Evaluation of Aboveground Forest Carbon Sequestration for Climate Change Mitigation Targets: A Case Study on McGill University Properties

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August 2019

A thesis submitted to McGill University in partial fulfillment of the requirements of the degree of Master of Science

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ABSTRACT

Human-induced climate change is one of the biggest threats facing human-kind and the global environment today. Climate action plans at the global, regional, and local scales set C neutrality (a state of no net increase in atmospheric C achieved by balancing emissions and sequestration) as a key climate change mitigation target. Action plans to achieve C neutrality often focus on emissions reduction, with limited focus on quantifying, measuring, and increasing C sequestration. Certain forms of C sequestration include afforestation, which can remove existing C trapped in the atmosphere through photosynthesis in a cost-effective way, while also providing additional ecosystem services, such as recreation or maple syrup. Higher education institutions, particularly universities, play an important role in climate change mitigation efforts due to their size, population, and influence in sustainable education. In this case study, I focus on McGill University's plan to become C neutral by 2040. McGill has developed an annual inventory that tracks major sources and amounts of annual GHGs emissions at McGill from travel, energy consumption, and power generation. However, missing from this inventory is a measurement of total C sequestered annually on university properties. To fill this gap in our knowledge, I measure, quantify, and evaluate the current rates of aboveground C sequestration on the two main forested properties owned by McGill University, the Morgan Arboretum (240 ha) and the Gault Nature Reserve (1000 ha). I also evaluate two different scenarios that could increase C sequestration through afforestation on the largest agricultural property at McGill University, the Macdonald Campus Farm (200 ha). To estimate C sequestration, I gathered data on tree species, tree diameter, and tree growth in 71 plots of 400 m^2 from both forests (34 at the Morgan Arboretum and 37 at the Gault Nature Reserve). I inputted this data into allometric equations to calculate the C sequestration in the plots and multiplied out by forest type to estimate C sequestration across the entire area of both forests. These two forested

properties are currently capturing just under 5% of the university's annual C emissions, indicating that there needs to be significant efforts to increase C sequestration or reduce C emissions to reach C neutrality by 2040. My results show that the Morgan Arboretum (managed, with some plantations) sequesters C at a greater rate per hectare and overall than the Gault Nature Reserve (old growth and primarily unmanaged). Differences in C sequestration between the two forests appear to be primarily related to the difference in management, forest age, tree mortality, and forest density, with little influence from differences in forest composition. Afforestation at the Macdonald Campus Farm could increase C sequestration by up to 87% over current rates and bring up the capture of C emissions to just over 9% of McGill University's current emissions. While net sequestration on campus may be small relative to emissions, the educational potential of on-campus C offsetting opportunities is large. This project provides an understanding of the potential to quantify and increase C sequestration at McGill and on other university and institutional properties in order to help reach climate change mitigation targets.

RÉSUMÉ

Les changements climatiques causés par l'homme sont l'une des plus grandes menaces qui pèse sur l'espèce humaine ainsi que sur l'environnement mondial aujourd'hui. Au niveau mondial, régional et local, les plans d'action pour le climat font de la neutralité carbone (état d'absence d'augmentation nette du carbone atmosphérique obtenu en équilibrant les émissions et la séquestration de carbone), un objectif clé afin d'atténuer le changement climatique. Les plans d'action visant à atteindre cette neutralité carbone mettent souvent l'accent sur la réduction des émissions et ne se concentrent que peu sur la quantification, la mesure et l'augmentation de la séquestration du carbone. Certaines formes de rétention du carbone comprennent le boisement, qui peut éliminer de manière rentable le carbone existant emprisonné dans l'atmosphère par la photosynthèse, tout en fournissant des services écosystémiques supplémentaires, tels que les loisirs ou le sirop d'érable. Les établissements d'enseignement supérieur, notamment les universités, jouent un rôle important dans les efforts d'atténuation du changement climatique en raison de leur taille, de leur population ainsi que de leur influence sur l'éducation durable. Dans cette étude de cas, je me concentre sur le plan de l'Université McGill qui vise à neutraliser ses émissions de carbone d'ici 2040. L'Université McGill a mis au point un inventaire annuel qui répertorie les principales sources et quantités d'émissions annuelles de GES provenant des déplacements, de la consommation et de la production d'énergie. Cependant, il manque à cet inventaire une mesure du carbone total retenu annuellement sur les propriétés de l'université. Afin de combler cette lacune dans nos connaissances, je mesure, quantifie et évalue les taux actuels de séquestration du carbone en surface sur les deux principales propriétés forestières appartenant à l'Université McGill : l'arboretum Morgan (240 ha) et la réserve naturelle Gault (1000 ha). J'évalue également deux scénarios différents qui pourraient augmenter la séquestration de carbone en boisant la plus grande propriété agricole de l'Université McGill : la ferme du campus

Macdonald (200 ha). Afin d’estimer la séquestration du carbone, j'ai rassemblé des données sur les espèces, le diamètre et la croissance des arbres dans 71 parcelles de 400 m^2 issues des deux forêts (34 à l'Arboretum Morgan et 37 à la réserve naturelle Gault). J'ai entré ces données dans des équations allométriques afin de calculer la séquestration du carbone dans chaque parcelle et je les ai multipliées par type de forêt afin d’estimer la retenue de carbone sur toute la superficie des deux forêts. Actuellement, ces deux propriétés forestières absorbent un peu moins de 5% des émissions annuelles de carbone de l’université, indiquant ainsi qu’il faut déployer des efforts importants pour augmenter la séquestration ou réduire les émissions afin d’atteindre la neutralité carbone d’ici 2040. Mes résultats montrent que l’Arboretum Morgan (géré, avec quelques plantations) séquestre le carbone à un taux plus élevé par hectare que la réserve naturelle Gault (vieux peuplement, principalement non géré). Les différences de séquestration du carbone entre les deux forêts semblent être principalement liées aux différences de gestion, d’âge, de mortalité et de densité des forêts, avec une légère influence due aux différences de composition de la forêt. Le boisement de la ferme du campus Macdonald pourrait augmenter la séquestration du carbone de 87% par rapport aux taux actuels et ainsi augmenter la capture des émissions de carbone à un peu plus de 9% comparé aux émissions actuelles de l’Université McGill. Bien que la séquestration nette sur le campus puisse être faible par rapport aux émissions, le potentiel éducatif des possibilités de compensation du carbone sur le campus est important. Ce projet permet de comprendre le potentiel de quantification et d’augmentation de la séquestration du carbone à McGill et sur d’autres établissements universitaires et institutionnels afin d’aider à atteindre les objectifs d’atténuation du changement climatique.

ACKNOWLEDGEMENTS

I want to start by thanking my supervisor, Dr. Elena Bennett. She has been an inspiration and a great mentor to me since my very first day at McGill. She has taught me so much about what it takes to be a strong researcher, communicator, and a woman. She has always been so patient with me, even when I have sent her some questionable drafts, had to redo my fieldwork, and sending late night panicked emails. She has always pushed and encouraged me to reach my full potential and allowed me to explore my passions outside of my masters. She has instilled in me skills that I will take with me wherever my path leads. Thanks for taking a chance on me, I am truly so lucky to have had the opportunity to work with you.

I would also like to thank Dr. Benoit Coté and Dr. Jim Fyles for helping me develop some of the methods of the thesis. Thank you for coming out into the forest with me during the 8-10 hour work days of hiking, tree hugging, and getting eaten alive by mosquitos. Thank you for not forsaking me during the black-fly season and imparting some of your knowledge about the history and management of the Morgan Arboretum. To Dr. Benoit, thank you as well for being so patient with my numerous unannounced visits to your office to help answer my excessive questions and allowing me to use your lab.

To my field assistant, Melissa Donnelly. Thank you for the countless laughs, the unintentional gliding down the hills, the patience in guiding us between sites when I was too cranky, and for sharing your food every time I forgot mine. To Erin Crocket, thank you so much for your time and patience in helping me figure out how to write a thesis, what to include, and asking all the right questions. I also want to thank every other field assistant and/or lab mate that selflessly came to aid me when I needed the extra hands and help both inside and outside the lab: Julie Botzas, Jesse Reib, Dalal Hanna, Amaia Albizua, Dan Haberman, Maria Creighton, Ali and

Toby from the McGill Office of Sustainability (MOOS). A special thank you also goes to Ali Rivers (MOOS) and Jerome Conraud (Utilities and Energy Management) for being incredible resources and for helping me with some of the logistical aspects of the thesis.

Finally, a very important thank you goes to my family and friends who were there to support me through the entire process. To my parents, thank you for your support in every aspect from my move to Montreal. Thank you for being there throughout my ups and downs. I would not be here without you. To my sister, Casy, thank you for always answering my calls to deal with my not so dramatic crises and making sure that I never lost sight of why I was doing this. To my friends: Gaby, Kyra, Janna, Alex, the squad, and the McGill Tennis Team, thank you for always being there to make sure I do not lose my mind and giving me so much love and laughter.

PREFACE

This thesis is manuscript-based and is presented as two chapters. The first chapter is a literature review and the second chapter is a research-based paper. As a result, there is some necessary repetition between the two chapters. Throughout both chapters, I aim to address the importance, the implications, and the relevance of forest carbon sequestration within climate change mitigation strategies, particularly with regards to climate action plans at the university level. Chapter 2 is prepared as a manuscript for submission to the *International Journal of Sustainability in Higher Education*.

In Chapter 1, I briefly touch on the current literature of today's state of climate change and the current practices in climate change mitigation. The role of forests in climate change mitigation and the methods to quantify carbon sequestration within forested properties are also discussed. I also discuss the importance of municipalities and higher education institutions in implementing climate action plans that focus on reaching carbon neutrality by reducing emissions as well as understanding carbon sequestration for carbon offsetting practices.

In Chapter 2, I present a case study for calculating the C sequestration within the forested properties at McGill University, the Morgan Arboretum and the Gault Nature Reserve. I also look at the agricultural property owned by McGill University, the Macdonald Campus Farm, and assess the potential for increased carbon sequestration within this property to see how close the university is to reaching its carbon neutrality target and what additional actions can be taken to attain it.

CONTRIBUTION OF KNOWLEDGE

The M.Sc. thesis candidate, Isabella Boushey, is responsible for leading the project design, data collection, analysis, and writing of both chapters of this thesis.

The supervisor and co-author of the manuscript, Dr. Elena Bennett, was actively involved throughout every stage of the thesis and helped in designing the methods and research questions, providing advice during the analysis and writing process, and editing the thesis. Erin Crockett, co-author on Chapter 2, helped in developing the methods, statistical analysis of the data, and editing various parts of the manuscript. Ali Rivers (McGill University Office of Sustainability) and Jerome Conraud (Utilities and Energy Management, McGill University) helped to develop the research question and goals, and provided contacts for the required datasets for the project.

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INTRODUCTION

The world is seeing an increase in catastrophic events as a result of global climate change (IPCC 2014). Anthropogenic forces are leading to a change in climate by increasing greenhouse gas (GHG) emissions, particularly carbon dioxide (CO_2, UNFCCC 2015; Plattner et al. 2008). About 82% of global greenhouse gas emissions are comprised of CO_2, which is one of the most dominant and long-lived GHGs in the atmosphere, and primarily released from the burning of fossil fuels for energy production (US EPA 2017; Lindsey 2018; UNFCCC 2019; IPCC 2014).

Action is being taken at the national and international scale to address the global climate crisis. Most action falls into one of two overarching approaches – adaptation or mitigation (IPCC 2014; Edenhofer 2015). Climate change adaptation focuses on reducing vulnerability and increasing resilience to some of the worst impacts of climate change (Smit et al. 2000). Mitigation, on the other hand, aims to limit climate change itself by reducing the amount of carbon (C) released into the atmosphere or by increasing C capture and storage. Reducing C emissions can be done through various means, including a transition towards renewable energy sources (wind or solar power) and away from coal and other fossil fuels (UCS 2019). Increasing C capture and storage can be accomplished through abiotic and biotic means (IPCC 2005). Abiotic means involve the separation of CO_2 from industrial sources, followed by transportation to a location to store CO_2 away from the atmosphere, such as in geological formations or in the deep ocean (IPCC 2005). This is a costly process and poses a risk of C leakage from the storage sites. Biological methods of C sequestration, in which C is captured from the atmosphere in trees, plants, and soils, are less costly and provide additional benefits beyond C sequestration, including improved air quality, food resources, water irrigation, and recreational uses (Lal 2007). The largest C sinks are forests and oceans. About 30%

of global emissions are sequestered by forests and surrounding vegetation, and about 23% are sequestered by oceans (Buis 2014; Running 2008).

Forests play a key role in the global net C balance and in mitigating climate change since they comprise about a third of the world's land area and have a high carbon density, making them the largest terrestrial C pools (Lamlom & Savidge 2003; Lambert et al. 2005). Trees sequester C through the process of photosynthesis and store it in above- and belowground biomass for long periods of time (US EPA 2014; Lambert et al. 2005; Running 2008). Variability in C sequestration between forests can be due to differences in forest age, climate, management, and density (Hansen et al 1991; Chatterjee et al. 2009; Jandl 2007). Older and unmanaged forests tend to have a lower C sequestration than young and managed forests (Hansen et al. 1991).

C sequestration can be quantified through estimations of the annual change in aboveground live biomass and C storage (Manickam et al. 2014). Aboveground forest biomass estimations provide an understanding of the impacts forest ecosystems have on mitigating global warming and environmental degradation (Manickam et al. 2014; Lambert et al. 2005). Aboveground forest biomass can be estimated through various allometric equations that quantify the amount of C within different parts of the trees (stem, branch, foliage, crown) (Lambert et al. 2005) based on the size and species of the tree. These biomass values can then be converted to C storage by multiplying by the species-specific C percentage in the wooded parts of trees; this value is approximately 50% for most tree species (Lamlom & Savidge 2003). C sequestration can then be calculated by subtracting C storage values from year to year to get an annual rate of C capture (Donovan 2012; Elbasiouny et al. 2017). C sequestration is the rate at which C is captured and stored in different C sinks; whereas, C storage is the amount of C in biomass (Jandl et al. 2007; Lal 2005).

Climate action plans and mitigation targets at institutions of higher education, such as universities, play an important role in addressing the climate change crisis through environmental research, teaching, institutional action plans and targets, and by managing land for C sequestration. Universities have many of the necessary resources to assess their environmental impact and foster innovative ideas on reducing emissions (Bezbatchenko 2010; Walton & Galea 2005; Stephens et al. 2008). Achieving C neutrality (which occurs when the rate of C emissions and sequestration are equal) is often one of the climate change mitigation targets put in place in university action plans, including at Central Connecticut State University (Walton & Button 2009), California State Polytechnic University (Willson & Brown 2008), Yale University (Yale Sustainability 2018), and McGill University (McGill Office of Sustainability 2017). Each of these universities sets clear targets to reduce their overall C emissions; however, targets to quantify and increase C sequestration within these plans are not included.

