurs personnes m'ont aidé dans la prise de données dont Ginette Vaillant (mère), Alain Bertrand (père), Virginie Rheault (fiancée), Jean-François Désaliers (ami) et David Marsolais-Roy (ami). Je les remercie tous pour leur appui.

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ADF Agrile du frêne

DBH Diameter at breast height

EAB Agrile du frêne (« Emerald ash borer »)

ES Services écosystémiques (« Ecosystem services »)

GIS Système d'information géographique (« Geographic Information System »)

GPS Système de positionnement global (« Global Positioning System »)

LAI Leaf area index

MWH Megawatt-hour

SE Services écosystémiques

SIG Système d'information géographique

VOC Volatile organic compound

RÉSUMÉ

La forêt urbaine a un impact sur la santé et le bien-être des résidents des villes. Dans un contexte de changements globaux, plusieurs pressions sont et seront exercées sur cette forêt. Ces pressions ont le potentiel d'entraîner des conséquences négatives à l'égard des aspects sociaux, environnementaux et économiques. Depuis 2011, la Ville de Montréal est aux prises avec une infestation d'agrile du frêne (ADF) qui met en péril le frêne, soit environ 20% des arbres municipaux. Dans le cadre de cette maîtrise, la forêt urbaine de l'arrondissement d'Ahuntsic-Cartierville a été étudiée. Les objectifs de cette étude étaient 1) d'établir et de quantifier les principaux services écosystémiques (SE) fournis par la forêt urbaine d'Ahuntsic-Cartierville comme référence pour 2) évaluer les impacts de quatre stratégies différentes de gestion issues de la recherche théorique et de la réalité sur le terrain. Le premier scénario correspond au scénario où l'insecte n'est pas présent. Le deuxième scénario a exploré l'effet de ne pas protéger les arbres et de planifier uniquement les activités d'abattage et de plantation d'arbres de remplacement, tandis que les troisième et quatrième scénarios ont exploré des styles proactifs de gestion avec des traitements insecticides appliqués sur 33 % et 50 % de tous les frênes publics par année. Pour chacun des scénarios établis, l'évolution de trois SE est effectuée par l'intermédiaire du dénominateur commun économique. Le quatrième scénario a démontré des résultats impressionnants puisque seulement 433 frênes ont été abattus en 6 ans et 92 % des SE ont été conservés comparativement à 56 % pour le troisième scénario. Grâce à l'exercice de monétarisation, ce travail permet d'aider les décideurs des municipalités qui sont ou seront infestées à l'avenir par l'ADF à mieux choisir leur stratégie de gestion pour combattre cet insecte et maintenir un maximum de SE aux citoyens.

MOTS-CLÉS : Agrile du frêne, foresterie urbaine, services écosystémiques, i-Tree.

CHAPITRE I INTRODUCTION

1.1 Contexte et problématique

« L'idée de services rendus à l'humanité par les écosystèmes est apparue à la fin des années 1970, avec des auteurs tels que Westman (1977) puis Ehrlich et Mooney (1983) » (Barnaud et coll., 2011). Par la suite, beaucoup d'autres chercheurs, dont Gretchen Daily et Robert Costanza, ont contribués à faire avancer cette idée en un concept beaucoup plus précis et tangible : le concept de service écosystémique (SE). Selon Daily et coll. (1997), les SE sont les conditions et les processus par lesquels les écosystèmes naturels et les espèces qui les composent soutiennent et comblent la vie humaine. Cette définition semble ne pas tenir compte des écosystèmes créés par l'Homme ou des écosystèmes artificiels de plus en plus présents dans le monde d'aujourd'hui. La définition a été modifiée peu de temps après par Costanza et coll. (1997) et elle inclut dorénavant les avantages que les populations humaines tirent, directement ou indirectement, des fonctions de l'écosystème. Beaucoup d'autres définitions ont été établies dans les années 2000 et elles portaient toutes sur le bien-être humain (Boyd et Banzhaf, 2007, Fisher et al., 2009 et TEEB Foundations, 2010). En milieu urbain, les arbres sont responsables de la fourniture de nombreux SE. On peut grouper ces services en quatre différentes catégories : l'approvisionnement, la régulation, le support et la culture (MEA, 2005). Ces services sont issus de combinaisons complexes de processus physiologiques et morphologiques et d'interactions entre individus et espèces. L'étude de ces services est ardue et leur intégration dans les plans de gestion municipale est trop souvent absente (MEA, 2005). Mais, selon Costanza (2006), c'est une nécessité si l'on veut préserver l'environnement puisque l'objectif de l'évaluation économique des SE est de faire prendre conscience aux décideurs de leur importance de sorte que les coûts associés à leur perte soient pris en compte dans les décisions. Cette prise en compte pourrait aussi mener à plus d'investissements dans l'infrastructure verte des villes et une amélioration des services aux citoyens.

L'environnement urbain est continuellement menacé (Konijnendijk et coll., 2005). Cet environnement est souvent rude, caractérisé par de nombreuses pressions et menaces notamment la pollution de l'air, les conditions climatiques et la place limitée pour la croissance des arbres (Konijnendijk et coll., 2006). Les arbres urbains sont particulièrement menacés par l'urbanisation, le vandalisme et les interactions avec des espèces non indigènes (Czech et coll., 2000). Ils sont aussi menacés par les changements globaux. Les changements globaux réfèrent aux changements dans l'environnement global qui peuvent altérer la capacité de la planète à soutenir la vie. Elle englobe, entre autres, le changement climatique, le changement d'affectation des terres, l'altération du cycle de l'eau, les changements dans les cycles biogéochimiques et la perte de biodiversité (U.S. Global Change Research Program, 2017). Cela implique aussi des ravageurs exotiques qui ont un impact sur l'écologie (Sala et al, 2000 tiré de Tylianakis et al., 2008).

Il existe deux catégories de perturbations naturelles : biotique et abiotique (Voller et Harrison, 1998). Les perturbations biotiques sont celles provenant d'êtres vivants et qui agissent sur d'autres êtres vivants. Par exemple, les insectes et les maladies en provenance d'autres écosystèmes qui modifient l'écosystème en place. Les perturbations abiotiques, quant à elles, sont de nature non vivante (Voller et Harrison, 1998). Les deux catégories de perturbations ont le potentiel d'exercer des pressions sur l'écosystème en place selon l'étendue touchée, les intervalles de retour et l'ampleur des perturbations (Voller et Harrison, 1998). Les sections 1.1 et 1.2 présentent des exemples d'une perturbation biotique (l'agrile du frêne) et abiotique (changements climatiques) qui font partie des changements globaux.

1.1.1 Exemple de perturbation biotique : Agrile du frêne

L'agrile du frêne (*Agrilus planipennis*) est un insecte de couleur vert métallique originaire d'Asie du Sud-Est mesurant de 1,4 à 1,8 cm de longueur. Il s'attaque majoritairement aux frênes (*Fraxinus* spp.) et il fut observé pour la première fois en Amérique du Nord en 2002 dans la région de Windsor en Ontario et Détroit aux États-Unis (Haack et coll., 2002). À Montréal, l'agrile du frêne (ADF) a été découvert pour la première fois au printemps 2011 par les inspecteurs de la ville. Cet insecte possède déjà l'habileté de se propager rapidement de façon naturelle, mais sa propagation est accélérée par l'entremise du transport de bois de chauffage en dehors des zones contrôlées. Depuis que cet insecte ravageur a été découvert à Montréal, plusieurs milliers de frênes sont morts. La Ville de Montréal est durement touchée, car sa forêt urbaine contient environ 20 % de frênes (Ville de Montréal, 2015). Si la Ville de Montréal est très proactive dans le remplacement des arbres coupés (ou à couper), il n'en demeure pas moins que les jeunes arbres prennent beaucoup de temps à devenir matures et à offrir un niveau de service non négligeable sans compter le succès parfois mitigé de l'établissement des nouveaux arbres en milieu urbain. Une recherche effectuée par Kovacs et coll. (2010) dans 25 états des États-Unis prévoyait que 17 millions de frênes devraient être remplacés entraînant des coûts de 10,7 milliards de dollars américains et que le double de frênes et de coûts serait à prévoir lorsqu'on ajoute les milieux urbanisés. Au Canada, une étude a démontré que si l'insecte suivait une vitesse moyenne de propagation de 30 km/année et que les gestionnaires urbains procèdent à un taux de traitement d'insecticide des frênes à 10 %, la valeur des coûts de traitement pourrait s'élever à 524 millions de dollars canadiens, mais la valeur augmente à 891 millions avec l'ajout des arbres privés (McKenney et coll., 2012). L'analyse des coûts est importante, mais l'analyse des SE perdus par une infestation d'ADF est aussi très pertinente compte tenu de l'importance des arbres pour la santé humaine. Le passage par l'évaluation économique est simplement pour mettre tous les services sur le même dénominateur commun afin de permettre une comparaison et obtenir une réponse intégrative par rapport aux choix de gestion de services qui ont été sélectionnés.

1.1.2 Example de perturbation abiotique : Le changement climatique

Selon Barack Obama, ex-président des États-Unis, le changement climatique représente le plus grand défi à relever pour les générations futures (Obama, 2015). Le rapport intitulé « Changement climatique 2013 – Les éléments scientifiques » émis par le Groupe d'experts intergouvernemental sur l'évolution du climat (GIEC) mentionne qu'il est extrêmement probable que l'influence de l'Homme est la cause principale du réchauffement observé depuis le milieu du XX^{e} siècle (GIEC, 2013). Ce même groupe d'experts définit les changements climatiques comme étant une variation de l'état du climat qu'on peut déceler par des modifications de la moyenne ou de la variabilité de ses propriétés et qui persiste pendant une longue période.

La communauté internationale tente actuellement d'éviter une augmentation des températures supérieures à 2 °C (United Nations, 2015). Cependant, l'inertie des émissions continuelles crée un potentiel de réchauffement planétaire comparable en magnitude à celle des plus grands changements globaux dans les 65 millions d'années précédentes (Diffenbaugh et Field, 2013). Les effets du changement climatique sont variés et les incertitudes sont grandes, car ils se produisent à un taux 10 fois plus rapide que tout changement survenu en 65 millions d'années (Diffenbaugh et Field, 2013).

Les forêts urbaines offrent deux types d'approches pour réduire les impacts du changement climatique : l'atténuation et l'adaptation. La première approche réfère à la réduction des quantités de gaz à effet de serre dans l'atmosphère et au ralentissement de la progression du changement climatique. La deuxième réfère à l'adaptation des villes aux changements environnementaux et sociaux que cause et causera le changement climatique (Canadian Forest Service, 2015).

Suivant le processus de la photosynthèse, les arbres séquestrent du carbone et l'emmagasine en tant que biomasse (Canadian Forest Service, 2015). L'un des plus importants services du point de vue pécuniaire est sans doute la séquestration de carbone, car Nowak et Crane (2002) ont estimé que les arbres urbains aux États-Unis (continental) séquestrent 22,8 millions de tonnes de carbone par année et un total de 700 millions de tonnes de carbone en stockage. Annuellement, la valeur économique a été estimée à 460 millions de dollars américains pour la séquestration et la valeur totale du carbone stocké a été estimée à 14 300 millions de dollars américains. Bien sûr, les insectes, maladies et autres perturbations peuvent grandement diminuer la performance de ce type de service en fonction de l'ampleur de la perturbation.

Cependant, les aspects abiotiques ne seront pas traités dans ce mémoire. Seulement l'exemple décrit à la section 1.1 sera approfondi.