McGill University aims to reach C neutrality by the year 2040 (McGill Office of Sustainability 2017). The targets laid out in the Climate and Sustainability Action Plan aim to significantly reduce emissions, in addition to quantifying C sequestration to determine the potential to increase sequestration through afforestation. Quantifying the potential to increase C sequestration could create potential for an internal C offsetting program to implement C sequestration projects on the university's properties. An internal C offsetting program could limit the need for externally purchased C offsets, which are less desirable because they often lack transparency.

The objective of my thesis is to evaluate current C sequestration at McGill University's two main forested properties, the Morgan Arboretum and the Gault Nature Reserve. I also evaluate the potential for additional C sequestration through afforestation at Morgan Arboretum and the Macdonald Campus Farm.

CHAPTER 1: Climate Change, Mitigation, and the Role of Forests in Storing Carbon

1.1 *Current State of Climate Change*

Climate change is one of the greatest issues affecting both humanity and the global environment today (IPCC 2014). There is an abundance of evidence to the significant anthropogenic influence on the climate system (UNFCCC 2015; Plattner et al. 2008), which has both direct and indirect effects on the environment, human health, and the economy (UNFCCC 2015; UNEP 2019). The most dominant anthropogenic cause of climate change is the release of greenhouse gases (GHGs), including carbon dioxide (CO_2), methane (CH_3), nitrous oxide (NO_2), and chlorofluorocarbons (CFC) (US EPA 2017; Allen et al. 2018; UNFCCC 2019; UNEP 2019). Of these three GHGs, CO_2 comprises about 82% of global annual emissions and remains in the atmosphere for much longer than other GHGs (US EPA 2017; Lindsey 2018). The release of GHGs into the atmosphere comes primarily from the burning of fossil fuels (oil, gas, and coal) for industry, electricity, and transportation, (Figure 1) as well as from solid waste and the decomposition of trees (US EPA 2017; UNFCCC 2019; IPCC 2014).

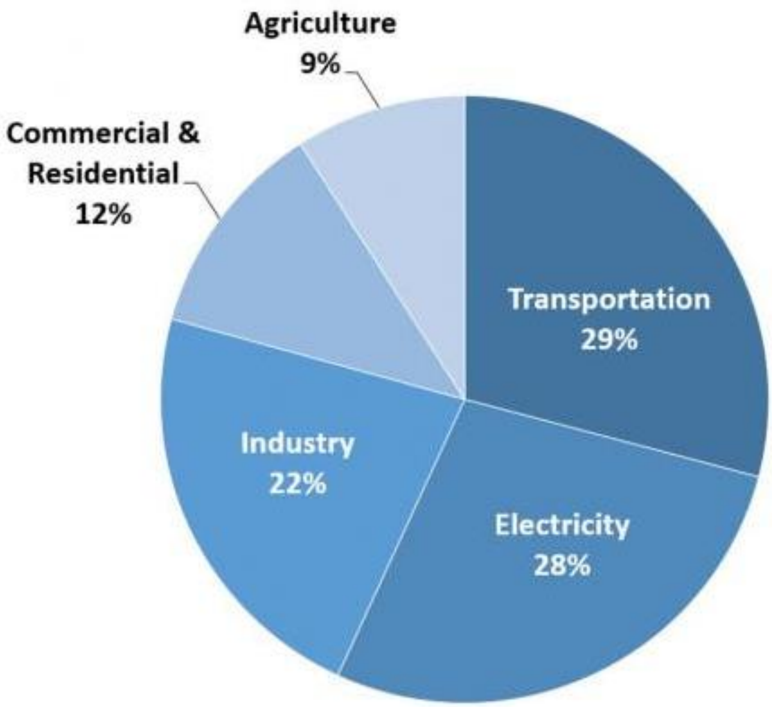

Figure 1. Proportion of the main anthropogenic sources of global CO_2 emissions into the atmosphere with transportation, electricity, and industry having the greatest influence. Values do not equate to 100% due to independent rounding. Figure is obtained from the US Environmental Protection Agency (2017).

There has been a rise in atmospheric CO_2 over time (Figure 2) as a result of increased human GHG emissions due ultimately to economic and population growth (ESRL 2019; IPCC 2014; Lindsey 2018). The increased amount of GHGs in the atmosphere has resulted in changes to the climate system (Lindsey 2018; IPCC 2014), including atmospheric heating of the planet. Temperatures in the last several decades are the warmest that the planet has experienced in the last 1400 years (IPCC 2014).

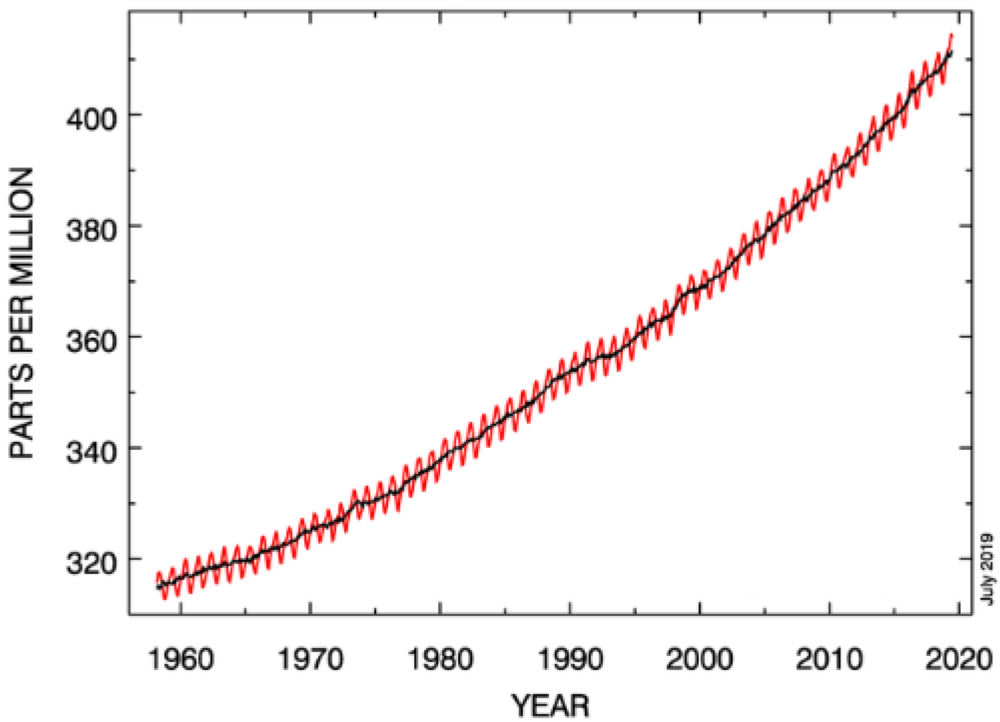

Figure 2. Keeling curve of the atmospheric CO_2 concentrations collected from the Mauna Loa Observatory since 1960. Figure is obtained and modified from the Earth Systems Research Laboratory (ESRL 2019). Red line represents the observed CO_2 concentration over time and the black line is the overall mean.

A rise in atmospheric temperatures, alongside increased demand for food due to population growth, is projected to affect global and local food security by reducing renewable surface water and groundwater resources (IPCC 2014; NASA 2019). The rise in temperatures is also predicted to reduce provision of other ecosystem services, including flood regulation and freshwater (Perrings 2010; Millennium Ecosystem Assessment 2005). Other observed effects of climate change include ocean acidification from the reaction of ocean water and atmospheric CO_2 (NASA 2019) and a rise in sea-level as a result of the thermal expansion of the ocean and the melting of the Arctic-sea ice (IPCC 2014). The rising sea levels are predicted to lead to catastrophic events, which include the destruction of coastal habitats, floods, and a loss in habitable terrestrial lands (IPCC 2014). As a result of the global climate crisis, there has been increased collaboration at the national and international scale (UNFCCC 2015) when it comes to tackling GHGs through the phasing out of fossil fuels, transitioning to renewable energy, and increasing the forms of C capture.

1.2 *Climate Change Mitigation*

In general, there are two overarching approaches established in the climate science and policy literature to address and combat climate change – adaptation and mitigation (IPCC 2014; Edenhofer 2015). Climate change adaptation focuses on reducing vulnerability and improving resilience against some of the worst impacts of climate change (Smit et al. 2000). For example, climate change adaptation includes changing building and road infrastructure to reduce exposure to hazards, growing drought resistant crops, and raising sea walls (Natural Resources Canada 2015). In other words, adaptation is about building the capacity for vulnerable communities to cope with the effects of climate change. Mitigation, on the other hand, aims to reduce climate change itself by reducing the amount of C released into the atmosphere, and increasing C capture.

Methods of mitigation - reducing C emissions and increasing C capture - include conservation and restoration efforts, as well as improved management practices in forest, wetland, and grassland biomes (Griscom et al. 2017; IPCC 2014). Emissions can be reduced through transitions to more renewable energy sources and away from coal and other fossil fuels, increasing vehicle fuel efficiency, reducing deforestation, and placing limits on the amount of C industries can emit (UCS 2019). Increasing the rate of C capture (C sequestration) can be accomplished through abiotic methods such as a variety of advanced technologies used to capture CO_2 directly from industrial sources, transporting them to a storage facility, and isolating the C from the atmosphere for a long period of time (IPCC 2005). They storage facilities include underground geological formations and injections into the deep ocean (IPCC 2005). Although abiotic techniques are effective at sequestering C, they are expensive and there is a high risk of leakage back to the atmosphere (Lal 2007).

Biological methods of C sequestration, such as in trees, plants, and soils, are more cost-effective than abiotic methods and have numerous additional benefits to humans and the environment, including improved air quality, food resources, water irrigation, and recreational uses (Lal 2007). Major areas for biological C capture, also called C sinks, include oceans (Matbr & Hirst 1999), soils (Lal 2004), and forests (Birdsey 1992). Currently, of the global amount of C emitted into the atmosphere, approximately 47% remains in the atmosphere, 30% is absorbed by forests and other land vegetation, and 23% by oceans (Buis 2014; Running 2008). Forests, in particular, play a key role in the global net C balance and in mitigating climate change since they comprise about a third of the world's land area and have a high carbon density, making them the largest terrestrial C pools (Lamlom & Savidge 2003; Lambert et al. 2005). Forests also provide additional ecosystem services beyond C sequestration for climate change mitigation, such as providing raw material and energy, maintaining biological diversity, protecting land and water resources, improving air quality, and providing recreational facilities (Manickam et al. 2014).

1.2.1 *Role of Forests in C sequestration*

Forests play an important role in the global C cycle since they have the ability to capture atmospheric C, convert it into organic matter through photosynthesis, and store it in the above- and belowground biomass for long periods of time (US EPA 2014; Lambert et al. 2005; Running 2008). Biomass consists of the root systems, soil, wood, stem, foliage, branches, and crown of the forest (Lambert et al. 2005). Around 30% of all forest C is stored in the aboveground live vegetation and about 70% is stored in the soils and dead organic matter, making belowground vegetation the largest terrestrial reservoir for C (Jandl et al. 2007; US EPA 2016; Buis 2014). On a global scale, tropical forests are the largest sink for atmospheric C; however, North American forests, particularly the Canadian boreal forest is a close second (Jandl et al. 2007; Buis 2014).

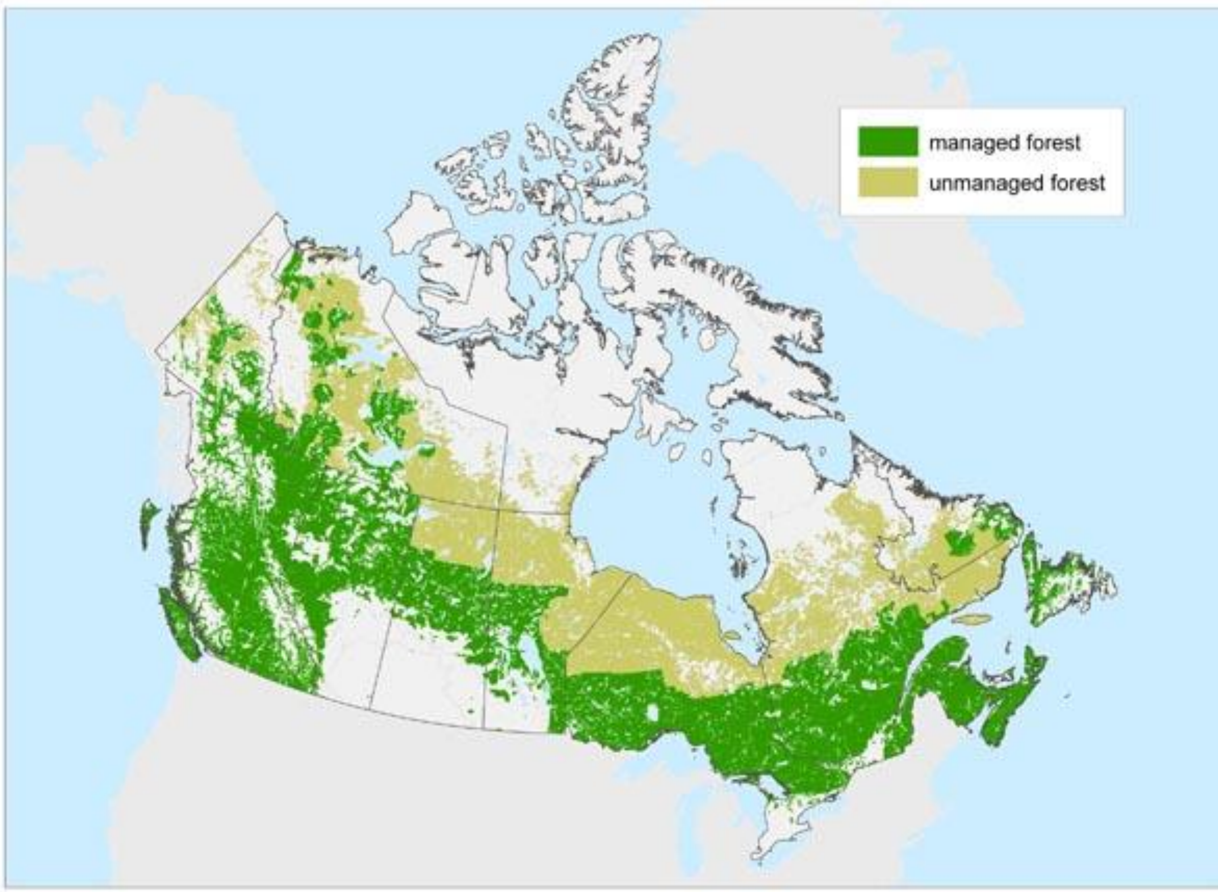

Figure 3. Map indicating the area of managed and unmanaged forested lands in Canada. Figure is obtained from The State of Canada's Forests: Annual Report 2018 presented by Natural Resources Canada (Natural Resources Canada 2018).