2.1 Cadre conceptuel et état des connaissances

2.1.1 Cadre conceptuel

Le cadre conceptuel du projet comprend l'inclusion de plusieurs concepts dont celui de la foresterie urbaine, les bénéfices tirés des SE, les traits en lien avec les SE et les changements globaux. Tout d'abord, le concept de la foresterie urbaine se définit généralement comme étant l'art, la science et la technologie de la gestion des ressources en provenance des arbres et des forêts à l'intérieur ou à l'extérieur de l'écosystème urbain pour les bénéfices physiologiques, sociologiques, économiques et esthétiques fournis à la société (Konijnendijk et coll., 2006). Cependant, dans le projet actuel, seulement les arbres individuels seront étudiés. En analysant la définition précédente, on remarque qu'elle intègre la définition des SE de Daily et al. (1997) citée à la section 1 : « ... bénéfices que les sociétés humaines tirent de la nature ». Donc ces deux concepts sont intimement liés et il importe de mieux comprendre leurs interactions de même que de quantifier les bénéfices que fournissent les arbres urbains aujourd'hui et à l'avenir. Ensuite, les traits fonctionnels des plantes sont, quant à eux, intimement liés aux SE. En effet, les services réalisés par un écosystème sont liés à l'existence de fonctions qui sont sous la dépendance du type d'organismes constituant cet écosystème ainsi que des processus régissant leurs interactions avec le milieu (Garnier et Navas, 2013). En d'autres mots, afin de bien quantifier les SE, les traits fonctionnels pertinents et leurs interactions doivent être connus. Finalement, comme il est mentionné au chapitre précédent, les changements globaux peuvent être de nature biotique ou abiotique. Ils vont influencer la composition de la forêt urbaine et aussi des SE fournit par celle-ci. Par contre, l'inverse est aussi vrai. C'est pourquoi il est important de gérer le mieux possible cet écosystème afin d'atténuer les effets potentiellement négatifs causés par les changements globaux. Ce projet vise à outiller les décideurs en place au conseil de ville quant à la valeur actuelle et future de la forêt urbaine afin de mieux gérer des pertes potentielles en SE dans un contexte de changements globaux. La monétarisation des SE pourrait faciliter la compréhension des fonctions environnementales qui sont souvent négligées et moins tangibles. Cette approche est particulièrement pertinente lorsqu'on prend en compte les budgets municipaux très serrés (Jim et Chen, 2008). La Figure 1 présente les liens qui existent entre les différents concepts du cadre théorique du projet.

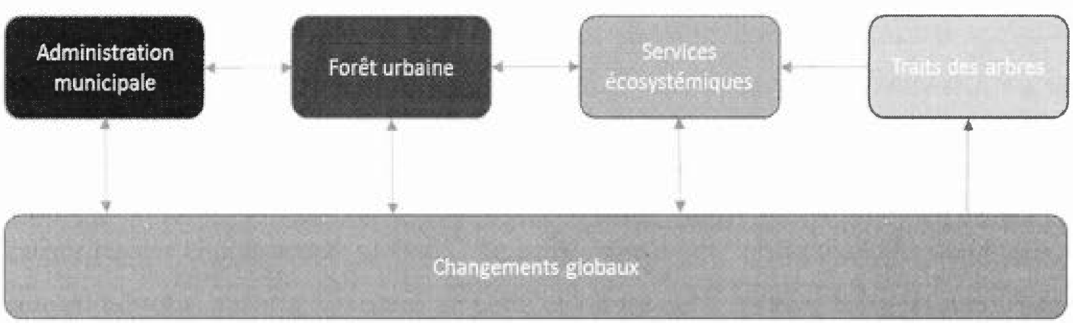


Figure 1.1 Liens entre les différents concepts du cadre conceptuel.

2.1.2 Services écosystémiques

Les services écosystémiques se trouvent au cœur des interactions entre les humains et les écosystèmes (Daily et al., 1997 ; Kareiva et al., 2007 ; Turner, Lambin et Reenberg, 2007). Les biens et services écosystémiques réfèrent aux bénéfices que les sociétés humaines tirent de la nature. C'est un concept relativement récent qui vise à concevoir les écosystèmes en une série d'attributs, vecteurs de bien-être, qui rendent la vie possible à l'être humain (Boyd et Banzhaf, 2007 tel que cité dans Dupras et al., 2013).

Un des exemples les plus récents provient de la Banque TD qui a produit deux rapports en 2014 sur la valeur des forêts urbaines de Toronto et sur la valeur des forêts urbaines des grandes régions d'Halifax, de Vancouver et de Montréal. En résumé, les rapports se concentrent sur les bénéfices pécuniaires de la forêt urbaine ($ total et $/arbre) en fonction des SE associés au cycle de l'eau, à la qualité de l'air, aux gains énergétiques et à la séquestration de carbone. L'objectif était de quantifier la valeur actuelle de ces forêts. La méthodologie n'est, par contre, aucunement explicite et il est difficile pour le lecteur de comprendre comment les économistes de la Banque TD sont arrivés à ces résultats (TD Bank [a], 2014 et TD Bank [b], 2014).

2.1.3 Analyse des outils d'évaluation de services écosystémiques des arbres urbains

Selon Costanza et coll. (1997), la valeur totale estimée des services écosystémiques de la Terre serait 33 trillions de dollars par année. À cette époque, ce chiffre était équivalent à plus du double du produit intérieur brut (PIB) de tous les pays au monde (Costanza et al., 1997). Depuis la parution de ce rapport, une panoplie d'outils sont apparus pour estimer la valeur pécuniaire des services fournis par les arbres et les boisés en milieu urbain et périurbain (Dupras et Revéret, 2015). On retrouve, entre autres, CITYgreen, InVEST et la suite i-Tree. Ces outils ont été développés pour l'évaluation et la quantification des services écosystémiques, mais ils possèdent tous leurs forces et leurs faiblesses. Il est donc nécessaire de sélectionner l'outil le mieux adapté aux objectifs.

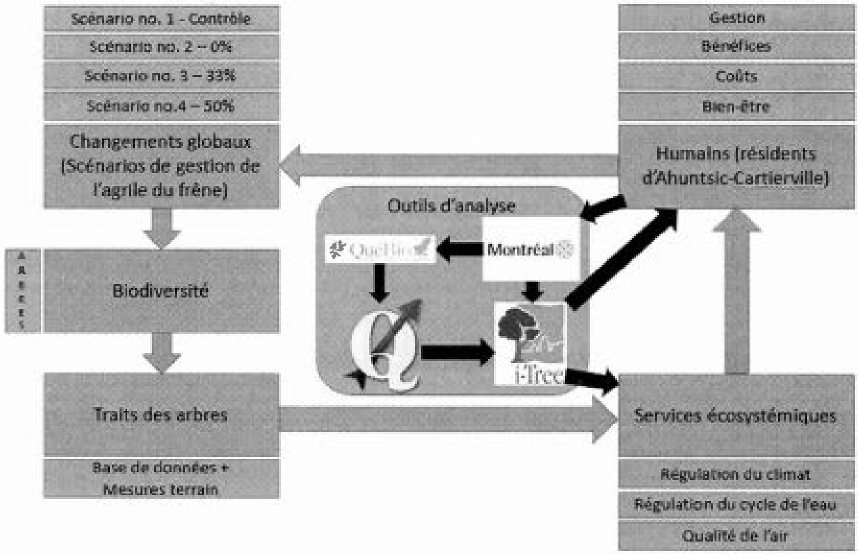
L'équipe de Bhalla et coll. (2010) ont compilé les avantages et les désavantages d'utiliser deux logiciels soit la suite i-Tree ainsi que le logiciel Citygreen. Les critères d'analyses pour ces outils étaient les suivants : la précision scientifique des évaluations, la pertinence des analyses, la crédibilité des analyses et la facilité d'utilisation du logiciel. Bhalla et coll. (2010) ont déterminé que la suite i-Tree correspondait à l'outil le plus complet, quant à CITYgreen, ils ont trouvé des lacunes dans chacun des critères. Finalement, le logiciel InVest ne semble pas être spécialisé dans la foresterie urbaine tandis qu'i-Tree a été spécialement mis au point pour mesurer les biens et services fournis par les arbres en villes. Dans ce projet, l'outil d'analyse des arbres urbains i-Tree est donc privilégié.

2.1.4 Outils d'analyse

i-Tree est une suite de logiciels sophistiqués et révisés par les pairs. Cette suite fut créée par le département de l'agriculture des États-Unis sous les services forestiers. Cette suite fournit des analyses et des outils d'évaluation de bénéfices en foresterie urbaine et communautaire (i-Tree, 2017). L'inclusion des données météorologiques et de la pollution atmosphérique permet de quantifier les bénéfices que fournissent les arbres quant à conservation d'énergie, la réduction du dioxyde de carbone et de la qualité de l'air (i-Tree, 2017).

L'utilisation du logiciel i-Tree comprend trois phases pour ce projet. La première phase consiste à ajuster les paramètres du logiciel pour les adapter aux conditions climatiques et atmosphériques de Montréal. La deuxième phase concerne la production d'une base de données Microsoft Excel afin de pouvoir transférer les données de l'inventaire terrain (données mesurées) et les données de l'inventaire de la Ville de Montréal dans le logiciel i-Tree en prenant soin d'effectuer un contrôle de la qualité des données. La troisième phase consiste en l'analyse des données par l'entremise des rapports générés par le logiciel i-Tree dans le but d'établir le scénario de base (la situation actuelle au niveau des SE). Par la suite, les autres scénarios alternatifs ont aussi été analysés par le logiciel dans le but d'effectuer des comparaisons.

Trois différents outils d'analyses sont associés au logiciel i-Tree. D'abord, la Ville de Montréal possède une base de données de ces arbres urbains par arrondissement. Montréal rend disponibles ces données à travers un portail de données ouvertes que le public peut télécharger gratuitement (http://donnees.ville.montreal.qc.ca/dataset/arbres). La base de données de l'arrondissement Ahuntsic-Cartierville est la source de données brutes sur laquelle cette étude de cas est basée. Aussi, le site internet Québio (parrainé par le Centre de la science de la biodiversité du Québec) a transformé les localisations GPS des arbres urbains de la Ville de Montréal pour les rendre accessibles sur un système d'information géographique (SIG). Le SIG sélectionné pour cette étude est QGIS, car c'est un logiciel libre (aucun coût associé). C'est ce logiciel qui a effectué la sélection aléatoire des arbres à échantillonner et le repérage des arbres (localisation). Les données des arbres sélectionnés aléatoirement dans ce logiciel ont ensuite été transférées dans le logiciel Microsoft Excel pour analyse dans i-Tree.



Adapté de Chapin III et al., 2000

Figure 1.2 Diagramme résumant les interactions entre les différents éléments du projet.

La Figure 1.2 ci-dessus présente un diagramme résumant les interactions entre les différents éléments du projet. Les humains ont une influence sur les changements globaux dont l'ADF fait partie. Au total, quatre scénarios de gestion de l'infestation d'ADF ont été construits et analysés dans le cadre de cette étude (voir détails dans le Chapitre II). L'ADF a une influence sur la biodiversité de l'écosystème urbain et plus particulièrement les frênes. Les frênes, qui composent environ 20 % des arbres de Montréal, possèdent des traits qui influencent la prestation de SE aux humains. Trois SE furent sélectionnés afin d'évaluer les bénéfices de la forêt urbaine d'Ahuntsic-Cartierville. Finalement, les coûts reliés aux scénarios de gestion seront évalués et mesurés par rapport aux bénéfices calculés afin de définir une aide à la décision basée sur la conservation maximale de SE.

3.1 Hypothèses de travail et objectifs

3.1.1 Objectif général

L'objectif général de cette recherche est de quantifier l'apport ou la perte potentielle des SE que fournissent les arbres aux résidents de l'arrondissement Ahuntsic-Cartierville à l'aide du logiciel i-Tree.

3.1.2 Objectifs détaillés

Les objectifs de cette étude étaient 1) d'identifier et de quantifier les principaux services écosystémiques fournis par la forêt urbaine d'Ahuntsic-Cartierville (arrondissement de Montréal) comme référence (en SE) pour 2) évaluer les impacts de quatre différentes stratégies de gestion de l'agrile du frêne par l'entremise du logiciel i-Tree. Finalement, cette étude de cas a pour but de mieux outiller les décideurs municipaux actuels quant à la gestion de leur forêt urbaine aux prises avec une infestation d'agrile du frêne sur leur territoire.

3.1.3 Hypothèses de travail

Les hypothèses suivantes ont été testées dans le cadre de ce projet :

1) Il est possible d'atténuer la perte de SE par des actions proactives telles que le remplacement préventif des arbres et la protection des arbres, et

2) Les coûts supplémentaires liés à ces actions préventives ne dépassent pas le gain associé à l'évitement des pertes en SE.

Afin de tester ces hypothèses, plusieurs grandes étapes ont été nécessaires. D'abord, des traits des arbres ont été sélectionnés afin de bien comprendre leurs effets sur trois SE. Ensuite, un inventaire terrain a été effectué et les données ont été extrapolées pour couvrir tout le territoire de l'arrondissement Ahuntsic-Cartierville. Puis, des scénarios ont été développés avec l'aide d'une référence scientifique et des départements de foresterie d'arrondissements participants. Enfin, les données ont été analysées à l'aide d'un logiciel spécialisé dans la quantification des SE des arbres en milieu urbain.

Tous les détails sont disponibles dans l'article scientifique présenté dans les prochaines pages.

CHAPITRE II THE IMPACT OF CONTRASTING STRATEGIES FOR THE MANGEMENT OF THE EMERALD ASH BORER (COLEOPTERA: BUPRESTIDAE) INFESTATION ON THE ECOSYSTEM SERVICES IN THE CITY OF MONTREAL, QC

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Abstract

The urban forest has an impact on human's health and well-being of city dwellers. In the context of global change, pressures from different sources are and will be present in this forest. These pressures have the potential to lead to negative consequences in regards to social, environmental and economic aspects. Since 2011, the City of Montreal suffers an Emerald Ash Borer (EAB) infestation which could decimate approximately 20% of the municipal trees. The objectives were to 1) identify and quantify the main ecosystem services (ES) provided by the urban forest of the Ahuntsic-Cartierville borough of Montreal to act as a baseline to 2) evaluate the impacts of four different management strategies by the municipal forest service. The ES that were selected for this study were climate regulation, air quality, water cycle regulation. The data collected in the field and acquired from the City of Montreal were analysed through the i-Tree software. The first scenario represents the control scenario where there is no EAB infestation. The second scenario explored the effect of ignoring this infestation and only planning tree removing and replanting activities while the third and fourth scenarios explored proactive management styles with insecticide treatments of respectively 33% and 50% of all public ash trees each year. The fourth scenario demonstrated very interesting results as only 433 ash trees were cut down in 6 years and 92% of ES were preserved compared to approximately 56% for the third scenario. In order to preserve maximum ES performance, the results demonstrate the importance of proactive management to maintain a high level of ES from ash trees over a long period of time.

KEYWORDS: Urban forestry, Ecosystem Services, Emerald Ash Borer, i-tree.

Résumé

La forêt urbaine a un impact sur la santé et le bien-être des résidents des villes. Dans un contexte de changements globaux, plusieurs pressions sont et seront exercées sur cette forêt. Ces pressions ont le potentiel d'entraîner des conséquences négatives à l'égard des aspects sociaux, environnementaux et économiques. Depuis 2011, la Ville de Montréal est aux prises avec une infestation d'agrile du frêne (ADF) qui met en péril le frêne, soit environ 20% des arbres municipaux. Dans le cadre de cette étude, la forêt urbaine de l'arrondissement d'Ahuntsic-Cartierville a été étudiée. Les objectifs de cette étude étaient 1) d'établir et de quantifier les principaux services écosystémiques (SE) fournis par la forêt urbaine d'Ahuntsic-Cartierville comme référence pour 2) évaluer les impacts de quatre stratégies de gestion différentes issues de la recherche théorique et de la réalité sur le terrain. Les aspects économiques des pertes de trois SE portant sur les frênes municipaux ont été évaluées pour chacun des scénarios établis par l'entremise du logiciel i-Tree. Le premier scénario est le scénario de contrôle où l'insecte n'est pas présent. Le deuxième scénario a exploré l'effet de ne pas protéger les arbres et de ne planifier qu'uniquement les activités d'abattage et de plantation d'arbres de remplacement, tandis que les troisième et quatrième scénarios ont exploré des styles proactifs de gestion avec des traitements insecticides de 33 % et 50 % de tous les frênes publics par année. Le quatrième scénario a démontré des résultats impressionnants puisque seulement 433 frênes ont été abattus en 6 ans et 92 % des SE ont été conservés comparativement à 56 % pour le troisième scénario. Afin de préserver un maximum de prestation des SE, les résultats démontrent l'importance d'une gestion proactive afin de maintenir un haut niveau de SE des frênes sur une longue période de temps.

MOTS-CLÉS : Agrile du frêne, foresterie urbaine, services écosystémiques, i-Tree.

2.1 Introduction

Urbanization progressed immensely in the 20th century (Konijnendijk, 2000). While only 13% of the world's human inhabitants lived in cities around 1900, in 2014 more than 54% of the world's population was residing in urban areas (United Nations, 2015). Urbanization involves mass population displacements into cities but it refers also to land use change from natural to urban landscapes (Mills, 2007). Many consequences results from urbanization such as higer demand for natural resources, ecosystem fragmentation, deforestation, higer levels of pollution and loss of biodiversity (Rajashekariah, 2011; Zipperer et al, 2012; Dupras et al., 2016). In the past 20 years, critical evidences were provided on how the loss of biodiversity affects the functioning of ecosystems, and thus affects society (Cardinale et al, 2012).

Adding to the urbanization challenge, cities must deal with global changes that are impacting them now and will be impacting them in the future. According to the U.S. Global Change Research Program (2017), global change refers to the changes in the global environment that may alter the capacity of the Earth to sustain life such as land use change, the alteration of water cycle and biodiversity loss. It could also include biotic invasions such as invasive pests that are promoted by human activities and climate variability (Sala et al, 2000).

An example of biodiversity loss in an urban landscape is the Dutch Elm Disease that nearly eradicated white elm in urban settings across Quebec, Ontario and New Brunswick since the late 1940s (Davidson, 1964). This disease was spread through the Europeen bark beetle who carries the *Ophiostoma ulmi* (Buisman) Nannf. fungus that infects the elm trees and rapidly dies. Similarly, the Emerald ash borer (EAB) (*Agrilus planipennis* Fairmaire (Coleoptera: Buprestidae)) has been discovered in Detroit, Michigan and Windsor, Canada in 2002 (Haack et al., 2002) and quickly spread in Southern Ontario and Southern Quebec. This invasive pest from Asia feeds and reproduce on all five species of ash trees (*Fraxinus* spp.) native to North America killing its host through this process. It has killed untold millions of ash trees in forests, riparian and urban settings (Rajarapu et al., 2011). Ash has been one of the most commonly planted trees in urban and suburban landscapes across the Continental United States comprising more than 20% of the trees in many municipalities across the country (Kovacs et al., 2010). According to the Montreal open data portal, this was also true for Montreal as approximately 20% of the public trees were ash before the discovery of this insect in 2010. This loss will affect the ecosystem services (ES) provided by the Montreal urban forest to its citizens. According to Daily (1997), ES are the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfill human life. The quantification of those ES could be beneficial in many ways. For example, Costanza (2006) mentions that the objective of the economic evaluation of ES is to make decision makers aware of the importance of these ES so that the costs associated with their loss are taken into account in decisions.

A recent study showed ash mortality due to EAB was correlated with an increase of more than 6,100 and 15,000 human deaths in a 15-state area due to lower respiratory disease and cardiovascular disease, respectively (Donovan et al., 2013). Lee et al. (2014) confirms that "epidemiological and clinical studies have increasingly shown that air pollution is associated with not only respiratory and pulmonary diseases but also cardiovascular diseases". However, "urban trees, and the urban forest as a whole, can be managed to have an impact on the urban water, heat, carbon and pollution cycles" (Livesley et al., 2016).

The intent of this case study was to assess the ES of the Ahuntsic-Cartierville borough of Montreal to provide an baseline and, through different management scenarios, verify how can resource management of an urban forest under an EAB infestation can have an impact on ES retention. The objectives of this study were to 1) identify and quantify the main ES provided by the urban forest of a Montreal borough, as a baseline, to 2) evaluate the impacts of four different management strategies through the i-Tree software.

2.2 Methods

2.2.1 Study area

Ahuntsic-Cartierville is a borough of Montreal (Quebec, Canada) (45°32'40.26"N 73°40'05.25"O). This borough is the fifth most populous of the City of Montréal and is home to nearly 127,000 people spread over a territory of 24.2 square kilometers. It was selected for this case study because of its diverse urban forest and tree database.

Montreal possesses a Microsoft Excel database as well as a GIS shapefile of their public trees with information such as species name, tree diameter and tree location. According to this database, there were approximately 4,472 public ash trees in Ahuntsic-Cartierville at the beginning of the EAB infestation in 2010.

2.2.2 Study Context

In 2012, a year after the EAB was first discovered in Montreal, the urban forestry department of the City of Montreal needed a management strategy to effectively deal with this new insect pest in order to reduce ash tree loss and the associated costs that would come with an EAB infestation. At that time, it was decided that the SLAM methodology would be the best to control the impact of the EAB and the intervention strategy was adopted by the city council. The SLAM (short for SLow Ash Mortality) methodology consists of locating outbreaks, eliminate trees where the insect is present, set traps and treat some specimens within a radius of 200 to 500 m with a biological insecticide. This decision to adopt SLAM was based in part on the work of McCullough and Mercader (2012) where they explored several scenarios for insecticide treatment of ash trees in the United States as part of the EAB epidemic. While their scenarios were theoretical simulations, they were nonetheless a great basis to explore scenarios in Montreal. McCullough and Mercader (2012) explored a first scenario where no insecticide treatment was administrated to ash trees, a second scenario where 10% of the trees where inoculated, a third scenario where 20 % of the trees where inoculated and a final one with an insecticide treatment at an intensity of 50%. This research showed very different results as all the trees had died after ten years under the first scenario, 25% of the trees had died after ten years under the second scenario and 99.5% of the trees were still alive after ten years under the 20% and the 50% scenarios.

However, as the years and the infestation progressed, the boroughs of Montreal had more and more flexibility as to how they managed the infestation. In order to present a comparison of the different management strategies in terms of ES and management costs, we here present a case study based on the work of McCullough and Mercader (2012) and applied to boroughs of the City of Montreal.

2.2.3 Tree functional traits and ES selection for this study

The delivery of ES has been linked to the biological characteristics of ecosystems (Kremen, 2005) and more specifically to functional traits (Kremen, 2005; De Chazal et al., 2008; De Bello et al., 2010). In particular, for plants there is increasing evidence for the effects of community-based functional traits on ecosystem processes that underlie important ecosystems (Suding and Goldstein, 2008). De Bello et al. (2010) carried out an inventory of important functional traits in order to identify the traits to be measured to quantify the ES of interest.

In this project, three ES were chosen: climate regulation, water cycle regulation and air quality. These ES were selected because, according to the literature review by Elmqvist et al. (2015), they have a greater recognition in the literature, unlike other ES with more social characteristics where very little research has been carried out, making their evaluation more difficult at the methodological level. Table 2.1 presents the relevant traits and their effects on processes and, ultimately, on ES.

Table 2.1 Plant traits and their effects on processes and ES.