There is ongoing debate and research regarding the influence of human factors and involvement of forests with C sequestration; however, evidence shows that certain aspects of forest management can have an effect on net C sequestration (Hansen et al 1991; Chatterjee et al. 2009; Jandl 2007). About 65% of all forests in Canada, excluding urban forests, are classified as managed and about 35% are unmanaged forests (Figure 3) (Natural Resources Canada 2018). Managed forests with plantations generally have higher C sequestration and differ from unmanaged forests by their structure and species composition (Hansen et al. 1991). There is greater structural complexity, a higher abundance of larger trees, greater stand size, shape, dispersion of trees, and abundance of bird and amphibians within unmanaged forests (Hansen et al. 1991). Forest age has also been shown to have an influence on the overall net C sequestration with older and unmanaged forests showing little potential for additional C sequestration; however, these older forests do generally already contain a large C pool (Chatterjee et al. 2009). Research does suggest that although C sequestration in forests slows down after a little over a century of growth (Haromon and Marks 2002), older and unmanaged forest do continue to sequester C steadily for several centuries (Luyssaert et al. 2008; Chatterjee et al. 2009; Jandl 2007). Based on the amount of fallen trees, dead biomass, and older age of unmanaged forests, managed forests generally have higher net C sequestration based on live tree biomass, changes in land-use, and differences in forest types (Chatterjee et al. 2009; US EPA 2014).

1.2.2 *Measuring Forest C sequestration*

Calculating C sequestration starts with accurate forest biomass estimations, which are essential to calculate C storage and C sequestration. The net change in forest biomass over time is an indicator of the change in C storage, as well as the function of stability, growth, decline of forest ecosystems, and a wide range of environmental conditions (US EPA 2014; Ketterings et al. 2001). Comparing C storage from biomass between different years provides the rate at which C is captured on an annual basis, in other words, C sequestration (Donovan 2012; Elbasiouny et al. 2017; Figure 4).

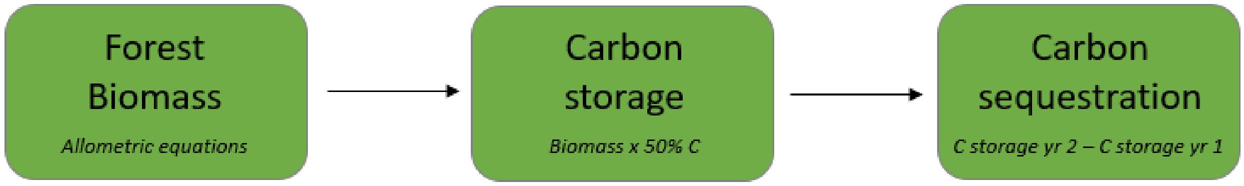

Figure 4. Diagram of an approach to calculating for C sequestration starting from forest biomass calculations. Forest biomass is calculated by using allometric equations and the diameter at breast height and species of the tree; C storage is calculated by multiplying forest biomass by the amount of C in that forest/tree type; and C sequestration, a rate, calculated by comparing C storage values between years.

There are five main components of forest biomass: aboveground, belowground, dead wood, forest floor litter, and soil organic C (US EPA 2014). Aboveground components, specifically live tree biomass, are good indicators when assessing the differences between the C storage in managed and unmanaged forests (Chatterjee et al. 2009). Measuring and calculating aboveground forest biomass using plot data is one of the main methods used to estimate C storage at the local, regional, and national scales (Lambert et al. 2005; US EPA 2014; Lamlom & Savidge 2003; Manickam et al. 2014). A universal system of equations has been created that calculates biomass data for all aboveground biomass components (Lambert et al. 2005). There are two sets of equations to calculate biomass of different parts of trees using species type, diameter at breast height (DBH), and/or height of the trees. At the local or regional scale, using the set of equations based on DBH alone is adequate; however, the set of equations incorporating overall tree height produces greater accuracy for forest biomass estimates at the national scale (Lambert et al. 2005).

By multiplying the amount of forest biomass by the percentage of C stored within a species of tree, we can approximate C storage (Lamlom & Savidge 2003). In general, approximately 50% of forest organic matter is comprised of C; however, differences in the chemical and anatomical composition of the wood in different tree species creates small variation in C content, ranging from 46.27 to 49.97% in hardwood trees and 47.21% to 55.2% in softwood conifer trees (Lamlom &

Savidge 2003). The higher lignin content in softwood trees (30%) compared to hardwood trees (20%) results in the higher C content in softwoods (Lamlom & Savidge 2003).

Incorporation of the quantity and the rate of C release from forests creates increased accuracy in biomass and C sequestration calculations (Running 2008). Forests emit C during respiration and decomposition of dead material (Running 2008; Russell et al. 2015; Woodall et al. 2008). Quantifying C emissions from these sources would have an effect on the overall C balance and alter the overall atmospheric net C sequestration; however, there is currently no universally defined method of calculating this (Russell et al. 2015). The patterns of C release from forests are difficult to measure using one universal method due to variability in forest ecosystems regions, forest disturbance patterns, climate, and other drivers of decomposition (Russell et al. 2015).

1.2.3 *Factors influencing C sequestration increase*

One of the most well documented solutions in climate change mitigation is to increase C sinks (Griscom et al. 2017; Zomer et al. 2008). Terrestrial ecosystems capture approximately a third of the overall anthropogenic C emitted into the atmosphere (Griscom et al. 2017; Running 2008; Buis 2014). Scientific literature suggests that one of the most effective ways to offset C emissions is by increasing C sink projects (Zomer et al. 2008; Griscom et al. 2017). Reforestation and afforestation are the largest and most cost-effective pathways for climate change mitigation and more attention needs to be placed on increasing these projects (Zomer et al. 2008; Griscom et al. 2017). However, only an average of 2.5% of the global climate change mitigation funds are put towards land-based mitigation projects and the majority allocated towards the development of renewable energy (Griscom et al. 2017). This is often due to the argument of the impermanence of C sinks in forested areas, the inevitable release of C into the atmosphere once the trees die after hundreds of years, and terrestrial biomes in general (Lamlom & Savidge 2003; Griscom et al. 2017).

1.3 *Climate Action Plans and Agreements*

The most recent global action plan, the Paris Climate Agreement (2015), brought together 174 countries from all over the world (Canada, United Kingdom, Australia, and many other) to set a multitude of goals and targets aimed at combating the climate crisis. These agreed-upon targets focus heavily on mitigation - reducing global GHG emissions to limit global temperature increase by less than 2°C from pre-industrial levels. The agreement also highlights the economic imbalance between developed and developing countries. Since developed countries have the financial advantage to implement change that reduces their overall C budget, the agreement encourages the governments of developed countries to take on the social and environmental responsibility for implementing stronger climate policies and supporting developing nations in their climate change mitigation and adaptation efforts (UNFCCC 2015; IPCC 2014). According to the agreement, countries are required to outline, report, and communicate their climate plans, also referred to as Nationally Determined Contributions (NDCs), on an annual basis. The purpose of these climate plans is to ensure that the targets put in place by each country are adequate to meet the long-term global goals of the Agreement (2015). Some of specific plans outlined to mitigate climate change in the NDCs include supporting sustainable agriculture, improving water resource management, emissions reductions from fossil fuel combustion, and providing better support for technology in renewable energy resources (World Resources Institute 2018).

1.3.1 *Carbon neutrality for climate change mitigation*

Many countries (Chile, Sweden, Germany, and multiple others) have highlighted reaching C neutrality as one of the mitigation targets in their climate plans (Climate Action Tracker 2019; UNFCCC 2017). Chile, for instance, aims to completely phase out coal, a high GHG emitting source of energy, by 2040 and aim for nation-wide C neutrality by 2050 (Climate Action Tracker 2019). Similarly, Sweden aims for C neutrality (net-zero emissions) by the year 2045 and soon after to reach net negative emissions (UNFCCC 2017). Reaching C neutrality at the national scale helps strengthen the global response to climate change because it means that these countries will balance C emissions and C capture/sequestration, reaching a state of no net emissions. In other words, C neutrality is reached when C sequestration per year is equivalent to C emitted per year by the entity (e.g., country, city, university) in question. Actions taken to reach C neutrality can involve significant reductions in C emissions and increasing biotic and abiotic capture of atmospheric C so that whatever remains in C emissions in the atmosphere can be naturally captured by the ocean, soil, and forests (UNFCCC 2017). However, there is little mention, if any, about the actions that can and will be taken by the countries to increase C sequestration opportunities (Climate Action Tracker 2019; UNFCCC 2017). National climate change policies and targets often require implementation efforts at the state and provincial level; therefore, collaboration with smaller scale municipalities and institutions play a key role in the framing and implementation of national level climate plans (Rabe 2007; Council of the Federation 2015).

1.3.2 *Carbon Offsetting and Sequestration as methods of GHG capture*

At the level of individual institutions, there is also great interest in C neutrality and reducing contributions to climate change. As at the global scale, institutions, businesses, and universities can be net C emitters, net sinks, or in C neutrality. In addition to reducing emissions, another way that institutions can bring their overall C budget towards neutrality is through increasing opportunities for C sequestration. Some institutions are able to increase C storage on their own lands, green spaces, and forested areas; others must purchase C "offsets". Offsets are projects or initiatives that capture

C emissions, for example through afforestation or projects that support transitions towards renewable energy (David Suzuki Foundation 2017; Government of British Columbia 2019). For example, the Government of British Columbia has a goal to reach C neutrality and part of reaching their target involves funding C offsetting projects, such as increased forest sequestration from reduced timber harvesting and advancement in green technology within communities in the province (Government of British Columbia 2019). Another example is an external company that sells C offsets, such as BullFrog Power (https://www.less.ca/en-ca/), and utilizes the money from purchased C offsets towards the development of renewable power projects.

There is, however, a gap in the transparency with C offset purchases. In particular, many people are concerned about whether the project ostensibly financed through the offset would have happened regardless of the additional financing (Broderick 2009; Mair & Wong 2010). For example, does a purchased offset in afforestation actually result in an increased incremental C sequestration? (Mason & Plantinga 2013). Moreover, there is uncertainty in the measurement of C emissions reductions with purchased C offsets, particularly with C sequestration (Brouwer et al. 2008; Mair et al. 2011). That is, it is hard to tell exactly how much additional C is sequestered as a result of a purchased offset. This puts into questions whether the amount of C emitted is the same amount of C that is sequestered by the purchased offset, such as afforestation. Purchasing external C offsets may also take away incentive for local innovation towards a low C emissions future or from implementing meaningful small-scale local mitigation projects (Anderson 2012). For all of these reasons, various environmental groups agree that purchased C offsets should be a last resort after placing active effort in reducing emissions and maximizing natural pathways of C capture (WWF 2019, BullFrog Power 2019, David Suzuki Foundation 2017).

1.3.3 *Municipalities and higher education institutions in climate change mitigation*

Regional and local actions play an important role in the implementation of climate change mitigation strategies (Wilbanks & Kates 1999; Okereke et al. 2009). Work at these levels can be very effective due to increased citizen interest and participation as well as greater control over GHG emitting and storing activities. Particularly with climate plans at the municipal level and within urban environments, there is a stronger drive for citizens to support local sustainability projects, which can, in turn, benefit the local economy (Measham et al. 2011; Council of Federation 2015). Additionally, there are more opportunities for local governments to reduce and regulate GHG emissions since they have control over public transportation, waste management, and land-use planning (Betsill & Bulkeley 2006).

Municipalities are taking steps towards climate change mitigation by reducing emissions and increasing C capture. For instance, some municipalities are creating inventories that track the main sources of GHG emissions, including from buildings, vehicles, waste, and power generation (Federation of Canadian Municipalities 2015; International Council for Local Environmental Initiatives 2009). These inventories help in creating stronger and more specified targets and strategies to combat climate change (Federation of Canadian Municipalities 2015). Some municipalities are working toward quantifying C capture and sequestration within urban green spaces and discouraging urban sprawl to protect lands with the potential for C sequestration (TRCA 2009; Government of Ontario 2015). In 2015, the provincial government of Ontario created a program focused on increasing C sequestration called the "Ontario 50 million Tree Program" (Government of Canada 2015). The program intends to plant 50 million trees throughout the province of Ontario in rural and urban areas. However, there is often a lack of clear targets and plans at the municipal and institutional level that aim to increase sequestration that go beyond protecting the already existing lands for C capture.

Research suggests that adopting a localized approach for climate change mitigation action plans is effective and can have a large influence when it comes to policy implementation (Federation of Canadian Municipalities 2015; Wilbanks & Kates 1999). Institutions, like businesses and universities, will experience social and economic benefits from adopting climate action plans and reducing their overall emissions (Lingl & Carson 2010). In addition, they will also experience the negative impacts of climate change through increased energy and fuel costs (Lingl & Carson 2010). Therefore, local businesses and institutions not only have an advantage in overall climate change mitigation, they also receive the benefits from adopting environmental and climate change strategies.

Institutions of higher education and universities in particular, have an advantage when it comes to taking localized action on climate change mitigation. Through interdisciplinary environmental research, teaching, institutional action plans and targets, as well as land for potential C sequestration, universities have many of the necessary resources to assess their environmental impact and foster innovative ideas on reducing emissions (Bezbatchenko 2010; Walton & Galea 2005; Stephens et al. 2008). Due to the large size of universities, the population, and the various activities taking place within campuses, they are often regarded as “small cities” and can have direct and indirect impacts on the environment through their actions (Alshuwaikhat & Abubakar 2008).

Various universities around the world have created climate action plans that focus on climate change mitigation. Central Connecticut State University (CCSU) set C neutrality as one of the goals within their sustainability action plan (Walton & Button 2009). At CCSU, there are clear goals regarding action and implementation of reduction in C emissions and increasing programs focused on campus sustainability awareness. CCSU purchases some C offsets from a renewable energy company; however, there is no other mention of methods and targets to increase C sequestration (Walton & Button 2009). Similarly, Yale University aims for C neutrality before 2050 and has developed several goals and objectives aimed at reducing emissions (Yale Sustainability 2018). The university is also working towards developing a C offset program; however, it remains unclear whether this is an internal offsetting program or a program that supports external purchased C offsets. Finally, California State Polytechnic University (CSPU) set eight emissions reduction goals aimed at reaching C neutrality, such as increased accessibility to sustainable modes of transportation for staff and students, as well as energy consumption reduction and increased investment in “green” buildings (Willson & Brown 2008). Willson & Brown (2008) used locally developed estimation methods and models to determine the effectiveness of these eight C emissions reduction goals on reaching C neutrality at CSPU and found that university level C neutrality goals are unattainable unless there is strong support in C sequestration initiatives.

Some universities focused on quantifying C sequestration as part of their actions on climate change mitigation. California State University (CSU) quantified C sequestration based on biomass growth from 3900 on-campus trees in order to measure C sequestration (Cox 2012). Similarly, the University of Pennsylvania developed and quantified a tree inventory to compare the ecosystem benefits and the economic benefits of their 6000 on-campus trees for future use in C sequestration evaluations (Bassett 2015). New Zealand University evaluated C sequestration using biomass calculations from over 4,000 trees on their 68-hectare (ha) property (Villiers et al. 2014). Villiers at al. (2014) used these C sequestration evaluations as a comparative assessment of their impact on the university’s C emissions. The on-campus C sequestration from the trees at New Zealand University will only capture about 6% of the total university’s emissions within a 10-year period.