Ecosystem Services	Processes	Impact	Main traits
Climate Regulation	Heat exchange (local)	Variable	- Architecture of aerial parts
			- Growth form composition
			- Phenology
			- Maximum speed of photosynthesis per unit of leaf mass
	Carbon sequestration (global)	Positive	- Wood density
			- Height
			- Relative growth ratio
			- Foliar nitrogen content
		Variable	- Architecture of aerial parts
			- Growth shape
			- Quantity of litter
			- Root size
		Negative	- Phenology including flowering date
Water Cycle Regulation	Evapotranspiration	Positive	- Size and architecture of aerial parts
			- Leaf area
		Variable	- Growth form composition (C3/C4)
			- Vegetative phenology
			- Root depth
			- Stomatal conductance
	Water Infiltration, moisture retention in the soil	Positive	- Size and architecture of aerial parts
		Variable	- Growth form composition
		Negative	- Quantity of litter
	Runoff	Variable	- Growth form composition
		Negative	- Size and architecture of aerial parts
			- Diversity
Air Quality	Atmospheric pollutant removal	Positive	- Leaf area index
			- Size of aerial parts

	- Maximum photosynthesis

Source : De Bello et al., 2010

2.2.3.1 Air Quality

Trees capture gaseous pollutants mainly by absorption through the stomata of their leaves. Once inside the leaf, the gases diffuse into the intercellular spaces and could be absorbed by water films to form acids and react with intra-leaf surfaces (Smith, 1990). Trees also remove pollutants from the atmosphere by intercepting particles on the surface of their leaves. Following this interception, these particles can be re-emitted into the atmosphere, washed by rain or brought to the ground when leaves and branches fall (Smith, 1990). So, the vegetation is only a temporary retention site for several polluting particles (Nowak, 2002).

In addition to the work of De Bello et al (2010), Smith and Nowak's research also appears to demonstrate that foliage is important in determining the ability of hardwood trees to capture air pollutants. The trait measured in this case would be the maximum leaf area index (LAI) of the species studied and compare the LAI of individuals within the species under study in order to be able to count the ES for that species. The LAI is a ratio of leaf area to ground cover of trees.

There is little research in the literature on air quality and urban forests. Most of the research done on this subject has been based on average parameters of urban forest structures such as leaf area, leaf area index and biomass. Modeling is often done by region or by whole city. Zipperer et al. (1997) recommend that different plots of tree cover be defined by land use in order to capture the spatial heterogeneity of vegetation cover (Escobedo & Nowak, 2009).

In summary, measuring the air quality service requires measurements of the LAI and the size of the aerial parts. The variables measured for this process are: species, diameter at breast height (DBH), tree height, crown height, crown width, crown dieback and percent crown missing.

2.2.3.2 Water Cycle Regulation

Ecosystems play an essential role in providing cities with drinking water because they have a great influence on the flow, storage and purification of water. Vegetation and forests influence the amount of water available locally (TEEB, 2011). Water regulation is an important service that includes several processes, such as: evapotranspiration, water infiltration and moisture retention in the soil and runoff avoidance. They both have important traits in common: the size and architecture of the aerial parts. For evaporation and infiltration / moisture, the effect is positive whereas for runoff, the effect is negative. In other words, the larger the tree size, the more branched the trees, the less runoff but the more evaporation and infiltration / moisture. Because, i-Tree Eco is able to calculate a price for avoided runoff, this process will be retained for this research. Although tree leaves, branches, and bark may intercept precipitation and thus mitigate surface runoff, only the precipitation intercepted by leaves is accounted for in this analysis. The value of avoided runoff is based on estimated or user-defined local values. As this project is in Canada, local values are used and the national average value for the United States is utilized and converted to Canadian currency with user-defined exchange rates. The U.S. value of avoided runoff is based on the U.S. Forest Service's Community Tree Guide Series (i-Tree Ecosystem Analysis, 2017). The associated variables sampled for this process are: species, DBH, tree height, crown height, crown dieback and percent crown missing.

2.2.3.3 Climate Regulation

For the climate regulation ES, there are two processes of interest for this research: heat exchanges and carbon sequestration. Similarly, to the runoff process earlier where the impact was variable, the larger and the tree is, the more effect this will have on heat exchange and building energy usage. The tree's phenology, growth form composition and aerial part architecture all influences the quantity and quality of ES delivered to citizens. According to i-Tree, "If appropriate field data were collected, seasonal effects of trees on residential building energy use were calculated based on procedures described in the literature (McPherson & Simpson, 1999) using distance and direction of trees from residential structures, tree height and tree condition data. To calculate the monetary value of energy savings, local or custom prices per MWH are utilized". The variables measured as part of this research related to this process are: species, DBH, tree height, crown height, crown dieback, percent crown missing, crown light exposure, building direction and building distance.

Carbon sequestration is the removal of carbon dioxide from the air by plants. For carbon sequestration, several traits have a positive effect on this process. This is the case for wood density, height, foliar nitrogen content and relative growth rate. The density of the wood, height, relative growth rate, root size, aerial part architecture and growth shape are all linked to the species. However, other factors may increase or decrease carbon sequestration rates. This is the case for foliar nitrogen content and quantity of litter per example. Those traits have not been sampled as there are no direct link to the i-Tree Eco software. The variables linked to this process are: species, DBH, tree height, crown height, crown dieback and percent crown missing.

2.2.4 i-Tree software, field measurements, and scenarios development

The i-Tree software was selected as a tool to calculate the ES from the urban forest data. "i-Tree is a peer-reviewed software suite from the United States Department of Agriculture (USDA) Forest Service that provides urban and rural forestry analysis and benefits assessment tools" (www.itreetools.org/about.php). Through data provided by the user (species, DBH, tree height, crown width, etc.), this software is able to quantify ES provided by the urban forest because of the many researches conducted by the USDA. i-Tree is specialized in urban forestry and is now adapted for use in Canada. There are multiple modules included in the i-Tree software suite, such as i-Tree Eco, i-Tree Streets, i-Tree Canopy, i-Tree Hydro. The module selected for this case study was i-Tree Eco version 6 as it allows users to input field data on the entire urban forest and is adapted for use in Canada.

A field inventory was done in the Summer of 2016 to measure a variety of variables on selected trees to be able to quantify three ES including four processes (carbon sequestration and storage, air pollution removal, avoided runoff and saved energy) provided by the urban forest of this borough. The variables measured as part of this inventory were determined by the USDA software i-Tree Eco v6 to be as precise as possible for the selected ES. The following is a list of all these variables: species, diameter, location, total tree height, crown height, distance between the ground and the crown, crown width (North-South and East-West), percent crown missing, crown dieback, crown light exposure, building direction and building distance. All of these variables were measured on the field according to the specific methodology developed in the i-Tree Eco User's Manual (i-Tree, 2017). However, the level of accuracy gained by including these tree variables instead of just including the minimum variables such as species and DBH is not known to the i-Tree Eco user. Tree height as well as crown height was measured with a Vertex IV (Haglof Sweden, 2017) ultrasound instrument system. DBH circumference was taken with a diameter tape while other measurements were taken by a tape measure. Crown dieback and percent crown missing were measured visually on a grade from 0 to 100% while crown light exposure was measure from 1 to 5 based on the number of sides the crown was exposed to the sun. Tree data was collected using a data collection software named ODK Collect (Open Data Kit, 2017) on an Android tablet. All of the trees sampled were selected from a QGIS

(Quantum GIS Development Team, 2017) shapefile containing all of Montreal's urban trees. This geomatics database was produced by the Quebec Centre for Biodiversity Science and from the Montreal open data portal.

The selection of the trees within the database was done in a semi-random fashion. First, twenty-nine tree species were selected because they were the most dominant species in the urban forest which allowed to cover approximately 90% of the borough's trees (21,833 individual trees). The other 10% of the urban forest consist of 100 species of trees for only 2,028 trees. Then, within each species selected, 20 individual trees were randomly selected for each (DBH) class (first class: 5-19 cm, second class: 20-39 cm and third class: 40+ cm) for a maximum of 60 trees per species. This was done using the random selection option within the QGIS software. The reason why they were separated into three classes was to measure the yield of the tree species per age group. In total, 1,222 trees were inventoried in the Ahuntsic-Cartierville borough's urban forest. Unfortunately, for some species, it was necessary to complete the inventory outside the borough because 1) not all tree species had sufficient specimens inside the borough and 2) the Montreal open tree database is not systematically updated which resulted in many trees either cut down in previous years, improperly located or species incorrectly entered in the database. In total, 933 trees were sampled in Ahuntsic-Cartierville while 289 trees were inventoried outside of the borough.

In order to prepare the final database for the i-Tree Eco software, predictions or extrapolations had to be made from the sample inventory of 1,222 trees to cover for all 23,855 trees of the Ahuntsic-Cartierville urban forest. Although the species, diameters and locations were already in the borough's database, all the other variables taken in the Summer inventory needed to be filled in order to have a complete inventory. Per example, all the trees in the Montreal database had DBH data ranging from 1989 to 2013. To correct this flaw, mean growth yield has been estimated for each species and and updated to 2016. After this step, the new tree DBH data would be used to predict tree height data based on the summer inventory of 1,222 trees. The predictions for the entire Ahuntsic-Cartierville database were made using the R software (R Core Team, 2017) with 95% confidence interval for all of the measured variables (total tree height, crown height, crown width, etc.). The only exception was the building distance variable where the methodology for the predictions were handmade using the mean of each street tree inventoried. Per example, some streets had a mean distance of 10 metres whereas other streets had a distance of 5 metres. The streets that were not inventoried in this research were automatically allotted 7 metres as a value since it was the overall distance mean in the inventory.

Because it is assumed that all dead trees are immediately replaced, the ES calculations within i-Tree had to amount for replacement trees that are assumed (by default) to be 5 cm at DBH when they are planted. Also, a mean yield of 1.12 cm/year (DBH growth per year) was calculated for most of the 29 species that were inventoried, although some species did not have enough data to calculate a mean yield for them. The yields ranged from 0.67 cm/year for *Picea glauca* to 1.42 cm/year for *Ulmus pumila*. The yields were calculated by subtracting DBH in year X in cm and year Y in cm and by dividing the number of years separating X and Y. For the replacement trees, this mean yield was applied and a wide variety of tree species (128) that were planted to replace dead ash trees in the borough. The quantification of the ES resulting from these i-Tree simulations were then subtracted to the quantification results of the ash trees ES. Because these replacement trees are theoretical, it was not possible to determine multiple variables such as crown health, crown width, tree height, etc., the i-Tree model default measures 13% crown dieback to these trees as a mean for each individual tree. However, it is important to note that this tends to over-estimate certain results as dead trees and trees in poor health will be considered 87% healthy (i-Tree Eco, 2017).

For the economic variables, benefit prices were set to (2016 Canadian dollars): $64.15 per MWH, $156.68/tonne for carbon pricing (or $42.73/tonne of CO_2), $2.325/$m^3$ as the avoided runoff value and pollution removal value was calculated based on the prices of $21,730 per tonne ($O_3$), $3,245 per tonne ($NO_2$), $1,182 per tonne ($SO_2$), $754,340 per tonne ($PM_{2.5}$). Where data came from American publications, the currency rate that was used was 1.37 US$/CAN$. The U.S. value of avoided runoff is based on the U.S. Forest Service's Community Tree Guide Series (McPherson et al., 1999; 2000; 2001; 2002; 2003; 2004; 2006a; 2006b; 2006c; 2007; 2010; Peper et al., 2009; 2010; Vargas et al., 2007; 2008). The building energy usage value are derived from McPherson & Simpson (1999) and the carbon value comes from Environment and Climate Change Canada (2016) where in 2016, the worth of one tonne of CO_2 equal $42.73 and $156,68 on a per carbon tonne basis. These pollution removal values were generated from the equations developed by Nowak et al. (2014) where y represents dollars per tonne and x represents population density per km^2:

NO_2: y ¼ 0.7298 þ 0.6264x ($r^2 = 0.91$)

O_3: y ¼ 9.4667 þ 3.5089x ($r^2 = 0.86$)

$PM_{2.5}$: y ¼ 428.0011 þ 121.7864x ($r^2 = 0.83$)

SO_2: y ¼ 0.1442 þ 0.1493x ($r^2 = 0.86$)

According to Kovacs et al. (2010), much of the economic impact of EAB is associated with treatment and/or removal and replacement of high-value trees in urban and residential areas. For the costs related to tree injections and the costs related to felling and replacing trees, the proxies used were taken from McCullough and Mercader (2012) and adapted to Canadian currency and context. Per example, the insecticide that is used in the McCullough and Mercader (2012) study is TreeAge while the insecticide used in Montreal during this period was TreeAzin and the cost for these two products differ. It is also assumed that costs did not evolve from 2012 to 2017 (discount rate of

0%). The cost used for felling and replacing is $1,120/tree while the cost for insecticide treatment is $3.60/DBH/tree.