There are many universities, in addition to CSU, the University of Pennsylvania, and New Zealand University, which have produced tree inventories, including California State University (Cox 2012), Utah State University (USU 2019), Indiana University (IUPUI 2019), the University of Washington (UW 2019), and the University of Texas at Austin (UTA 2019. However, these inventories are created mainly for the focus of tree management and maintenance purposes rather than for evaluation of current or potential C sequestration (Cox 2012).

1.4 *Summary of Knowledge Gaps*

Although there are international (2015 Paris Agreement) and national (NDCs) climate change mitigation targets, action on the municipal and local level can have a large impact on overall global climate change mitigation. Higher education institutions, particularly universities, play a key role through their action plans focused on climate change mitigation. Due to their size, population, and influence in sustainable development, universities can have a cascading impact in climate change mitigation. Some universities have focused on achieving C neutrality as one of the targets in their action plans; however, this generally only involves reductions in C emissions and very little focus on quantifying and increasing C sequestration.

Implementation plans to reach C neutrality lack clear and concrete targets set to increase C capture and sequestration. There needs to be more research in the implementation process of C neutrality when it comes to identifying and critically assessing the capacity for local C offsetting in climate change mitigation (Ball et al. 2009). By increasing knowledge on the methods and impacts of quantifying and increasing C sequestration within university properties, we can develop a better understanding of how to reach C neutrality targets. The university forested properties have the potential to be either C sinks or sources; however, it remains unclear to what extent forest C emissions and sequestration have on reaching C neutrality. In order to maximize C sequestration within forested properties of universities, there needs to be a clear understanding of the existing land-use, current sequestration, and areas for potential C sequestration. Evaluations for C neutrality should include both on-campus C sequestration in addition to C emissions evaluations. Gaining an understanding of C sequestration within university properties can help in developing internal C offsetting projects, such as afforestation, as an alternative to purchasing external C offsets.

CHAPTER 2: Evaluation of Aboveground Forest Carbon Sequestration for Climate Change Mitigation Targets: A Case Study on McGill University Properties

1. INTRODUCTION

The effects of global climate change are growing, including increasing temperature (Allen et al. 2018; Intergovernmental Panel on Climate Change (IPCC) 2018), escalating frequency of extreme flooding events (US Climate Change Science Program 2008), ocean acidification (Hoegh-Guldberg et al. 2007), and loss in food security (Parry et al. 2004). Scientific experts agree (United Nations Framework Convention on Climate Change (UNFCCC) 2019) that global climate change is influenced by human actions, which are causing an accumulation of atmospheric C due to increasing emissions of greenhouse gases (GHGs, Vitousek et al. 1997; Solomon et al. 2009).

There are two main approaches to address and combat climate change – adaptation and mitigation (IPCC 2014; Edenhofer 2015). Adaptation focuses on reducing vulnerability and improving resilience against some of the worst impacts of climate change (Smit et al. 2000). For example, changing building and road infrastructure to reduce exposure to hazards, growing drought resistant crops, and raising sea walls all reduce the impacts of climate change on people (Natural Resources Canada 2015). Mitigation, on the other hand, aims to reduce climate change itself by reducing GHG emissions and increasing GHG capture and sequestration (IPCC 2014). Climate change mitigation actions include reforestation projects to increase C sequestration and the phasing out of fossil fuels to reduce overall C emissions (IPCC 2007; IPCC 2014).

Action is being taken to mitigate climate change and to help communities adapt to its effects both locally and through global partnerships (UNFCCC 2016). The 2015 Paris Climate Agreement, signed by 195 countries, requires all signatory countries to report on their annual emissions and provide updates on the initiatives put in place to achieve the globally agreed-upon targets, including keeping global temperature increase to well below 2°C (UNFCCC 2015). One way to achieve these targets is by reducing greenhouse gas emissions, for example by transitioning to renewable energy and reducing fossil fuel burning (US Energy Information Administration 2019; Centre for Climate and Energy Solutions 2019). However, current plans for emission reduction are not steep enough to keep the global temperature increases to below 2°C (Rogelj et al. 2011). Therefore, it will also be important to increase the capture and sequestration of atmospheric C (Schrag 2007). C sequestration is the rate at which C is captured and stored. Such sequestration can happen through biological uptake, such as afforestation (Bonan 2008) or through technological capture of C and storing it in geological formations or in the deep ocean (Figueroa et al. 2008; White et al. 2003; IPCC 2005).

The Paris Climate Agreement also highlights the important role of cities, regions, and local authorities in reducing emissions, increasing C capture, building resilience against the adverse effects of climate change, and maintaining regional and international cooperation (European Commission 2019). Action on climate change at the local scale can have real implications globally by changing dynamics in the microeconomy, local resource use, population structures, and through sustainable urban development (Wilbanks & Kates 1999; Reid & Satterthwaite 2007). Cities, municipalities, and other local institutions are often leaders when it comes to mitigation and adaptation to reach global and national climate targets (NASA 2019; Wilbanks & Kates 1999). Through local actions to transition towards more resilient urban infrastructure, development of energy-efficient technology, and by setting ambitious targets such as C neutrality (UNFCCC 2015), cities can have a real impact on climate change mitigation (Reid & Satterthwaite 2007).

C neutrality, which means no net C emissions, can be achieved by a reduction in the rate of C emissions, an increase in C sequestration, or both (Martin 2006). While C neutrality is an appealing concept, there is a limited understanding of how C neutrality can best be attained (Willson & Brown

2008). C offset purchases finance projects to capture and store carbon to balance emissions released elsewhere (Broderick 2009; David Suzuki Foundation 2017). Examples of purchased C offsets include paying for afforestation or reforestation or paying to support transitions towards renewable energy. These typically invest in C storage somewhere other than where C is emitted. Many people, however, feel uncomfortable with C offsets because of a lack of transparency about what the C offset money is actually paying for. For example, some wonder whether a C capture project would happen regardless if it is being financed through C offset purchases or not (Broderick 2009; Mair & Wong 2010). There is also uncertainty in the measurement of how much C emissions are reduced through purchased C offsets, particularly with projects focused on C sequestration (Brouwer et al. 2008; Mair et al. 2011). Moreover, there is also a gap in our understanding of the positive implications at a local scale on the livelihood and micro-environment of the area resulting from C offsetting projects (Smith & Scherr 2002). Some also argue that purchasing C offsets might take away the incentive for local innovation towards a low C future and may reduce implementation of meaningful local C sequestration projects (Anderson 2012).

Institutions of higher education, like universities, around the world have a strong advantage when it comes to taking action on climate change. Through interdisciplinary environmental research, teaching, and institutional action plans and targets, universities have many of the necessary resources and opportunities to combat climate change and encourage future generations to take on leadership roles when it comes to environmental issues (Betzbatchenko 2010; Walton & Galea 2005; Stephens et al. 2008). University environment and sustainability action plans aim for climate change mitigation by not only reducing their overall GHG emission, particularly carbon dioxide (CO_2) emissions (UBC 2014), but also by developing methods and strategies to transition towards renewable energy infrastructure (Queen’s University 2016) and by creating more green spaces on and near their campuses (Harvard University 2016). Investing in local and community level sequestration projects is effective in offsetting C emissions and may also create more transparency and a higher level of climate change education and awareness (UNESCO 2019). Local C sequestration projects can increase community engagement through their involvement in global climate change mitigation policies and the initiatives required to achieve them, such as through tree planting and preservation of "green" areas (UNESCO 2019).

McGill University's Climate & Sustainability Action Plan outlines McGill's aim to reach C neutrality by 2040 (McGill Office of Sustainability 2017). To achieve C neutrality, the university must be aware of both its total rate of C emissions and total C sequestration (Mg C/hectare/year and Mg C/year). Each year, the university releases a report highlighting the main sources of GHG emissions from each of the university's properties, including the downtown campus, Macdonald Campus, Gault Nature Reserve, Morgan Arboretum, and the Macdonald Campus Farm (McGill GHG Inventory Report 2018). In 2017, McGill University emitted 56,004 Mg of CO_2 equivalents[1] (McGill GHG Inventory Report 2017). Approximately 68% of McGill University's CO_2 equivalent emissions were due to energy use through natural gas combustion, and about 15% were from air travel by university employees and student-based activities. Although this annual report is essential for monitoring emissions and achieving emissions reductions targets, this report does not evaluate a key component of goal of C neutrality— the amount of C that is sequestered by the university's properties. There are currently only a few universities that have quantified the C sequestration from their urban and on-campus forests and other properties (Cox 2012; Bassett 2015). However, the

[1] CO_2 equivalents are used to represent GHGs on a common scale by adjusting the quantity of any GHG to the equivalent impact that CO_2 would have on global warming (Brander 2012). For example, 1 Mg of methane emitted into the atmosphere can be expressed as 25 Mg of CO_2 equivalents.

University of Pennsylvania quantified the ecosystem and economic benefits of their 6000 on-campus trees (Bassett 2015). Similarly, California State University Northridge specifically quantified C sequestration based on biomass growth from their 3900 on-campus trees (Cox 2012). However, an evaluation of C sequestration has never been completed for the McGill University properties.

In this study, I evaluate aboveground forest C sequestration at two McGill properties, the Morgan Arboretum and the Gault Nature Reserve. I also estimate the potential for increasing C sequestration through afforestation at the Macdonald Campus Farm and the Morgan Arboretum. I aim to elucidate the capacity of McGill's forests to contribute to McGill's ability to reach its goal of C neutrality. In so doing, I also expand our understanding of the differences in C sequestration between managed and unmanaged forests and help to develop a better understanding of the potential for local C offsets at McGill University and other universities.

2. METHODS

In order to calculate current and potential C sequestration at McGill University, first I selected three study areas owned by the university that have the greatest capacity for C sequestration (Section 2.1). Within these study areas, I randomly selected a representative sample of forest plots (Section 2.2). For each of the forest plots, I calculated biomass using a set of allometric equations that require input of tree species and diameter (Section 2.3). I calculated current C sequestration by converting biomass to C storage using the percent C content of different tree species and comparing C storage from year to year to estimate sequestration, which is the rate at which C is added to the biomass. To estimate the potential to increase C sequestration at McGill University, I used measured values of C sequestration for different forest types with the amount of new land that could be afforested on the Morgan Arboretum and the Macdonald Campus Farm properties (Section 2.4).

2.1 Study Areas

I selected three properties at McGill University on which to conduct this study (Figure 5), which I will subsequently call “study areas”. For the first research question about current C sequestration, I selected the Gault Nature Reserve and the Morgan Arboretum since these are the largest forested properties at McGill University and have the greatest capacity for C sequestration. For the second research question about potential C sequestration with afforestation, I selected the Morgan Arboretum and the Macdonald Campus Farm, because these study areas represent a large portion of non-forested land with the potential for effective afforestation projects. I did not include the Gault Nature Reserve in the potential afforestation calculations since there is very little unforested land on which trees could be planted.

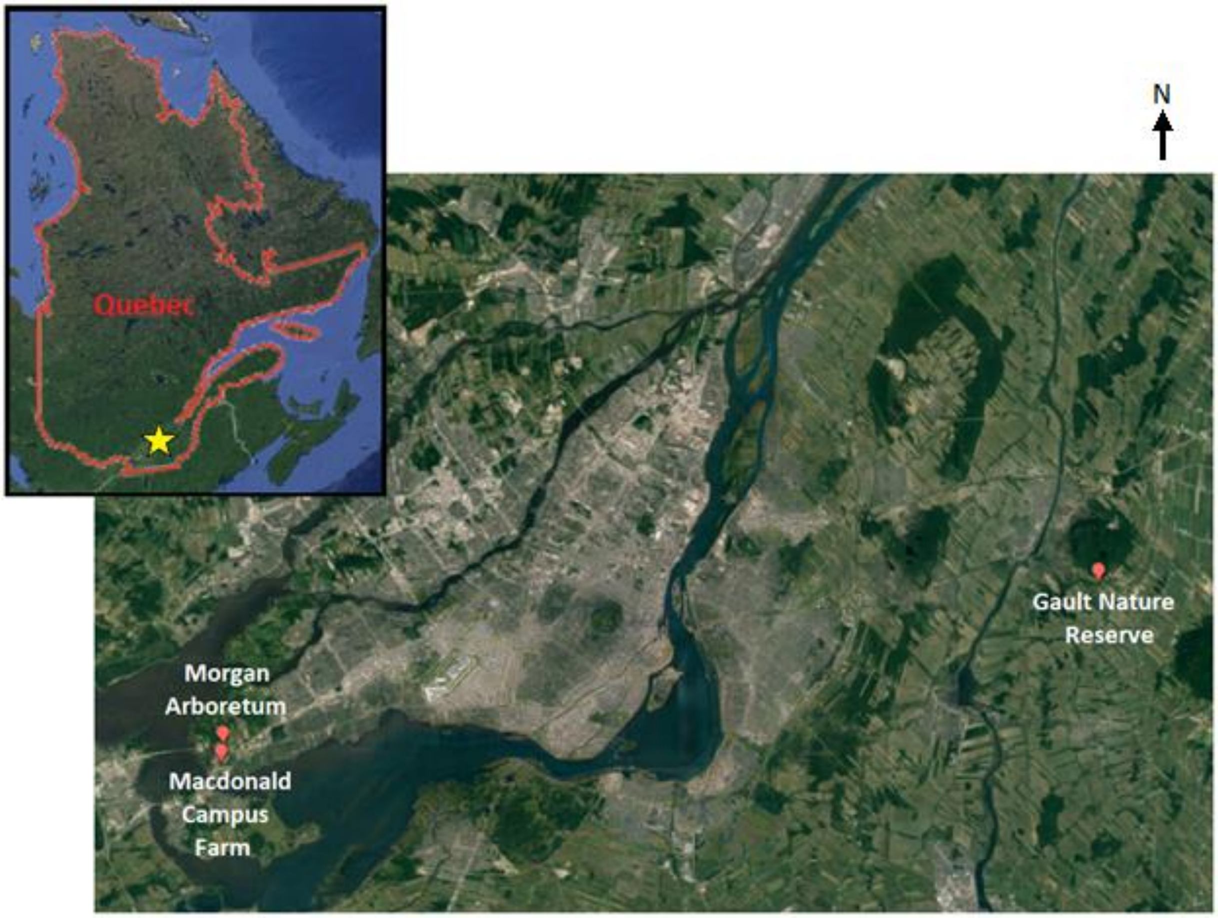

Figure 5. Map of the Island of Montreal located in southern Quebec, Canada, indicating the location of the three main study areas; Gault Nature Reserve, Morgan Arboretum, and the Macdonald Campus Farm.

The Morgan Arboretum is a managed forest located in the western region of the Island of Montreal in Saint-Anne-de-Bellevue, Quebec, Canada. This forest reserve is around 240 ha and contains mixed forest types and plantations. It has been managed for conservation, research, and recreational purposes by McGill University since 1945, and is open to visitors year-round (Morgan Arboretum 2019). The dense forest consists predominantly of maple (*Acer*) and beech (*Fagus*) trees (Aiken et al. 2013), but also consists of a variety of exotic trees, and some softwood and hardwood plantations developed in the 1960s. There is also a sugar maple forest stand within the Morgan Arboretum that is used for maple syrup production and a bog area in the south-west region.