As for the ash tree management scenarios, all tree removals have been generated in a random fashion using the RAND (Random) function is Microsoft Excel. Indeed, the trees that had the lowest numbers allotted by this function would be the first to die. This was done for each year starting in 2011 until 2017. The results from i-Tree have all been compiled in Microsoft Excel as well. Four scenarios have been developed: Scenario #1 has been established for comparison purposes in regards to the other scenarios. In this scenario, it is assumed that there would be approximately 15 trees that would need to be removed and replaced for reasons independent of EAB each year between 2011 and 2017. Scenario #2 consists of treating 0% of the public ash trees under an EAB infestation scenario. McCullough and Mercader (2012) ran multiple simulations during a ten-year span to predict the outcome of the EAB outbreak on a theoretical 2,314 ash only urban forest beginning with a 400 EAB population. The percentages of ash tree removals are consistent with the percentage found by McCullough and Mercader (2012) but adapted to the number of trees present in Ahuntsic-Cartierville. Scenario #3 consists of inoculating approximately one in three ash trees in the borough of Ahuntsic-Cartierville while Scenario #4 is derived from the current strategy of the Saint-Laurent borough (2,850 ash trees in 2010) adapted to the number of trees of the Ahuntsic-Cartierville borough (approximately 4,472 ash trees in 2010). This borough, a nearby neighbor of Ahuntsic-Cartierville, inoculates approximately 50% of its ash trees each year.

The hypotheses to be tested through these scenarios are i) it is possible mitigate the loss of ES by proactive action such as preventive tree replacement and tree protection, and ii) additional costs associated with these preventive actions are not surpassing the gain associated with avoiding ES losses.

2.3 Results

2.3.1 Field inventory

In order to establish a baseline for the Ahuntsic-Cartierville urban forest, a tree inventory has been performed in the summer of 2016. Table A1 summarizes this inventory work.

In total, 29 species and 1,222 trees have been inventoried. Those 29 species are covering 90% of Ahuntsic-Cartierville. The DBH classes have been divided in four classes: 0 to 19 (Class I), 20 to 39 (Class II), 40 to 59 (Class III) and >60 (Class IV). For every species, a minimum of 18 specimens and a maximum of 60 were sampled. Some species were more difficult to find so the sampling was completed of outside of the borough of Ahuntsic-Cartierville. The structure or age class of the urban forest is as follows: 27% for Class I, 39% for Class II, 24% for Class III and 9% for Class IV. Richards (1983) proposed that "...a good age distribution for a [street tree] population stability would be about 40% trees under 20 cm diameter, 30% 20-40 cm in the early functional stage, 20% 40-60 cm functionally mature and 10% older trees with most of their functional life behind them". This study shows that the urban forest of Ahuntsic-Cartierville is a slightly older than the ideal distribution proposed by Richards (1983) but is overall well distributed.

Excluding the ash trees infestation, from our sample, the Ahuntsic-Cartierville borough seems to have a very healthy urban forest. As mentioned in the methodology, the health of each tree sampled was examined on a grade from 0 to 100. The threshold to determine if a tree is healthy was set 20% dieback, and of the 1,222 sampled, over 86% of the trees had no significant dieback in their crown. Only six species of trees were showing signs of being less healthy than the other such as *Acer negundo*, *Gleditsia triacanthos inermis*, *Picea glauca*, *Populus deltoides*, *Tilia cordata* and *Ulmus pumila.*

However, no definitive conclusion as to why these six species seem to be less healthy can be drawn from this inventory. It is important to mention that the purpose of this inventory was not to perform a complete tree health inspection for every tree but concentrated on crown health, which reflect general tree health. Tree crown is a component of net primary production and is associated with potential or previous vigorous growth rates (Schomaker, 2003). A more thorough inspection of each tree would provide a better understanding of the overall health of this urban forest.

2.3.2 Ecosystem services of the Ahuntsic-Cartierville borough

After the field inventory was completed, the next step was to transfer this database into the i-Tree Eco software for analysis of its ES. As mentioned in the methodology section, energy savings (heat exchange), carbon sequestration, avoided runoff and pollution removal have been selected as the ES of interest for this research. Table 2.2 presents the results for the current Ahuntsic-Cartierville urban forest analysed by the i-Tree Eco software.

Table 2.2 Ecosystem benefits linked with the current Ahuntsic-Cartierville urban forest.

Benefits	**Calculated benefits**	**Value ($)**	**$/Tree**
Energy savings	333.92 MWH	$21,421	0.90
Sub-total ($)	-	$21,421	0.90
Carbon sequestration	333.34 tonnes/year	$52,224.82/year	2,19
Avoided runoff per year	42,525.68 cubic metres/year	$98,860.02 /year	4.14
Pollution removal per year	9,05 tonnes/year	$493,236.92 /year	20.68

Sub-total ($/year)	-	$644,321.76 /year	27.01
Total benefits over 23 years	-	$14,840,821.50	622.13

Energy savings is being calculated in terms of dollars for the average lifetime of the tree species in the inventory while the three other ES were calculated in 2016 CAN$/year. As noted in this table, an average of 23 years of life per tree was used to estimate the contribution of these ES to the urban forest. This life expectancy comes from the meta-analysis of Roman & Scatena (2011) where they found that life expectancy of a city tree is estimated to be between 19 and 28 years. The use of 23 years is conservative as it is closer to 19 than 28. The total benefits are estimated to be $14,8M, which would equal to $622 per tree (23,855 trees in total). There was no discount rate used in this case study as some argues that it's only relevant if it accounts for the exogenous possibility of extinction (e.g. Stern, 2006).

Energy savings consist of the avoided usage of energy from tree proximity to buildings. The results for Ahuntsic-Cartierville is estimated to 333.92 MWH saved which is equal to $21,421 or $0.90/tree. This ES was calculated based on the price of $64.15/MWH. It should be noted that the i-Tree threshold to calculate a benefit for energy savings is 6 metres or more in height for a tree and a distance of 18 metres or less away from a building.

Carbon sequestration represents the process of retaining captured CO_2 from the atmosphere. A total of 333.34 tonnes of CO_2 per year was calculated, which represents $52,224 and $2.19/tree. To estimate the gross amount of carbon sequestered annually, average diameter growth from the appropriate genera and diameter class and tree condition was added to the existing tree diameter (year x) to estimate tree diameter and carbon storage in year x+1. The value of carbon sequestration was calculated based on the price of $156.68 per tonne.

Avoided runoff water is defined as the rainfall interception by vegetation, and specifically the difference between annual runoff with and without vegetation. Annual avoided surface runoff is calculated based on rainfall interception by vegetation, specifically the difference between annual runoff with and without vegetation (i-Tree, 2017). The trees of Ahuntsic-Cartierville are able to intercept approximately 42,525.68 cubic metres/year, which corresponds to $98,860/year or $4.14/tree/year.

Pollution removal is calculated for ozone, sulfur dioxide, nitrogen dioxide, carbon monoxide and particulate matter less than 2.5 microns (i-Tree, 2017). Air pollution removal estimates are derived from calculated hourly tree-canopy resistances for ozone, and sulfur and nitrogen dioxides based on a hybrid of big-leaf and multi-layer canopy deposition models (Baldocchi, 1988; Baldocchi et al., 1987). The Ahuntsic-Cartierville urban forest is removing approximately 8,98 tonnes of pollutants/year, which would equal $493,237/year or $20.68/tree/year.

Table 2.3 presents the top ten tree species in this borough placed in decreasing order of individual trees according to the Montreal open tree database portal. Structural value is the value of a tree based on the physical resource itself or, in other words, it's the cost of having to replace a tree with a similar tree (i-Tree, 2017). Structural values were based on valuation procedures of the Council of Tree and Landscape Appraisers, which uses tree species, diameter, condition, and location information (Nowak et al., 2002a; 2002b). Bioemission is defined as the hourly urban forest volatile organic compound emissions and the relative impact of tree species on net ozone and carbon monoxide formation throughout the year (i-Tree, 2017). Water interception is the interception of rainfall by the surfaces of leaves, branches and trunks (Nisbet, 2005). Canopy cover is defined as the proportion of the forest floor covered by the vertical projection of the tree crowns (Jennings et al., 1999) and Leaf Area is the surface in hectare of all the leaves in the tree canopy. The first species on this list is still *Fraxinus pennsylvanica.* This shows how important this species is in this borough and in Montreal in general. Adding to the 3,820 *Fraxinus pennsylvanica* trees, *Fraxinus americana* comes in eight place with 652 specimens for a total of 4,472 ash trees representing approximately 20% of all trees in this borough. The other trees species in this table are *Acer saccharinum*, *Tilia cordata*, *Gleditsia triacanthos inermis*, *Acer platanoides*, *Acer negundo*, *Celtis occidentalis*, *Acer saccharum* and *Ulmus pumila.*

Table 2.3 Top 10 species with specific characteristics.

Species	# of trees	Leaf area (ha)	Canopy cover (m^2)	Water intercepted (m^3/year)	Bioemissions (kg/year)	Structural value ($)
Fraxinus pennsylvanica	3,820	214	497,936	33,221	26	15,456,251
Acer saccharinum	3,482	304	649,757	47,332	419	31,967,829
Tilia cordata	2,485	157	286,574	24,442	0	20,759,750
Gleditsia triacanthos inermis	2,454	41	270,531	6,307	0	6,736,886
Acer platanoides	2,414	238	404,029	36,971	336	16,154,100
Acer negundo	1,132	36	71,833	5,602	86	1,291,071
Celtis occidentalis	726	47	69,091	7,347	9	2,822,285
Fraxinus americana	652	23	52,428	3,648	3	1,597,435
Acer saccharum	610	32	68,166	5,046	51	3,158,816
Ulmus pumila	598	45	82,263	6,934	6	2,576,609

A few results are worth pointing out. Per example, while *Fraxinus pennsylvanica* has more trees, *Acer saccharinum* has a larger canopy cover and leaf area which seems to influence its ability to intercept water. *Acer saccharinum* also seems to emit approximately 16 times more volatile organic compounds (VOCs) and has a structural value more than twice the amount of *Fraxinus pennsylvanica*. Some species do not emit VOCs while *Acer* species emit a lot of VOCs. However, integrative studies have revealed that an increase in tree cover leads to reduced ozone formation (Nowak & Dwyer, 2000).

2.3.3 Variation of ecosystem services value according to EAB management scenarios

Scenario #1 represents the control scenario for ash trees only, where we hypothetically state that EAB has not yet arrived in Montreal and will not infest Montreal in the foreseeable future. It is assumed that an average of 15 trees must be felled and replaced each year due to natural attrition. The replacement trees are assumed to be 50 mm at DBH when planted for all of the scenarios. Table A.2 presents the evolution of the ES under Scenario #1.

A total of $112,330/year was generated by ash trees in 2010, and by 2017, only $909 have been lost due to the replacement of trees. It is worth noting that the replacement trees represent a wide variety of trees available at random in this simulation that could include other ash trees. This may explain why there is an increase between 2010 and 2011 for the pollution removal and avoided runoff processes. It is possible that other tree species who intercepts more pollution and rainfall than ash trees were planted as a replacement tree.