Controlled and selective cutting at the Morgan Arboretum is permitted only at the practice grounds for the McGill University woodsmen/women team.

The Gault Nature Reserve is an old-growth and unmanaged forest located on Mont Saint-Hilaire in the Saint-Lawrence Valley southeast of Montreal, Canada. At about 1000 ha in size, it is the larger of the two forested properties and is used for many recreational and research purposes. It was donated to McGill University in 1958 with the aim to preserve over 600 different plant species, including many threatened and vulnerable species (Gault Nature Reserve 2019). The Gault Nature Reserve contains the only remaining old growth sugar maple-hickory forest in the Saint-Lawrence Valley. Sugar maple (*Acer saccharum*) and American beech (*Fagus grandifolia*) are the dominant tree species in the forest. The eastern side of the Gault Nature Reserve is closed to the public, but access is permitted for researchers. The western side of the Gault Nature Reserve is open for public access and contains trails and hiking paths. The entire forest is protected in the sense that no form of deforestation is permitted, including selective cutting.

The final property I studied was the Macdonald Campus Farm, which is the largest agricultural property on the western region of the Island of Montreal, located in Saint-Anne-de-Bellevue. The property consists of around 230 ha of fruit, vegetable, and pasture fields. The farm provides areas for agricultural research and produces a large supply of the fresh produce served on the university's campuses. Due to the limited biomass in the form of trees and other perennial vegetation on this property, I used the Macdonald Campus Farm to investigate for the potential C sequestration from afforestation of the agricultural fields.

2.2 Selecting Forest Plots

For each of the two forest sites, I used a stratified random sampling design (stratified by forest type) to select plots. First, I gathered data within ArcGIS 10.1 to map the different land uses and forest types in each study area (forest type, field, recreational park, etc.). I then mapped the existing permanent forest plots on both properties (Figure 6 & 7; Data Reference: the director of the Morgan Arboretum, the associate director at the Gault Nature Reserve, and the researchers who maintain the existing databases for the forests). The Morgan Arboretum and the Gault Nature Reserve use different naming conventions to identify the dominant forest types based on how the forest is used and managed. Since my goal was to estimate overall C sequestration for the study areas rather than to compare C sequestration of particular forest types between the two study areas, I used the existing forest type classifications in the data provided.

2.2.1 Morgan Arboretum

The Morgan Arboretum includes eight different forest types ranging from softwood and hardwood plantations, to mixed deciduous maple and beech forests (Table 1). In addition to forested land cover, the Morgan Arboretum contains non-forested areas for public access, land clearings, and parking lots. Since these non-forested areas have little to no aboveground biomass, I excluded them from my C sequestration estimates. Researchers had previously established nine permanent forest plots in the Morgan Arboretum (Figure 6). These circular 400 m^2 (r = 11.28 m) plots were originally selected based on a random stratification by forest type. Within these plots, previous researchers collected data on tree species type and diameter at breast height (DBH) in 1980, 1998, and 2008. For a better representation of the forest types within this study area, I established 25 additional sampling plots with at least one forest plot per 5 ha in any given forest type. Overall, this provided a total of 34 plots for analysis (Table 1).

Table 1: The number of plots and the area under each of the different forest types in the Morgan Arboretum.

Forest Type	**Area (ha)**	**# of new plots**	**# of permanent plots**
Softwood Plantation	17.3	4	0
Sugar Maple (Sugar Bush)	23.1	4	1
Arboreta Garden	6.5	0	0
Sugar Maple and other Hardwoods	10.5	3	0
Hardwood Plantation	10.7	1	1
Tolerant Hardwood – red maple and beech	78.8	8	3
Red Maple, Hemlock, and Beech	31.8	3	4
Mixed Regenerated Red Maple	2.5	1	0
Red Maple, Shagbark Hickory, and Black Ash	6.9	1	0
Clearing	10.2	0	0
Road and Parking	0.8	0	0
Total	199.1	25	9

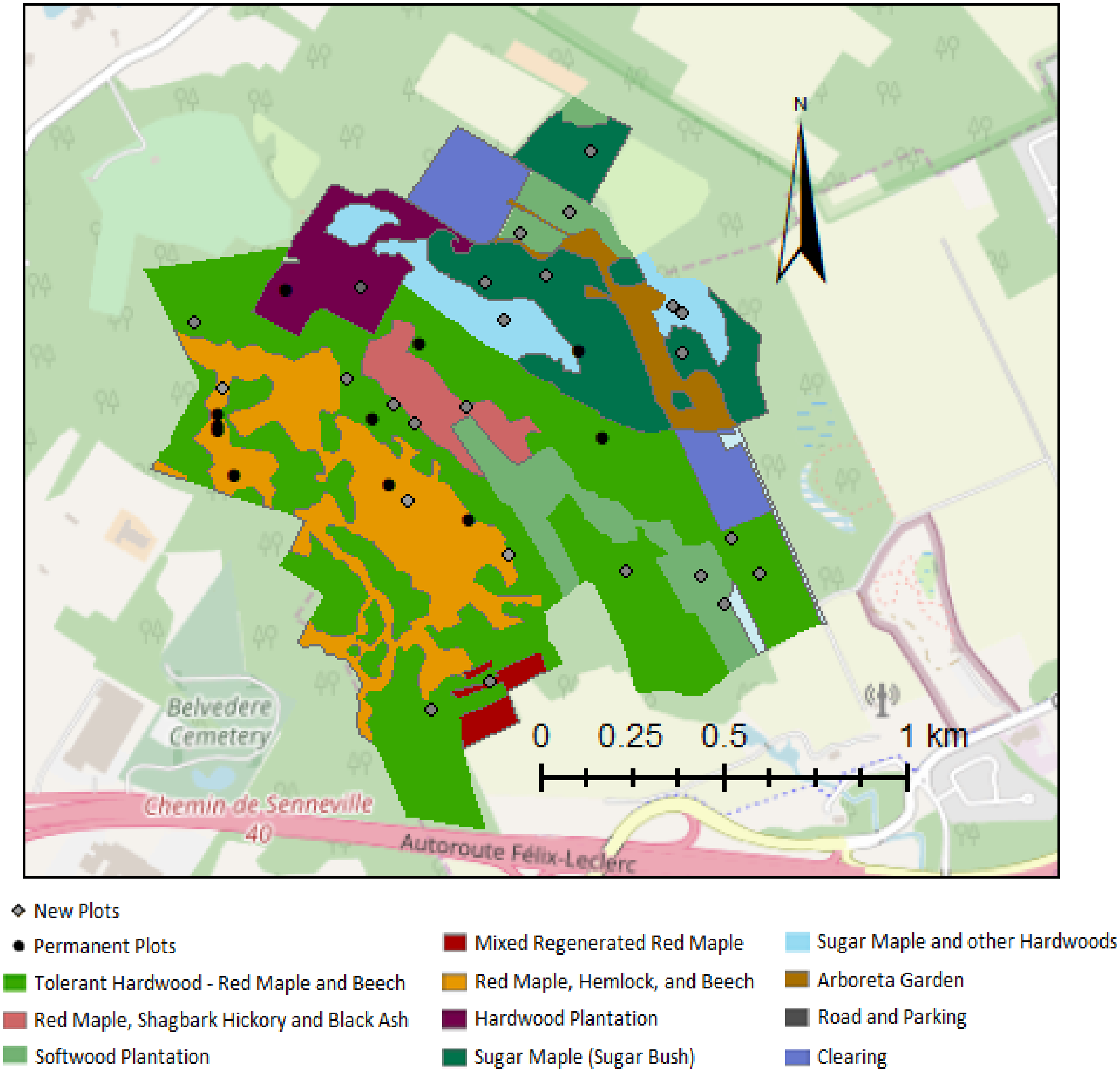

Figure 6. Land-use map of the Morgan Arboretum located in Saint-Anne-de-Bellevue showing both permanent and newly selected forest sampling plots.

2.2.2 Gault Nature Reserve

The Gault Nature Reserve has fewer forest types than the Morgan Arboretum; at Gault Nature Reserve, there are five different forest types mapped. Lac Hershel is located at the center of the forest; the remainder of the property consists primarily of forested areas. Researchers previously established eight permanent forest plots (400m^2), where they collected data on tree species and DBH in 2002 and 2007. I also established new plots in the Gault Nature Reserve; since the Gault Nature Reserve has fewer forest types than the Morgan Arboretum and because the property is much larger. I ensured that there was at least one forest plot per every 25 ha of a given forest type at the Gault Nature Reserve (rather than one plot for every 5 ha at the Morgan Arboretum). I used stratified random sampling (stratified by forest type) to determine the locations of 29 new forest plots. This provided a total of 37 sampling plots within the Gault Nature Reserve (Figure 7).

Table 2: The number of plots and the area under each of the different forest types in the Gault Nature Reserve.

Forest Type	**Area (ha)**	**# of new plots**	**# of permanent plots**
Maple and Beech	394.9	13	3
Oak and Pine	125.5	3	2
Maple and Ash	285.7	7	1
Maple, Oak, and Beech	106.6	5	0
Maple and Oak	70.4	1	2
Other	5.3	0	0
Total	**988.4**	**29**	**8**

Figure 7. Land use map of the Gault Nature Reserve located on Mont Saint-Hilaire, Quebec showing both permanent and newly selected forest sampling plots.

2.3 Calculating C sequestration in Forest Plots

In this study, C sequestration was calculated differently based on the type of plot. I used plot-based data from both new and permanent plots (set up and measured in previous years) to calculate C sequestration. I also calculated both net and gross C sequestration, where *net* C sequestration accounts for C emissions from decomposition of the different forest types and *gross* C sequestration does not account for any C emissions. These were calculated differently in permanent versus newly established plots (Section 2.3.3).

2.3.1 C sequestration as difference in C storage

Aboveground C sequestration is measured by estimating the difference in current C storage and C already stored in previous years (Donovan 2012; Elbasiouny et al. 2017). To calculate C storage, I first estimated the biomass of each tree using a set of species-specific allometric equations (Lambert et al. 2005). Using the DBH and species identity as input data, these equations calculate the aboveground biomass for different parts of each individual tree (stem, foliage, branch, wood, and bark). I then converted the overall biomass to the mass of C by multiplying the biomass by the average percent C within each tree species, using data for C from Lamlom & Savidge (2003). If I found a tree species in the field that was not listed in Lambert et al. (2005) or in Lamlom & Savidge (2003), I applied the allometric equation coefficients or the C percent value from the most closely related species listed. For multi-stemmed trees, I calculated C storage separately for each stem and then summed the values together to estimate the total C storage.

2.3.2 Field Data Collection for Plots at Both Study Areas

I conducted fieldwork from May to August 2018. In both the permanent forest plots and in my newly created plots, I measured the DBH and recorded the species identity of all trees ≥ 9cm. I used a hand-held Global Positioning System (GPS) to locate the center of each forest plot. Then I placed a flag at the centre, outlined the 400 m^2 circular plot by placing a measuring tape of 11.28 m from the center, and then circled that around to get the exact boundaries of the plot. I then placed flags to mark the boundaries of the plot.

2.3.3 Different Components of C sequestration

In this study, I present both net and gross C sequestration results and evaluate the difference between net and gross rates among the forest types and between study areas. The *net* C sequestration accounts for C emissions from decomposition of the different forest types. The *gross* C sequestration does not account for any C emissions. Estimating the net and gross C sequestration helps in evaluating the impact of C emissions from tree mortality and decomposition based on forest type and management. I use different methods to calculate for net and gross C sequestration. Because the permanent plots have existing biomass data from previous years, I can calculate net C sequestration (Section 2.3.2.1). The new plots do not have previous biomass data; therefore, in these plots, I can only calculate gross C sequestration, and must estimate the net C sequestration (Section 2.3.2.2).

2.3.3.1 Methods for Permanent Plots

For each of the permanent forest plots, I calculated the annual *net* C sequestration based on the change in C storage between 2018 and the year of the most recent previous field measurements in each study area (i.e. 2008 at the Morgan Arboretum and 2010 at the Gault Nature Reserve). I then divided this change in C storage by 10 years (for plots at the Morgan Arboretum) or by 8 years (for plots at the Gault Nature Reserve) to estimate the average annual net C sequestration for each plot.

2.3.3.2 Methods for Newly-Created Plots

In newly-created plots, there were no data from previous years, so I used a slightly different method; I calculated the annual *gross* C sequestration based on the change in C storage from 2018 to 2008 based on individual tree growth over the past 10 years. I used a 10-year window because the last measurement year from the existing database for the permanent plots for both properties was, on average, 10 years prior (varies for different plots). Gross C sequestration for all the plots was calculated by gathering tree cores for tree ring analysis to estimate the change in diameter at breast height (DBH) needed to calculate for C storage (Lambert et al. 2005).

In order to calculate net C sequestration in these new plots, I also needed data on the rate of C emissions from the forests (e.g. as a result of decomposition). I estimated the annual a mount of C emissions for each forest type by calculating the difference between the net C sequestration and the gross C sequestration from the permanent plots. I used the same method of C sequestration calculation from the new plots (by assuming I did not have data from previous years and using the averaged measurements from the tree core analysis) in order to estimate the gross C sequestration for the permanent plots. The net C sequestration is estimated using the permanent plot data collected from previous years and the data collected in 2018 to calculate C storage; whereas, the gross C sequestration is calculated by using the tree core analysis to estimate for the C storage from 10 years prior and comparing that with the 2018 data. I then calculated the value for C emissions by using the following equation:

$$C_{net} = C_{gross} - C_{emissions}$$

Using an increment borer, I collected tree cores from the three to four largest and most dominant (tallest and largest DBH) trees of each species within each new plot. The number of tree cores collected per plot varied based on the number of large trees and the tree species diversity within the plot. Approximately four tree cores were collected from the forest plots with higher tree species diversity and three cores were collect from forest plots with less tree species diversity. I mounted the cores on a wooden plaque and then used a mechanical hand-held sander to sand down the tree cores for clearer visibility of the individual rings. To increase the accuracy of the measurements, I scanned the plaques containing the cores and counted the rings using the tree-ring image analysis program, WinDENDRO. I counted the rings back to 10 years from the pith of the core and measured the difference to estimate growth over the past 10 years, doubling the length to account for the change in diameter (rather than the radius) between 2008 and 2018.

2.4 Scaling C sequestration from Plots to the Study Areas

Once I calculated the plot-based measurements and found the average C sequestration for each forest type, I needed to put this information together to find the total C across the study area. To find the total C sequestration across the eight forest types at the Morgan Arboretum and the five forest types at the Gault Nature Reserve, I calculated a weighted sum. Ai is the area of forest type i, Ci is the average C sequestration of forest type i, and n is the number of forest types within the study area:

$$Total\ C\ Sequestration = \sum_{i=1}^{n} Ai * Ci$$

I calculated upper and lower estimates of C sequestration since the average values calculated by forest type come from a sample; therefore, the measured average of the sample may be slightly different from the true average of the population. To estimate for the range of possible C sequestration at each study area, I calculated the 95% confidence intervals of the mean for each forest type. I repeated the weighted sum calculations with all the upper 95% confidence intervals to get the lower and upper bounds of possible values.

I assessed for significant differences in net and gross C sequestration between study areas and forest types in order to see if forest type has a significant influence on C sequestration. I used an analysis of variance (ANOVA) test to evaluate if there were any significant differences in C sequestration between the forest types of each study area using the average annual net and gross C sequestration for all the plots measured. I also used follow-up Tukey-Kramer tests to evaluate which of the forest types were significantly different from the other. The ANOVA test is used since it best represents the comparison of means from multiple groups and the Tukey-Kramer test is used to determine which of the pairs within a group have statistically significant differences (Driscoll 1996).

2.5 Potential C sequestration

In addition to calculating current C sequestration, I also estimated the potential to increase C sequestration through the creation of new forest plantations on currently unforested portions on McGill University properties. Within each of the two study areas for this research question (the Morgan Arboretum and the Macdonald Campus farm), I selected zones with potential for afforestation based on consultations with the director of the Morgan Arboretum and the director of the Macdonald Campus Farm. The directors indicated which areas are not actively being used by the public, for scientific purposes, or are not as agriculturally or ecologically productive as other areas, and could therefore potentially be afforested.

To assess the potential to increase C sequestration, I used the average net C sequestration per hectare that I calculated for the "Hardwood Plantation" and "Softwood Plantation" forest types at the Morgan Arboretum. I then multiplied the C sequestration per hectare for these forest types by the area of the non-forested, but potentially afforestable, zones at McGill. I assessed two different scenarios for plantations within the Morgan Arboretum and the Macdonald Campus Farm. In Scenario 1, I assessed the potential C sequestration on the areas of the Macdonald Campus Farm and the Morgan Arboretum that have the greatest capacity for plantations. This includes the two clearings (~10 ha) at the Morgan Arboretum (Figure 6) and the three zones (~8 ha) within the Macdonald Campus Farm (Figure 8). At the Macdonald Campus Farm, these three units are zones that have limited agricultural production, are not easily accessible for farming, or are not essential for farm productivity. In Scenario 2, I calculated the potential for C sequestration if there was a hardwood or softwood plantation on all non-forested zones of the Morgan Arboretum and the Macdonald Campus Farm. This includes the same two clearings at the Morgan Arboretum as Scenario 1, as well as all agricultural fields of the Macdonald Campus Farm.

Figure 8. Land use map of the Macdonald Farm from 2018 in Saint-Anne-de-Bellevue, Quebec. Areas for potential plantations in Scenario 1 indicated by the red circles.

3. RESULTS

The gross C sequestration from both forested properties – the Morgan Arboretum and the Gault Nature Reserve – is collectively is around 2390 Mg C yr^{-1}, or 2.58 Mg C ha^{-1} yr^{-1}. The total net C sequestration from both forests is approximately 717 Mg C yr^{-1}, or 1.68 Mg C ha^{-1} yr^{-1}. This is equivalent to capturing just under 5% of the university's annual C emissions (56,004 Mg C ha^{-1} yr^{-1}) in 2018 (McGill GHG Inventory Report 2018). Gross C sequestration at the Morgan Arboretum ranges from 2.46 to 4.06 Mg C ha^{-1} yr^{-1} and C emissions per hectare range from -2.35 to 0.55 Mg C ha^{-1} yr^{-1} (Table 3). At the Gault Nature Reserve, gross C sequestration ranges from 1.35 to 2.54 Mg C ha^{-1} yr^{-1} and C emissions per hectare range from 0.99 to 2.64 Mg C ha^{-1} yr^{-1} (Table 4). The negative C emission values at the Morgan Arboretum means that the net C sequestration is greater than the gross C sequestration. The gross C sequestration is what is being sequestered by the trees into the aboveground C biomass; whereas the net C sequestration accounted for C lost from dead trees. This suggests that there has been little C lost from dead trees, but rather an increase in aboveground C over time (net increase in C sequestration).

Table 3. Annual gross C sequestration and C emissions from decomposition for the eight different forest types at the Morgan Arboretum.

Forest Type	Gross C sequestration (Mg C ha^{-1} yr^{-1})	C emissions (Mg C ha^{-1} yr^{-1})
Tolerant Hardwood – Red Maple and Beech	2.46	-2.35
Mixed regenerated Red Maple	4.06	0.018
Red Maple, Hemlock, and Beech	2.75	0.55
Softwood Plantation	3.50	0.018
Hardwood Plantation	2.53	0.39
Sugar Maple (Sugar Bush)	3.04	-0.72
Red Maple, Shagbark Hickory, and Black Ash	3.45	0.018
Sugar Maple and other Hardwoods	3.72	0.018

Table 4. Annual gross C sequestration and C emissions from decomposition for the five different forest types at the Gault Nature Reserve.

Forest Type	Gross C sequestration ($Mg\ C\ ha^{-1}\ yr^{-1}$)	C emissions ($Mg\ C\ ha^{-1}\ yr^{-1}$)
Maple and Beech	2.04	0.99
Oak and Pine	2.54	2.64
Maple and Ash	2.15	1.77
Maple, Oak, and Beech	1.73	2.76
Maple and Oak	1.35	1.57

3.1 C sequestration between forests

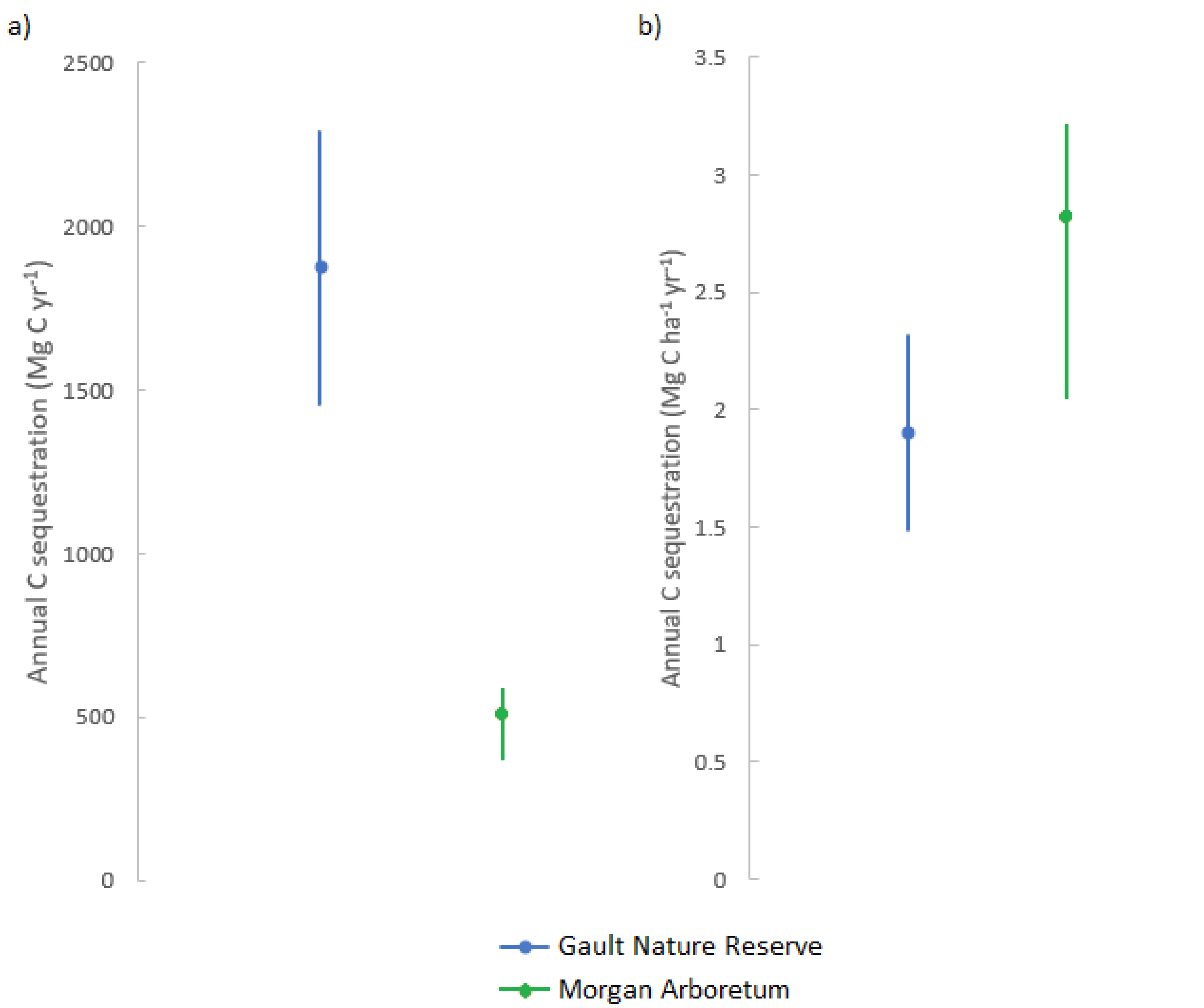

Figure 9. (a) the mean annual gross C sequestration and, (b) the mean annual gross C sequestration per hectare for the Gault Nature Reserve and the Morgan Arboretum. Lines represent the 95% confidence interval around the mean.

Overall, Gault Nature Reserve has a higher annual gross C sequestration (1877 Mg C yr^{-1}) than the Morgan Arboretum (513 Mg C yr^{-1}) (Figure 9a). However, the annual gross C sequestration *per* hectare at the Morgan Arboretum is higher, 3.19 Mg C ha^{-1} yr^{-1}, as compared to 1.96 Mg C ha^{-1} yr^{-1} for the Gault Nature Reserve (Figure 9b).

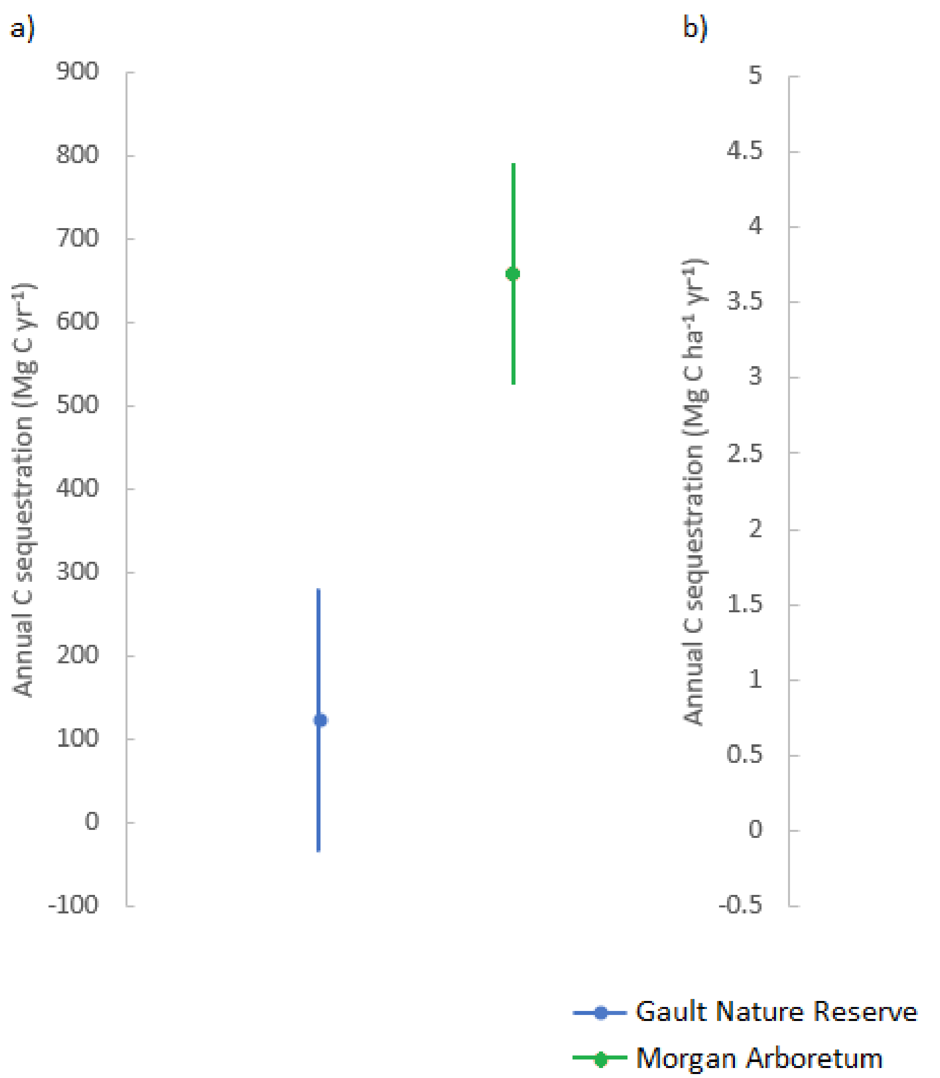

Figure 10. (a) the mean annual net C sequestration and, (b) the mean annual net C sequestration per hectare for the Gault Nature Reserve and the Morgan Arboretum. Lines represent the 95% confidence interval around the mean.

The annual net C sequestration at the Gault Nature Reserve (25 Mg C yr^{-1}) is significantly lower than the Morgan Arboretum (690 Mg C yr^{-1}) (Figure 10a). Per hectare, the annual net C sequestration at the Gault Nature Reserve is 0.016 Mg C ha^{-1} yr^{-1} and at the Morgan Arboretum is 3.17 Mg C ha^{-1} yr^{-1} (Figure 10b).

C emissions from decomposition per hectare from the Gault Nature Reserve is 1.77 Mg C ha^{-1} yr^{-1}, which is significantly higher than the Morgan Arboretum, where there is decomposition of 0.0175 Mg C ha^{-1} yr^{-1}. The negative net C sequestration values for the Gault Nature Reserve indicates higher C emissions from decomposition than is sequestered by the forest.