Scenario #2 (*Insecticide treatment at an intensity of 0%*) was taken from McCullough and Mercader (2012). As mentioned in the methodology section, their ash tree numbers were modulated to correspond to the ash tree numbers in Ahuntsic-Cartierville while respecting the percentage of decline on a per year basis. Table A.3 presents the evolution of the ES under this scenario.

Based on McCullough and Mercader (2012) assumptions for EAB infestation, the evolution of ash population remains stable the first two years after the initial infestation (all of the trees are still standing). The ash population showed a rapid decline starting at year 5 after initial infestation. From this drastic decline resulted a drastic loss of all ES. Between 2011 and 2017, the total value of these four ES as dropped from $112,330/year to $51,375/year, which equals a 46% loss compared to a 42% ash tree loss during the same time. This means that the young replacement trees only help mitigate 3.5% in this time span. In the year 8 through 10, the decline continues until it reaches 100% mortality at year 10.

Scenario #3 (*Insecticide treatment at an intensity of approximately 33%*) is based on the available information gathered from the Ahuntsic-Cartierville borough. The tree numbers shown in Table A.4 come from city personnel through personal communication. However, not all of the information regarding ash trees inoculation and removals were available for this study. Based on our calculations and understanding, since 2012, this borough has inoculated approximately 33% of their public ash trees. It should be noted that the 33% insecticide treatment rate is not a goal that was set out by this borough. A mixture of financial availability for ash tree inoculation and tree health resulted in less trees being treated. However, in recent years, this borough as increased its insecticide injections compared to the first years of the infestation. However, because it took a little too long to unblock funds from the city to proceed with insecticide treatments, many ash trees were too infested to try to save them and had to resort to removal activities.

While the beetle was found in Montreal in 2011, it is believed that a small population of the EAB was present in Montreal a few years prior and that Ahuntsic-Cartierville may have been one of the initial focal points of the infestation. Nevertheless, the proactivity of the borough resulted in maintaining the majority of the ash trees and more than the half (56%) of the associated ES value between 2011 and 2017.

Scenario #4 (*Insecticide treatment at an intensity of 50%*) represents the EAB management scenario of the Saint-Laurent borough. The tree numbers have been modulated to correspond to the Ahuntsic-Cartierville borough. Table A.5 presents the evolution of the ES under Scenario #4.

The results are very interesting as only 11% of ash trees have been lost in Scenario #4, which would equal to 433 trees in Ahuntsic-Cartierville. Scenario #4 was also able to conserve more than 91% of the ES value, which is considerably more than 56% for Scenario #3.

Table 2.4 Summary of all the ES by management scenarios from 2010 to 2017.

Year	Scenario #1			Scenario #2			Scenario #3			Scenario #4		
	# of trees		Total ($)	# of trees		Total ($)	# of trees		Total ($)	# of trees		Total ($)
	Exis.	Rep.	ES/year	Exis.	Rep.	ES/year	Exis.	Rep.	ES/year	Exis.	Rep.	ES/year
2010	4,472	0	112,329	4,472	0	112,329	4,472	0	112,329	4,472	0	112,329
2011	4,457	15	112,451	4,472	0	112,329	4,418	54	112,037	4,394	78	110,669
2012	4,442	30	112,169	4,472	0	112,329	4,335	137	109,887	4,346	126	109,445
2013	4,427	45	111,894	4,466	6	112,397	4,263	209	108,161	4,331	141	109,157
2014	4,412	60	111,781	4,400	72	110,662	4,042	430	102,625	4,299	173	108,394
2015	4,397	75	111,688	4,000	472	101,042	3,467	1,005	88,917	4,221	251	106,479
2016	4,382	90	111,622	3,000	1,472	77,231	3,104	1,368	80,166	4,142	330	104,775
2017	4,367	105	111,420	1,890	2,582	51,374	2,360	2,112	62,513	4,039	433	102,293

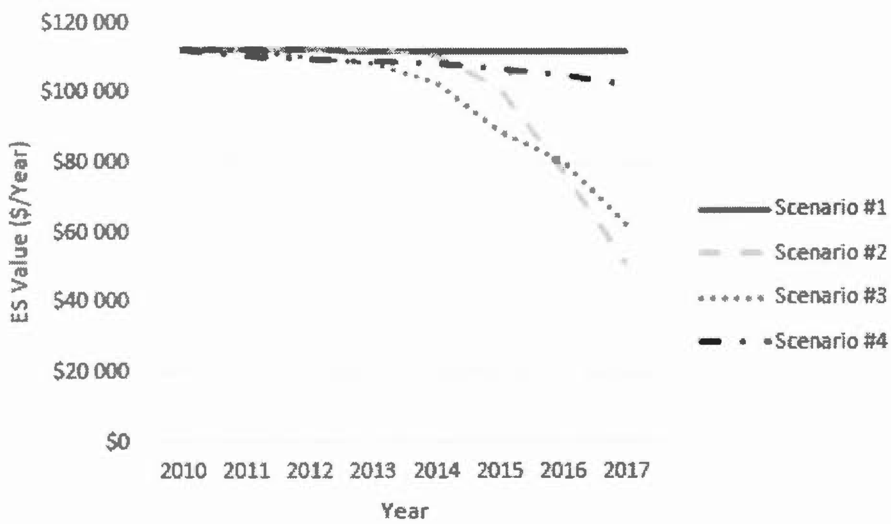

Figure 2.1 Summary of ES related to all the management scenarios from 2010 to 2017.

2.3.4 Evaluation of the costs and costs benefits analysis

In this section, all of the four scenarios presented in the last section were analysed for their cost. Indeed, there are a lot of costs involved in conserving ash trees from the EAB infestation but, as mentioned in the methods section, much of the economic impact of EAB is associated with treatment and/or removal and replacement of trees. These are the two major costs that were explored in this case study.

Table A.6 presents the picture of normal species management duties where only 15 ash trees per year must be felled and the costs associated with this activity are stable through time at $18,000/year.

Table A.7 shows the costs associated with the Scenario #2. In this scenario, the funds spent in the removal and replanting of young trees (on average 50 mm DBH trees) quickly evolves from only $6,720 in 2013 to an estimated $1,24M in 2017 and culminates to more than $5M (cumulative) in 2020. After 2020, it is assumed that there are no ash trees to fell anymore, hence, no more costs related to the management of this species.

Table A.8 presents the costs of removing and replanting as well as treating approximately 33% of ash trees from 2011 to 2017. In comparison to Scenario #2, the costs are more balanced throughout the years but the cumulative costs end up $156,160 more in 2017 than Scenario #2.

Table A.9 presents the costs for ash tree management of Scenario #4. The number of trees felled over the years is slowly and steadily increasing as well as the insecticide injections. Between 2013 and 2017, the costs seem to have stabilized to approximately $300,000/year. In 2017, the cumulative cost of $1,671,520 which consists of a 45% decrease in cost compared to Scenario #3.

Table 2.5 Summary of all costs by management scenario between 2011 and 2017.

Year	Scenario #1			Scenario #2			Scenario #3			Scenario #4		
	# of trees		Total	# of trees		Total	# of trees		Total	# of trees		Total
	Exis.	Rep.	$/year	Exis.	Rep.	$/year	Exis.	Rep.	$/year	Exis.	Rep.	$/year
2011	4,457	15	18,000	4,472	0	0	4,418	54	60,480	4,394	78	87,360
2012	4,442	30	18,000	4,472	0	0	4,335	137	122,912	4,346	126	85,440
2013	4,427	45	18,000	4,466	6	6,720	4,263	209	91,469	4,331	141	268,397
2014	4,412	60	18,000	4,400	72	73,920	4,042	430	423,891	4,299	173	254,720
2015	4,397	75	18,000	4,000	472	448,000	3,467	1,005	801,248	4,221	251	351,283
2016	4,382	90	18,000	3,000	1,472	1,120,000	3,104	1,368	599,520	4,142	330	273,952
2017	4,367	105	18,000	1,890	2,582	1,243,200	2,360	2,112	948,480	4,039	433	350,368

A cost-benefit analysis usually estimates and totals up the equivalent money value of the benefits and costs to the community of projects to establish whether they are worthwhile. In this case, the EAB infestation is not a choice but a plague that Montreal had to go through because, in part, to global changes. Nevertheless, the city personnel had a choice as to how they would handle this unfortunate situation although without proper knowledge of the consequences of an infestation, it is very difficult to convince the municipality to invest all the necessary funds to mitigate as much as possible the effects of an insect pest like the EAB. Figure 2.2 to 2.5 presents the net benefits and net costs of all four scenarios in regards to the selected ES as part of this case study and the costs associated with felling and replacing ash trees as well as treating specific percentages of ash trees on a per annum basis.

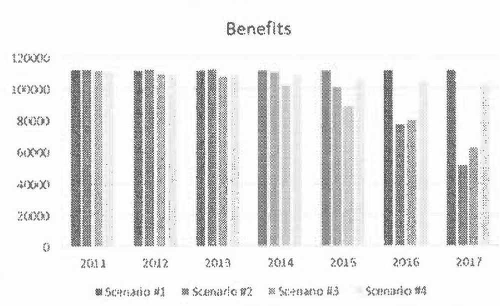

Figure 2.2 Benefits by scenario ($/year).

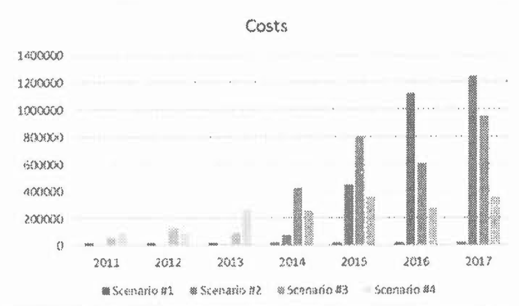

Figure 2.3 Costs by scenario ($/year).

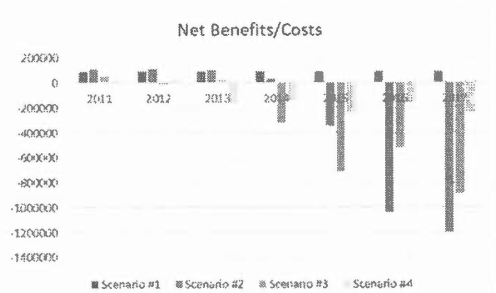

Figure 2.4 CBA by scenario ($/year).

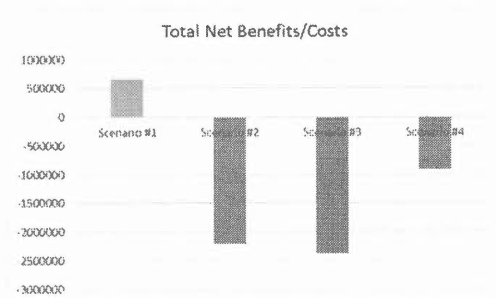

Figure 2.5 Total CBA by scenario ($/year).

As shown in Figure 2.2 to 2.5, aside from Scenario #1, none of the other scenarios can be construed as beneficial or cost effective as they all show deficit. However, Scenario #4 stands away from Scenario #2 and #3 with a deficit of $0.9M compared to more than $2,2M for the other two other scenarios. Scenario #3 is the worst over the seven-year span but at least conserves more ES than Scenario #2 starting in 2016 and in the future.

2.4 Discussion

The first objective of this study was to identify and quantify the main ES provided by Ahuntsic-Cartierville's urban forest. To do so, three ES were selected based on their importance and ability to be quantitively assessed using measurable tree traits. Then, predictions were performed using all the 23,855 trees of the borough, which were calibrated based on the field-measurements of a subsample of 1,222 trees. Using these traits, and to be comparable, the economical values of the selected ES were calculated using i-Tree and this estimation resulted in a total benefit of $14.8M corresponding to $622.13 per tree.