3.2 C sequestration among different forest types

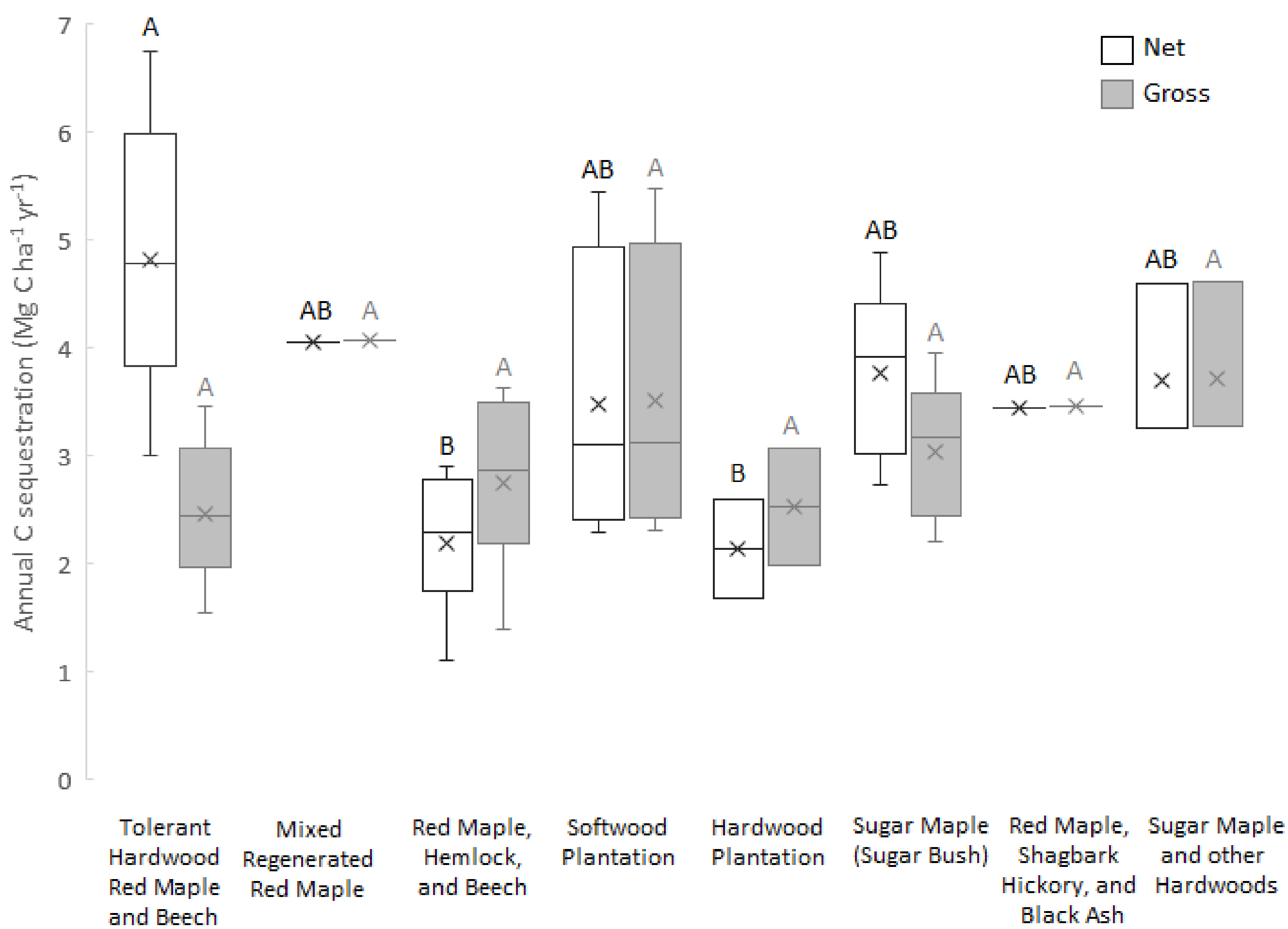

Figure 11. Annual **net** and **gross** C sequestration of the different forest types at the Morgan Arboretum. The middle line indicates the median and the x indicates the mean. The ANOVA test

for the gross C sequestration showed no significant differences between forest types ($P>0.05$); but the net C sequestration showed a couple of significant differences ($P<0.01$).

There are no significant differences in annual gross C sequestration per hectare between any of the eight different forest types at the Morgan Arboretum (Figure 11). However, in general, the “Mixed Regenerated Red Maple” forest type has the highest rate (4.06 Mg C ha^{-1} yr^{-1}) and “Tolerant Hardwood-Red Maple and Beech” forest type has the lowest annual gross rate per hectare (2.46 Mg C ha^{-1} yr^{-1}). The “Softwood Plantation” forest shows the greatest variability in terms of gross sequestration between plots. The “Red Maple, Hemlock, and Beech”, the “Hardwood Plantation”, and the “Sugar Maple (Sugar Bush)” forests have generally a similar variability. There is a lack of variability in the “Mixed Regenerated Red Maple” and the “Red Maple, Shagbark Hickory, and Black Ash” forest types since there was only a single plot measured for each of the forest types.

There is a slightly lower overall average annual *net* C sequestration at the Morgan Arboretum compared to the annual *gross* C sequestration with some notable exceptions. There are no significant differences in net C sequestration between the forest types except for the “Red Maple, Hemlock, and Beech” and “Hardwood Plantation” forest types which are significantly lower than the “Tolerant Hardwood – Red Maple and Beech” forest type. The forest type with the highest annual net C sequestration is the “Tolerant Hardwood – Red Maple and Beech” with a rate of 4.81 Mg C ha^{-1} yr^{-1}. The forest type with the lowest annual net C sequestration is the “Hardwood Plantation” with a rate of 2.14 Mg C ha^{-1} yr^{-1}. The variability for the “Softwood Plantation” forest type remains generally the same between the net and gross C sequestration; however, the “Tolerant Hardwood - Red Maple and Beech” forest type shows an increase in variability for the net sequestration compared to the gross sequestration between the plots within that forest type.

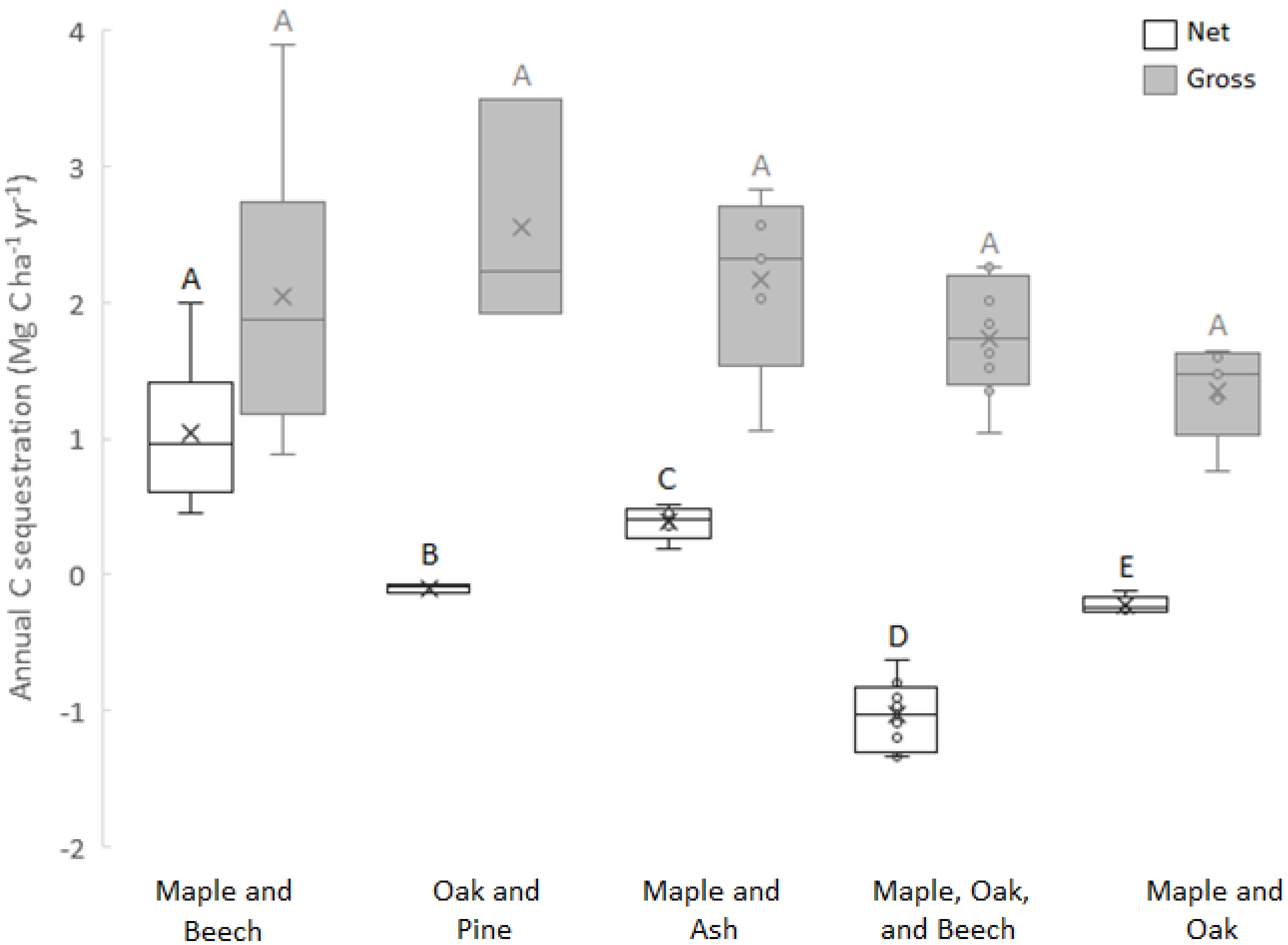

Figure 12. Annual **net** and **gross** C sequestration of the different forest types at the Gault Nature Reserve. The middle line indicates the median and the x indicates the mean. The ANOVA test for the gross C sequestration showed no significant differences between forest types (P>0.05); but the net C sequestration showed significant differences between all forest types (P<0.01).

There is little variability in the gross C sequestration per hectare between the different forest types at the Gault Nature Reserve (Figure 12). The Maple and Beech forest type shows the greatest variance in terms of the measured plots and the least variance with the “Maple and Oak” forest type. The mean gross C sequestration between all five forest types show no significant difference between each other ($p>0.05$) and appear to be relatively similar, with the largest visible difference being between the "Maple, Oak and Beech" and the "Maple and Oak" forest type.

There is greater variability in the annual net than the annual gross C sequestration per hectare between the different forest types at the Gault Nature Reserve. The negative sequestration values shown suggest an increase in emissions due to decomposition of dead trees rather than a positive value indicating a net positive C sequestration over the past year from that forest type. This is particularly dominant with the "Oak and Pine", the "Maple, Oak, and Beech", and the "Oak and Maple" forest types. All forest types at the Morgan Arboretum had positive C sequestration. All five of the forest types are significantly different from one another ($p<0.05$) with Maple and Ash forest type having the lowest net C sequestration and Maple and Beech forest type having the largest.

3.3 Scenarios to increase C sequestration

Together, the Morgan Arboretum and the Gault Nature Reserve sequester a total of 717 Mg C yr^{-1}. If McGill planted forests at the Morgan Arboretum and the Macdonald Campus Farm, C sequestration of current university emissions could result in an increase between 1% and 5%.

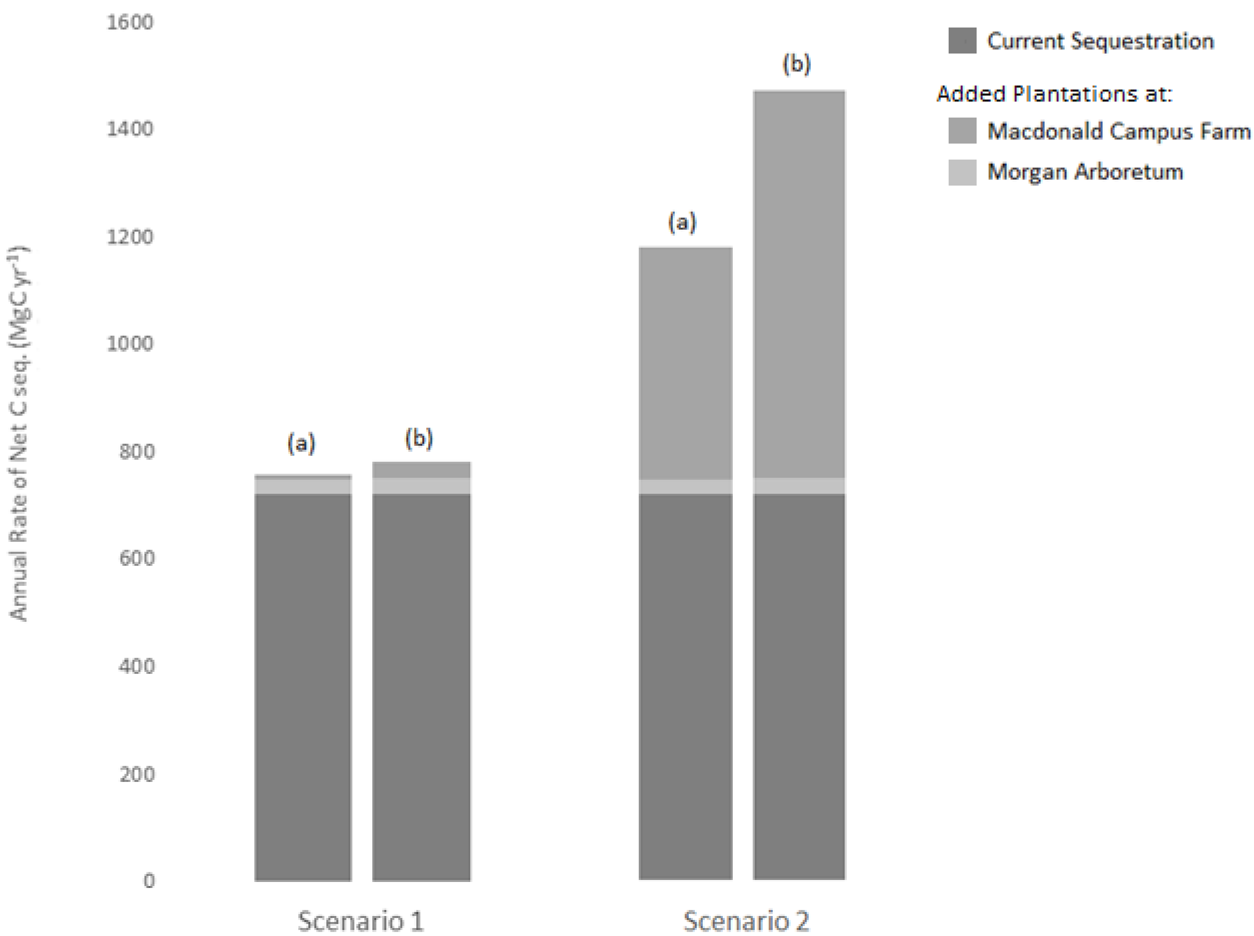

Figure 13. C sequestration for **Scenario 1** and **Scenario 2**. Scenario 1 is the comparison of annual **net** C sequestration if (a) hardwood versus (b) softwood forests were planted in the clearings of the Macdonald Campus Farm and the Morgan Arboretum. Current sequestration is C sequestration from all study areas in all forest types and the added plantations represents the afforested areas at the Morgan Arboretum and the Gault Nature Reserve

The total annual net C sequestration would increase more from an added softwood plantation, which increases C sequestration by 63.1 Mg C yr^{-1} to a total of 780 Mg C yr^{-1}, than from an added hardwood plantation, which increases C sequestration by 42.7 Mg C yr^{-1} to a total of 760 Mg C yr^{-1} (Figure 13). Afforestation in Scenario 1 would result in an increase in the net C sequestration of McGill University's current emissions from the current 4.7% of total emissions sequestered to around 5.0% from an added hardwood plantation and around 5.1% of total emissions sequestered from an added softwood plantation.

In scenario 2, an added hardwood plantation would increase the overall net C sequestration to 1,150 Mg C yr^{-1} and an added softwood plantation would increase the net sequestration to 1,430 Mg C yr^{-1} (Figure 15). Afforestation in Scenario 2 would result in approximately a 3.0 to 5.0% increase in sequestration from the current net C sequestration of 4.7% to about 7.6% from an added hardwood plantation and to about 9.4% of emissions sequestered from an added softwood plantation.