The objective of the study was to evaluate the impacts of different management strategies linked to an EAB infestation. In the above section, the results show that Scenario #4 was the most likely to conserved the most ash trees and ES by its management strategy facing this infestation. Indeed, by injecting insecticide to approximately half of the ash trees every year, this strategy allows retaining more than 92% of the ES between 2011 and 2017 while Scenario #3 was only able to retain 56%. Furthermore, the result of the cost-benefit analysis (CBA) in Figure 2.5 showed that Scenario #4 performed very well compared to the two other scenarios linked to the EAB infestation (more than 42% and 39% more benefits retained than Scenario #2 and #3 respectively).

The costs and benefits that are part of the CBA are not of the same nature. Unlike budgeted costs and benefits, the ES concept is not an official accounting tool that urban foresters and their municipal department can manage as public funds. Rather, this approach aims at helping urban foresters to strategize on how to deal with such insect pests or other infestations caused or exacerbated by global changes. It can be incorporated for economic comparison of management alternatives for a more in-depth decision-making process. However, until natural infrastructures are valued in the same fashion as all other urban infrastructures, the implementation of this type of approach is still a challenge (Dupras et al., 2015a). In that sense, the inclusion of positive non-market externalities (i.e. here the ecosystem services provided by trees) in decision making processes would provide a more comprehensive and complete portrait of the environmental situation in urban setting. However, the inclusion of ES concept and ES valuation approaches in planning and management processes is not frequent in Canada (Dupras et al., 2015a) and elsewhere (Daily et al., 2009; Laurans et al., 2013). Nonetheless, the repercussions are real for the residents. The felling of 3,000 public ash trees within a Michigan state city resulted in a 33% increase in water consumption for exterior usage which forced the city to increase the water tax by 10% (Ouellet, 2014). By these results, the hypothesis that proactive management can mitigate the loss of ES is verified. Indeed, the use of adequate intensive management activities spread out the costs associated with ash removal and replacement on a longer period of time while keeping ES the highest.

2.4.1 Case Study Limits

There are some limits that have to be acknowledge in this case study. First, the quality of available tree database on which all services are estimated is limited. Montreal has a good knowledge of their population of trees, however, because of its cost, the inventory is not updated often nor systematically. It is our understanding that the internal database used by the city personnel of every borough to manage their urban forest is more precise but not accessible for public use. Second, to be more precise on tree services determination, additional traits have to be measured but it is clearly not feasible to sample the entire population of trees. Thus, the semi-random subsample of trees inventoried had to be carefully design to allow the best representativeness. Here, 1,222 trees were sampled which accounted for approximately 5% of the total urban forest. It's not a high percentage but with the borough's baseline inventory it's sufficient to extrapolate the data. By orienting this subsampling in a way to have individual trees of each species and each diameter classes, we maximized the representativeness of the sampling effort. With only 29 species out of approximately 130 species present on the territory, it was possible to cover approximately 90% of the trees and the rest were treated as generic trees with no ground-truthing validations. For these trees, calculations were made only on the basis of their DBH. Third, an element that could have been added to this case study would be a life-cycle analysis of each management strategies to quantify their impacts. The occurrence of activities in more intensive scenarios would in theory incur more pollutants to be released into the atmosphere and thus, have a mitigating influence on the results. As Nowak et al. (2002) noted, maintaining healthy trees will keep the carbon stored in trees, but tree maintenance can contribute to carbon emissions. However, the inclusion of these emissions should not constitute a significant difference in the results. Finally, it should be acknowledged that we evaluated three ES provided by trees while many others could have been estimated, such as their impact on biodiversity, pollination, aesthetics, or culture. If these other ES would have been taken into account, maybe this would have changed the CBA results and made the benefits more important than the costs in the three EAB management scenarios. However, limited data, and time and monetary constraints have not allowed us to assess these extra ES. In the end, although the monetary values should not be considered as absolute values, but rather an order of magnitude, the results allow useful comparisons between management strategies.

2.4.2 Invasive Pest Management Strategy

City inventories demonstrated that *Fraxinus* is still a very important tree species in Montreal urban area, what made this research on EAB impact really helpful in determining the consequences and possible response strategies in the case of a sever pest invasion in city vegetation management practices. The results showed that depending on scenario, consequences on ES maintenance can differ markedly after only a few years. Scenarios with less proactive actions were less successful in retaining a healthy population of ash trees and thus in maintaining the associated ES. However, many different factors could explain why Scenario #3 was less successful, such as: 1) their urban forest was one of the first to be infested in Montreal which led to multiple years of untreated infestation, 2) the missing funds for ash treatment in 2013 really hurt their chances to slow ash mortality, 3) they have, on average, older trees than neighboring boroughs (i.e. Ahuntsic-Cartierville ash trees average 32 cm at DBH and Saint-Laurent average 23 cm at DBH) and larger ash trees typically i) are among the first to be attacked by *Agrilus planipennis* and attract more EAB adults (Eberkart, 2007; Marshall et al., 2009; Porter, 2009) and ii) provide higher amount of ES.

In comparison, Scenario #4 seemed to be the more desirable scenario. Indeed, this scenario materialized what Clark et al. (2015) suggested as an efficient strategy, that is to say: removing trees that have the highest probabilities of dying within the immediate future (1–3 years), while retaining trees that will live beyond the next three years, would likely result in a potential financial benefit of distributing removal costs over several years. In this case, the use of insecticide on a larger number of trees also helped maintaining the tree population in time. However, treating high proportion of tree population is costly and one should take into consideration the absolute number of tree to be treated to determine is a ratio of 50% per year is financially viable. Boroughs with higher numbers of ash trees treated with insecticide will surely have to face more difficult decisions. Also, this case study analyzed costs and benefits between 2011 and 2017. Unfortunately, it's not possible to determine how these costs and benefits will progress over time. It's possible that Scenario #4 will be less attractive has time goes by. However, it will have successfully protected important ES during an extended time span while saving municipal funds and provide time to plan other tree plantings to offset to loss of future trees.

This study examined management strategies over a relatively short period of time (seven years). While Scenario #4 seems like the most promising in terms of management costs at this time, the future remains unknown. If the health of the currently standing ash trees declines over time, this scenario will likely be the less desirable in the mid to long-term. However, even if this happens and costs increase, at least the ES would have been conserved for many years and the level of service to the residents would have been preserved to a maximum while the replacement trees grow back to a respectable size in which they can quantitative ES.

In past research, where comparative scenarios have been developed or studied, the results often find that the more profitable course of action is to proceed with early tree felling. This is because no economic valuation of ES was completed as part of these studies. For instance, in the 1980s, literature regarding the Dutch Elm Disease favored the more cost effective early tree felling activities compared to the chemical treatment of elms (Cannon et al., 1982, Kostichka & Cannon, 1984). In a EAB case study, Vannatta et al. (2012), found that the chemical treatment option was the least cost-effective at managing for EAB while the removal option (without tree replacement activities) was the most cost-effective over a 20-year period. However, this study also mentions that it is likely that treatment of urban ash trees in park-like and residential settings is economically justified if ES values are included in the evaluation approach. Indeed, as shown in the above section, ES value alone for ash trees was calculated to be worth more than $17,000,000 in 2010. Furthermore, the inclusion of all quantifiable ES would have surely modified the result of the CBA potentially transforming all scenarios into net benefits, reinforcing the idea of investing in maintaining adult trees alive as well as the services they provide. As Ouellet (2014) noted, it appears evident that that if ES value was incorporated in the economic valuation of EAB management, the tree felling approach would be less attractive.

Other researches on urban forest management of invasive pests tend to confirm our results that the best strategy to handle a pest infestation is to be proactive, like Montreal for the EAB. Per example, Smith et al. (2009) analyzed the Asian long-horned beetle (*Anoplophora glabripennis* (Motschulsky) (Coleoptera: Cerambycidae)) infestation of several American cities, Europe and Canada. While the approaches and their respective strategies have often differed among the invasive populations and among the landscapes infested, there have been certain unifying components among the eradication programs such as the establishment of regulated zones for wood transportation, tree survey and detection of the invasive pest, scientific research to know the patterns of the invasive pest, felling trees suspected to be infested and suspected to be at risk, insecticide injections of trees considered to be at high risk of attack and public outreach (Smith et al., 2009). Montreal, with the implication of other levels of government, has implemented all of these strategies and established a financial help program destined to citizens with ash trees on their private property. Without this program, it is possible that the public trees of Montreal would have died at a higher rate. They were also the first Canadian city to adopt SLAM with the objective to slow the progression of this insect pest (Ouellet, 2014).

2.5 Conclusion

The first objective of this study was to quantify the ES of the Ahuntsic-Cartierville using a specific methodology including the i-Tree software. The urban forest of this borough provides $14.8M in ES which equals to $622.13 per tree. The second objective was to evaluate ES benefits and costs for four management scenarios of the EAB. The different scenarios explored demonstrated how the EAB infestation was and still is decimating Montreal's urban forest. All the scenarios linked to the infestation resulted in a major loss of ES although Scenario #4 has clearly been able to mitigate the costs associated with the infestation (58% and 61% less costs than Scenario #2 and #3) while also being able to preserved significant benefits (92% over the seven-year time frame of this study). Scenario #2 proved to be the worst strategy to maintain ES and the second worst in terms of costs. As for Scenario #3, although more ES were preserved, the lack of funding at a crucial time mixed with a lower average injection rate than Scenario #4 resulted in early removal and replacement of ash trees. The young replacement trees will take several decades until they are able to provide the same level of services provided by the removed ash trees.

The herein findings could be used by other newly infested municipalities to optimize their management strategies related to this disturbance. The goal of municipalities is to maintain or to provide better services to their citizens and using an ES-based approach is easier than ever before.

As the field of ES continues to evolve and to progress, it would be interesting to evaluate the same approach tested herein on other urban forests by adding more ES into the analysis. Perhaps, the evaluation of ES in management strategies will someday be the norm for green infrastructure decision-making processes.

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ANNEX A COMPLEMENTARY TABLES

Table A.1 Ahuntsic-Cartierville tree inventory and species crown dieback per DBH class.

		DBH Class							
		I		II		III		IV	
Species	# of trees sampled	% Trees	% Crown dieback	% Trees	% Crown dieback	% Trees	% Crown dieback	% Trees	% Crown dieback
Acer negundo	22	0	0	32	14	36	11	32	16
Acer platanoides	59	27	7	31	9	29	13	14	14
Acer rubrum	47	26	13	47	5	21	9	6	10
Acer saccharinum	56	30	2	30	5	13	4	27	7
Acer saccharum	51	16	7	39	8	37	13	8	6
Aesculus glabra	50	28	1	38	2	34	0	0	0
Aesculus hippocastanum	39	15	2	38	2	28	2	18	14
Catalpa speciosa	45	20	1	31	8	33	1	16	6
Celtis occidentalis	60	20	4	45	5	33	6	2	0
Fraxinus americana	51	12	17	61	13	22	20	6	20
Fraxinus pennsylvanica	44	14	11	45	12	34	14	7	10
Ginkgo biloba	23	43	1	48	0	9	8	0	0
Gleditsia triacanthos inermis	55	24	18	38	30	29	20	9	16
Gymnocladus dioicus	40	48	1	20	3	33	17	0	0
Malus	39	46	6	36	10	18	11	0	0
Picea Abies	41	32	1	37	19	32	4	0	0
Picea glauca	21	57	19	29	26	14	15	0	0
Picea Pungens	49	20	5	59	6	16	8	4	5
Pinus nigra Austriaca	48	25	2	63	7	13	10	0	0
Pinus strobus	18	61	3	22	5	17	5	0	0
Pinus sylvestris	19	53	3	32	6	16	7	0	0
Populus deltoides	39	5	15	44	15	36	7	15	7
Quercus macrocarpa	28	50	2	29	14	7	15	14	9
Quercus robur fastigiata	32	41	5	28	5	31	3	0	0
Quercus rubra	58	33	4	31	19	22	11	14	6
Syringa reticulata Ivory Silk	35	54	4	46	7	0	0	0	0
Tilia americana	54	26	3	39	12	24	8	11	8
Tilia cordata	54	20	16	37	15	26	17	17	20
Ulmus pumila	45	22	18	38	20	16	13	24	15
Total	1,222	27	8	39	10	24	9	9	7

Table A.2 Evolution of ES under Scenario #1.