4. DISCUSSION

McGill University is not currently C neutral, and only a small portion of its annual emissions are sequestered on campus, or even have potential to be sequestered on campus. In fact, of the 56,004 Mg CO_2 emitted by the University each year, only about 4% of these emissions are being sequestered by the forested areas at the Morgan Arboretum and the Gault Nature Reserve. Even if McGill University was to apply the afforestation envisioned in Scenario 1 and Scenario 2, the amount of total annual emissions sequestered would only increase to just over 5% and 9% of total emissions, respectively. That is, McGill University's current and potential annual sequestration is small relative to its annual emissions.

4.1 Gross and Net C sequestration at the Gault Nature Reserve and Morgan Arboretum

Although the Gault Nature Reserve is a significantly larger property than the Morgan Arboretum and sequesters more C overall, the gross and net annual C sequestration *per hectare* is significantly lower in the Gault Nature Reserve than the Morgan Arboretum. Differences in the gross sequestration might be due to the differences in tree mortality between managed forests with plantations (Morgan Arboretum) and unmanaged forests (Gault Nature Reserve), as well as the lower tree density and older age of the Gault Nature Reserve. The Morgan Arboretum is a managed forest with plantations and occasional harvesting of individual trees throughout the property, resulting in a forest with an uneven age and variability in terms of its growth, mortality, and therefore, differences in C sequestration between forest stands. The higher density of trees at the Morgan Arboretum means there is greater biomass per hectare for C capture. The Gault Nature Reserve, which is an unmanaged forest without any plantations, has larger trees and a less dense forest; therefore, there is greater biomass per tree and less biomass per hectare than at the Morgan Arboretum.

The difference between the two forests is greater for net C sequestration than for gross C sequestration since net sequestration incorporates the C emissions from decomposition, which is around a hundred times higher at Gault Nature Reserve than it is at Morgan Arboretum. Although the exact age of Gault Nature Reserve forest is not known, it is classified as an old-growth forest (Gault Nature Reserve 2019). The older and larger trees in old-growth forests typically capture C at a slower rate than the younger and faster growing trees in managed forests or plantations (Pukkala 2017). Old growth and unmanaged forests, like that of the Gault Nature Reserve, will continue to sequester C for centuries; however, both gross and net C sequestration will gradually decrease as the growth rate of forests decline over time (Chatterjee et al. 2009; Harmon & Marks 2002; Luyssaert et al. 2008). Generally, old-growth forests decrease their C sequestration, ultimately reaching a point of neutrality where the amount of C they are taking in is balanced with the amount of C they are releasing from decomposition and respiration (Jandl et al. 2007). Old growth forests also usually have a higher number of dead trees which increases the C release from decomposition (Hansen et al. 1991).

4.2 Gross and Net C sequestration Between Forest Types

The results from this study show that the net C sequestration at the Morgan Arboretum and the Gault Nature Reserve is significantly influenced by forest type, as well as stand age, density, decomposition and mortality rate, and forest management. This echoes earlier findings, which showed that C sequestration in any given location is mainly controlled by stand age, density, and management practices, all of which influence the live biomass, which ultimately plays a large role in determining C sequestration in forests (Chatterjee et al. 2009). Although my study found some differences in net C sequestration between forest types at the Gault Nature Reserve, there was no significant difference between the gross C sequestration among the different forest types of either study area. This lack of differences in gross C sequestration between forest types might be explained by the imprecision in forest composition and boundaries with the current naming convention. For instance, the “Maple and Beech” forest type within the Gault Nature Reserve mostly consisted of maple trees and some oak trees; however, very few beech trees. For the “Maple and Oak” forest type within the Gault Nature Reserve, the three new plots created had either only oak trees or only maple trees, rather than a mix of both. The similarity between tree composition (mostly maple and oak trees) of the measured plots in the “Maple and Beech” forest type and in the “Maple and Oak” forest type can explain the lack of significant differences in the C sequestration between the two forest types.

4.2.1 *Morgan Arboretum*

The total and per hectare aboveground C sequestration at the Morgan Arboretum is not significantly influenced by forest type. There are no significant differences in the *gross* C sequestration among forest types at the Morgan Arboretum. There are, however, some statistical differences in the *net* C sequestration between the forest types, including the Tolerant Hardwood –

Red Maple and Beech forest type, which is significantly higher than the Red Maple, Hemlock, and Beech forest type and Hardwood Plantation. The Tolerant Hardwood – Red Maple and Beech forest type showed an increase from gross to net C sequestration once C emissions from decomposition were included. This forest type had the lowest negative emissions compared to the seven other forest types at the Morgan Arboretum. The negative C emission rate suggests that the net C sequestration is higher than the gross C sequestration. The low negative C emissions rate for the Tolerant Hardwood – Red Maple and Beech forest type suggests that there is a low mortality rate and a high potential for C sequestration. However, this could be an error as the high net C sequestration compared to the lower gross C sequestration would mean that there was an increase in aboveground C biomass between the two measurement years. Unless there was a significant increase in growth of the existing trees in the forest type, or an increase in new trees within the forest type, it is likely that there was an error in locating the exact plot and method data gathering between the two separate years of data collection.

Although the Softwood and the Hardwood Plantations are the youngest forest types at the Morgan Arboretum and would likely have a higher net C sequestration, they have similar net and gross C sequestration per hectare as the other forest types. The Softwood Plantations did, however, have the highest variability in gross and net C sequestration. For data collection of the Softwood Plantation, four plots were randomly selected within the forest type; however, only one of the plots contained softwood trees of Norway spruce and hickory, exclusively. The other three plots within the Softwood Plantation forest type included a 60% majority softwood tree species of pine, spruce, or hemlock and about 40% of the species composition within the plots is hardwood tree species of maple or elm. This difference among plots might explain the high variability in softwood C sequestration. As for the Hardwood Plantation, which had less variation in its results, had the two plots include exclusively hardwood tree species ranging from maple, oak, ash, and basswood.

The Tolerant Hardwood - Red Maple and Beech forest type also has a high variability and the highest net C sequestration among the different forest types. However, it has the lowest gross rate indicating that the C emissions from decomposition are relatively low in the Tolerant Hardwood - Red Maple and Beech forest type. The high net compared to the low gross C sequestration suggests that the Tolerant Hardwood - Red Maple and Beech forest type is very productive and has been sequestering more C than calculated in the last 10 years than what we saw with the gross C sequestration estimate. The rest of the forest types have relatively similar gross and net C sequestration, since overall C emissions from decomposition in the Morgan Arboretum are relatively small.

4.2.2 *Gault Nature Reserve*

The total and per hectare aboveground *net* C sequestration at the Gault Nature Reserve is significantly influenced by forest type. However, there is no significant difference in the *gross* C sequestration among forest types at the Gault Nature Reserve. The lack of significant differences in the *gross* C sequestration between forest types indicates that the rate of C emissions from decomposition have a significant influence on *net* C sequestration.

The net C sequestration is highest for the Maple and Beech forest type, but lowest for the Maple, Oak, and Beech forest type. The negative net C sequestration for the Maple, Oak, and Beech forest type is a result of the higher C emissions from the forest compared to sequestration. Additionally, the Oak and Pine, as well as the Maple and Oak forest types are also emitting more C annually than they are sequestering. Among these three different forest types, the common dominant tree species is the oak (*Quercus*). There is limited literature to explain the correlation of negative net

C sequestration with oak trees; however, one study looked at C sequestration and storage in old-growth hardwood, mixedwood, and softwood forest plots in New Brunswick. The results found that, over a 20-year period, around 25% of the 602 plots measured were actually sources of C and about 7% were C neutral (Bashir et al. 2019). Other studies found that the leading causes of oak tree mortality in Europe and North America is due to the presence of a pathogen, *Phytophthora ramorum* (Eliott et al. 2012; Vettraino et al. 2002). Unlike many other pathogens that target the root systems of trees, *P. remorum* specifically targets the aboveground biomass of tree and plant species (Eliott et al. 2012). There have not been any studies that have looked at the presence of *P. remorum* with oak tree species mortality at the Gault Nature Reserve; however, I would suggest that further research should look into this and any other external influences that effect oak mortality.

4.3 Potential for Increased C sequestration

For Scenario 1, afforestation on five selected areas of the Macdonald Campus Farm and the Morgan Arboretum, and for Scenario 2, afforestation on two areas at the Morgan Arboretum and on the entire Macdonald Campus Farm, the results demonstrate that there is potential for an increase in annual net C sequestration through afforestation on McGill University's existing properties. A study done on European forests from 1950-2010 demonstrated that increased afforestation on cropland is the main contributor to forest C sequestration (Fuchs et al. 2016). My study also showed that C sequestration would increase most on these properties from a softwood plantation compared to a hardwood plantation. Softwood trees typically have a higher range of C content and can therefore sequester C at a greater rate. The higher C content in softwood trees is due to their higher lignin content which is a polymer found in trees and is responsible for the wood and bark firmness (Lamlom & Savidge 2003).

4.4 Limitations

The focus of this study was exclusively aboveground C sequestration in forests; however, approximately 70%, of the CO_2 in the atmosphere is captured and stored in soil and grasslands (Fierer et al. 2009; Jobbágy & Jackson 2000; De Deyn et al. 2008). Thus, I almost certainly underestimated C sequestration at McGill. This study also does not account for the C sequestration from the other areas of the university's campus, including the grassy fields of the downtown and the Macdonald Campuses.

I would recommend that future research expands the potential for C sequestration throughout the entire campus including the Downtown and Macdonald Campus grassy areas, and potentially below-ground C sequestration. This study solely focused on forests in rural areas, however, there is growing research looking at quantifying C sequestration from urban forests as they can be effective in climate change mitigation (Pasher et al. 2014; Nowak et al. 2002; Nowak et al. 2013). Quantifying the urban trees at McGill University, like on the Downtown and Macdonald Campus, can help in better understanding on-campus C sequestration with meeting C neutrality targets. I would also suggest that future research works more into finding the causes of tree mortality, especially with regards to oak trees which seem to be causing a significant drop in C sequestration at the Gault Nature Reserve. Moreover, research in forest sciences is looking at the capacity for urban trees and forests to effectively sequester and store C (Nowak et al. 2018; Pasher et al. 2014).

It is challenging to quantify exactly the different sources and proportions of C that are emitted from forests. Pests and diseases (Hicke et al. 2012), decomposition (Burke & Raynal 1994), respiration (Reichstein et al. 2005), natural disasters (Bowman et al. 2009), and climate change (Allen et al. 2010; Alongi 2008) can influence the mortality rate of forests. This study calculates mortality based on various assumptions, including: (1) when a tree is decomposing, I assumed that all of the CO_2 is emitted into the atmosphere instead of some of it being taken into the soil, and (2) when a tree dies, I assumed that it is completely decomposed from the year of the last measurements to the time of the most recent measurement.

The data used to create the map for the land-use area for the Gault Nature Reserve was created over 20 years ago and the Morgan Arboretum land use map was created about 50 years ago. The lack of up –to-date digital maps indicating the different forest types at Gault Nature Reserve and the Morgan Arboretum could result in changes in the calculated C sequestration by the variability in tree composition and boundaries of the different forest types. It also limited me to using the identified forest types which prevented the opportunity to compare the C sequestration of the forests types if they used the same naming system. In addition, some of the forest types only had one measured plot compared to others which had as many as 16 plots. The number of plots per forest type was determined based on the area; however, it is difficult to draw an accurate conclusion of C storage and sequestration data given only one measured value.

Finally, I would suggest that McGill University and the sustainability groups at the university push for afforestation projects identified in the five areas of Scenario 1. As this study suggests, it would be best to implement a softwood plantation in order to maximize C sequestration. Further research and consultations would be required to see the feasibility of plantations within these areas and whether it could interfere with other previously existing habitats.

5. CONCLUSION

This study estimated aboveground forest C sequestration in the context of meeting local climate change mitigation targets, such as C neutrality at McGill University. Forest management, stand age, mortality rate, and forest density have the greatest influence compared to forest composition when it comes to net aboveground C sequestration within the Morgan Arboretum (managed) and the Gault Nature Reserve (unmanaged). Through implementation of afforestation projects, particularly softwood plantations, overall C sequestration would increase, as well as provide opportunities for local and more transparent C offsetting projects. Higher education institutions, like McGill University, have an advantage and can benefit by supporting frameworks for climate change mitigation and sustainable innovation through management of their on-campus C sinks. Although the on-campus C sequestration is small relative to university emissions, there is a large educational value that comes from understanding the capacity for sequestration and what can be done to increase it. While reducing the university's overall C emissions is key when it comes to attaining C neutrality, this project provides the necessary research in order to create a starting point for local and on-campus afforestation C offsetting projects that can have a bottom-up approach to tackling climate change.

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CONTRIBUTIONS TO KNOWLEDGE AND FUTURE DIRECTIONS

Actions at the local and municipal level have a large influence on climate and environmental education and can have cascading effects on overall global climate change mitigation (Bezbatchenko 2010; Walton & Galea 2005; Stephens et al. 2008; UNESCO 2019). Universities, in particular, can have direct and indirect impacts on the environment through their actions on climate change due to the large size of universities, the population, and the various activities taking place within campuses (Alshuwaikhat, & Abubakar 2008). Institutions and universities around the world are right now looking at how to reach C neutrality by reducing GHG emissions and increasing C sequestration. Climate action plans at the university level often focus exclusively on methods of reducing GHG emissions; however, there is limited focus on methods of quantifying and increasing C sequestration within their properties. Identifying the potential for on-campus C sequestration can provide the required understanding for the value of C offsetting projects, such as afforestation, and the contribution of C sequestration in reaching C neutrality beyond reducing emissions. Purchasing external C offsets does not provide the same transparency (Broderick 2009; Mair & Wong 2010) and local benefits as on-campus C offsetting projects would.

This case study at McGill University quantified the current and potential for C sequestration within the university's owned properties in order to reach the target of C neutrality by 2040 (McGill University Office of Sustainability 2017). Although the net C sequestration at the two measured forested properties are small relative to annual emissions by the university, this research provides the necessary understanding of the positive implications of local offsetting projects such as afforestation. I suggest that McGill University aim to create an internal C offsetting program that focuses on increasing C sequestration within the Morgan Arboretum and the Macdonald Campus Farm. I also suggest that the university investigates and quantifies the potential for on campus urban trees to sequester C as it can have a real influence on climate change mitigation (Nowak & Crane 2002; Nowak et al. 2013)

Furthermore, the results from this study not only help to contribute to the understanding of how best to meet McGill University's C neutrality target, but it contributes to the research for different case studies evaluating local aboveground C sequestration measured in the field without using modelling software (Pasher et al. 2014). Better understanding how to evaluate C sequestration capacity and its potential is an important step towards encouraging increased policy within forestry activity and better climate change mitigation strategies (Running 2008).

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I would like to dedicate this thesis to Clark Bolliger. A fellow environmental scientist and a wonderful person I was lucky enough to know in my life. You were taken too soon and too suddenly, you should have been able to finish your master's too...

This one is for you, buddy.