Year	2010	2011	2012	2013	2014	2015	2016	2017
Existing trees	4,472	4,457	4,442	4,427	4,412	4,397	4,382	4,367
Rep. trees	0	15	30	45	60	75	90	105
Gross C seq. (t/yr)	35	35	34	34	34	34	34	34
Gross C seq. ($/yr)	5,494	5,488	5,475	5,462	5,457	5,451	5,446	5,432
Avoided runoff (m3/yr)	6,701	6,721	6,704	6,688	6,682	6,678	6,674	6,663
Avoided runoff ($/yr)	15,579	15,625	15,586	15,549	15,535	15,524	15,516	15,490
Pollution removal (t/yr)	2	2	2	2	2	2	2	2
Pollution removal ($/yr)	91,089	91,172	90,943	90,719	90,625	90,549	90,496	90,335
Energy savings (MWH)	59	59	59	58	58	58	58	58
Energy savings ($/yr)	166	165	164	164	163	163	162	162
Total ($/yr)	112,329	112,451	112,169	111,894	111,781	111,688	111,622	111,420

Table A.3 Evolution of ES under Scenario #2.

Year	2010	2011	2012	2013	2014	2015	2016	2017
Existing trees	4,472	4,472	4,472	4,466	4,400	4,000	3,000	1,890
Rep. trees	0	0	0	6	72	472	1,472	2,582
Gross C seq. (t/yr)	35	35	35	35	34	31	24	16
Gross C seq. ($/yr)	5,494	5,494	5,494	5,488	5,406	4,939	3,797	2,549
Avoided runoff (m3/yr)	6,701	6,701	6,701	6,717	6,615	6,048	4,651	3,138
Avoided runoff ($/yr)	15,579	15,579	15,579	15,615	15,378	14,062	10,813	7,296
Pollution removal (t/yr)	2	2	2	2	2	2	1	1
Pollution removal ($/yr)	91,089	91,089	91,089	91,127	89,714	81,892	62,508	41,457
Energy savings (MWH)	59	59	59	59	58	53	39	25
Energy savings ($/yr)	166	166	166	165	162	148	111	70
Total ($/yr)	112,329	112,329	112,329	112,397	110,662	101,042	77,231	51,374

Table A.4 Evolution of ES under Scenario #3.

Year	2010	2011	2012	2013	2014	2015	2016	2017
Existing trees	4,472	4,418	4,335	4,263	4,042	3,467	3,104	2,360
Rep. trees	0	54	137	209	430	1,005	1,368	2,112
Gross C seq. (t/yr)	35	40	39	38	36	31	28	22
Gross C seq. ($/yr)	5,494	6,312	6,195	6,099	5,792	5, 013	4,526	3,532
Avoided runoff (m3/yr)	6,701	6,645	6,519	6,420	6,097	5,299	4,792	3,771
Avoided runoff ($/yr)	15,579	15,447	15,156	14,925	14,173	12,319	11,141	8,768
Pollution removal (t/yr)	2	2	2	2	2	1	1	1
Pollution removal ($/yr)	91,089	90,113	88,376	86,979	82,509	71,455	64,383	50,126
Energy savings (MWH)	59	58	57	56	53	46	41	30
Energy savings ($/yr)	166	163	160	157	149	128	114	86
Total ($/yr)	112,329	112,037	109,887	108,161	102,625	88,917	80,166	62,513

Table A.5 Evolution of ES under Scenario #4.

Year	2010	2011	2012	2013	2014	2015	2016	2017
Existing trees	4,472	4,394	4,346	4,331	4,299	4,221	4,142	4,039
Rep. trees	0	78	126	141	173	251	330	433
Gross C seq. (t/yr)	35	34	34	34	33	33	32	31
Gross C seq. ($/yr)	5,494	5,405	5,348	5,331	5,296	5,202	5,118	5,000
Avoided runoff (m3/yr)	6,701	6,615	6,543	6,527	6,483	6,371	6,272	6,127
Avoided runoff ($/yr)	15,579	15,378	15,212	15,174	15,071	14,812	14,581	14,245
Pollution removal (t/yr)	2	2	2	2	2	2	2	2
Pollution removal ($/yr)	91,089	89,722	88,722	88,490	87,867	86,307	84,922	82,898
Energy savings (MWH)	59	58	57	57	57	56	55	53
Energy savings ($/yr)	166	163	161	160	159	156	153	149
Total ($/yr)	112,329	110,669	109,445	109,157	108,394	106,479	104,775	102,293

Table A.6. Evolution of costs under Scenario #1.

Prop. treated (%)	Year	Number of trees	Cumul. loss	Trees loss/ year (%)	Removal and replant cost ($)	Treatment cost ($)	Total cost ($/year)	Cumul. cost ($)
-	2010	4,472	0	0	0	0	0	0
-	2011	4,457	15	0.34	18,000	0	18,000	18,000
-	2012	4,442	30	0.67	18,000	0	18,000	36,000
-	2013	4,427	45	1.01	18,000	0	18,000	54,000
-	2014	4,412	60	1.34	18,000	0	18,000	72,000
-	2015	4,397	75	1.68	18,000	0	18,000	90,000
-	2016	4,382	90	2.01	18,000	0	18,000	108,000
-	2017	4,367	105	2.35	18,000	0	18,000	126,000

Table A.7. Evolution of costs under Scenario #2.

Prop. treated (%)	Year	Number of trees	Cumul. loss	Trees loss/ year (%)	Removal and replant cost ($)	Treatment cost ($)	Total cost ($/year)	Cumul. cost ($)
0	2010	4,472	0	0	0	0	0	0
0	2011	4,472	0	0	0	0	0	0
0	2012	4,472	0	0	0	0	0	0
0	2013	4,466	6	0	6,720	0	6,720	6,720
0	2014	4,400	72	2	73,920	0	73,920	80,640
0	2015	4,000	472	11	448,000	0	448,000	528,640
0	2016	3,000	1,472	33	1,120,000	0	1,120,000	1,648,640
0	2017	1,890	2,582	58	1,243,200	0	1,243,200	2,891,840
0	2018	900	3,572	80	1,108,800	0	1,108,800	4,000,640
0	2019	120	4,352	97	873,600	0	873,600	4,874,240
0	2020	0	4,472	100	134,400	0	134,400	5,008,640

Table A.8. Evolution of costs under Scenario #3.

Prop. treated (%)	Year	Number of trees	Cumul. loss	Trees loss/ year (%)	Removal and replant cost ($)	Treatment cost ($)	Total cost ($/year)	Cumul. cost ($)
33	2010	4,472	0	0	0	0	0	0
33	2011	4,418	54	1	60,480	0	60,480	60,480
33	2012	4,335	137	3	92,960	29,952	122,912	183,392
33	2013	4,263	209	5	80,640	10,829	91,469	274,861
33	2014	4,042	430	10	247,520	176,371	423,891	698,752
33	2015	3,467	1,005	22	644,000	157,248	801,248	1,500,000
33	2016	3,104	1,368	31	406,560	192,960	599,520	2,099,520
33	2017	2,360	2,112	47	833,280	115,200	948,480	3,048,000

Table A.9. Evolution of costs under Scenario #4.

Prop. treated (%)	Year	Number of trees	Cumul. loss	Trees loss/ year (%)	Removal and replant cost ($)	Treatment cost ($)	Total cost ($/year)	Cumul. cost ($)
50	2010	4,472	0	0	0	0	0	0
50	2011	4,394	78	2	87,360	0	87,360	87,360
50	2012	4,346	126	3	53,760	31,680	85,440	172,800
50	2013	4,331	141	3	16,800	251,597	268,397	441,197
50	2014	4,299	173	4	35,840	218,880	254,720	695,917
50	2015	4,221	251	6	87,360	263,923	351,283	1,047,200
50	2016	4,142	330	7	88,480	185,472	273,952	1,321,152
50	2017	4,039	433	10	115,360	235,008	350,368	1,671,520

CHAPITRE III CONCLUSION

La décision de Montréal de choisir la méthodologie SLAM en 2012 pour lutter contre l'infestation d'agrile du frêne ne semble pas fournir les résultats escomptés si l'on compare avec l'étude de McCullough et Mercader (2012) qui prédisait que le traitement de 20 % des frênes n'entraînerait presque aucune perte sur un horizon de dix ans. Par contre, certains arrondissements semblent mieux s'en sortir que d'autres. La gestion proactive des SE est très importante en foresterie urbaine ; non seulement dans l'inoculation des frênes, mais aussi dans l'abattage des frênes qui n'ont pas d'avenir à court terme. De cette façon, ces arbres peuvent être remplacés par d'autres essences qui ne seront pas affectées par l'ADF, mais ils auront un faible impact sur la fourniture de services aux citoyens compte tenu de leur taille et du nombre d'années avant l'atteinte de la maturité.

Outre l'inoculation et l'abattage préventif, la meilleure façon de lutter contre une infestation d'ADF consisterait à intégrer d'autres stratagèmes anti-agriles. Par exemple, il existe des guêpes parasitoïdes spécialisées qui pondent leurs œufs à l'intérieur des larves de l'ADF. Ces guêpes peuvent être relâchées dans les villes aux prises avec ce type d'infestation. De plus, la dissémination d'un champignon entomopathogène pourrait aussi être bénéfique puisqu'il affecte spécifiquement la capacité de l'ADF à se reproduire. En ce qui a trait à cette dernière méthode, les résultats en laboratoires sont très prometteurs, car 80 % des insectes meurent durant les quatre premiers jours suivant la contamination (Ressources naturelles Canada, 2014). Malheureusement, il est encore trop tôt pour évaluer le taux d'efficacité de ces méthodes sur le terrain. Cependant, ces méthodes ou une combinaison de ces méthodes pourraient augmenter l'efficacité de la lutte contre l'ADF dans le court à moyen terme. Par contre, en 2012, la méthodologie adoptée par Montréal était le meilleur choix à l'époque compte tenu des connaissances disponibles et étant donné que les autres moyens de contrôle de cet insecte n'étaient pas encore disponibles. Un plus grand investissement au niveau des paliers de gouvernements impliqués dès la découverte de l'ADF au Canada depuis 2002 et à Montréal depuis 2011 aurait certainement contribué à ralentir la progression de cette espèce envahissante et freiner la perte de milliers de frênes. Enfin, puisque la majorité des arbres des villes sont privés, la sensibilisation des citoyens à la protection des arbres est un élément important à considérer dans l'élaboration d'une stratégie intégrative sur la lutte face à un insecte envahissant. Comme le mentionne Ressources naturelles Canada (2014), « ces efforts seront en vain sans la participation active de la population pour freiner la dispersion de l'ADF ». L'efficacité de la campagne de sensibilisation de la Ville de Montréal à ses citoyens n'est pas connue actuellement.

L'étude de cas pourrait être utile pour les municipalités situées à l'est de Montréal où l'ADF n'a pas encore été détecté afin de sélectionner la stratégie qui leur convient en fonction de leurs objectifs de gestion de l'infestation. Il pourrait aussi y avoir d'autres utilisations de cette étude puisque c'est la première fois qu'un inventaire i-Tree Eco de cette envergure a eu lieu à Montréal. La Ville de Montréal mène actuellement des relevés aériens avec l'objectif futur de caractériser leurs infrastructures naturelles de façon très précise avec l'aide de la télédétection et de la géomatique. Les informations recueillies dans le cadre de cette étude pourraient aider la Ville de Montréal à affiner leurs données concernant leur forêt urbaine.

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