Investigating the carbon sequestration and storage capacity of trees in a university campus environment

ENVS 4902 Environmental Science Undergraduate Honours Thesis

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Abstract

Rising anthropogenic greenhouse gas emissions are well established as the main driver of climate change, which has led to concentrated global and regional efforts to mitigate emissions. At a localized level, individual institutions are likewise engaging in a variety of mitigation practices, helping to support broader frameworks. These mitigation practices can include managing and enhancing local carbon sinks to offset site-specific greenhouse gas production. In particular, urban forests have been a focus in recent literature for their capacity to sequester and store carbon. This study quantified the carbon sequestration and storage capacity of the urban forest located on Dalhousie University's campuses in Halifax, Nova Scotia. Using an inventory of trees collected in the 2009-10 academic year, literature-derived growth rates were applied to approximate the current size of the campus trees. Carbon sequestration and storage values for individual trees were then estimated using i-Tree Eco v6 modelling software. The total annual sequestration rate was found to be less than 0.1% of Dalhousie's annual greenhouse gas emissions, suggesting a considerable need to increase the campus urban forest's capacity to act as a carbon sink. Additional relationships between carbon sequestration and characteristics such as diameter at breast height and species were also examined, suggesting that larger trees and species with rapid growth rates should be prioritized in maintaining the urban forest. This study is intended to be used as a baseline assessment of the on-campus urban forest carbon pool, from which future changes to the campus tree inventory can be made. Recommendations from this study may be used to inform updates to Dalhousie's natural environment management policies and shape future development of the campus carbon sink.

1.0. Introduction

Increasing concern surrounding anthropogenic greenhouse gas (GHG) emissions and their impact on the climate has led to the advent of numerous global mitigation efforts (IPCC, 2014; UNFCCC, 2015). While most mitigation strategies focus on reducing GHG emissions below set targets, the importance of managing carbon sinks is also a key component of the climate change narrative (Canadell & Raupach, 2008). The implementation of carbon pricing policies, such as the federal carbon tax recently announced in Canada, emphasizes the need to account for all carbon, including that which is naturally stored by the environment (Campion-Smith, 2016; Metcalf & Weisbach, 2009). In particular, forest stands have long been considered in climate research for their capacity to offset emissions by converting carbon dioxide (CO_2) to biomass (Kurz & Apps, 1999; Nowak & Crane, 2002). This research has led to the development of national forest inventory programs, such as Canada's National Forest Carbon Monitoring, Accounting and Reporting System (NFCMARS) (Natural Resources Canada, 2016a). However, considerably less research has been conducted on a smaller scale, particularly at the level of individual businesses or institutions.

Estimating the carbon sequestration capacity of individual trees associated with a particular institution, particularly those in urban areas, can be beneficial within the context of localized mitigation (Ravin & Raine, 2007). On international, national and regional scales, governments have established mitigation policies and signed onto various climate change agreements (UNFCCC, 2015; Council of the Federation, 2015; NSE, 2009). However, research has also highlighted the importance of developing climate change plans that are specific to individual organizations (Wilbanks & Kates, 1999; Measham et al., 2011). Information collected on the relative importance of trees to act as carbon sinks can be integrated into existing GHG inventories and can inform decision-making on forest management and climate change mitigation. This study therefore aimed to characterize the relationship between carbon sequestration by individual trees and anthropogenic GHG emissions in a localized environment, focusing on an urban university campus in Halifax, Nova Scotia.

Forests are an integral part of the carbon cycle due to their capacity to sequester and store carbon. Carbon sequestration refers to the process by which CO_2 is stored as biomass as it is converted to sugars during photosynthetic processes (Nowak & Crane, 2002). Globally, terrestrial ecosystems, of which forests are a major component, are estimated to sequester approximately 3 billion tons of anthropogenic carbon per year, accounting for nearly 30% of fossil fuel- and deforestation-related CO_2 emissions (Canadell & Raupach, 2008). As carbon sequestration occurs, individual trees act as carbon sinks because atmospheric CO_2 becomes locked away in their tissues and is only returned to the atmosphere when the trees decompose. Larger trees are also able to sequester more carbon per year due to their increased foliage biomass and therefore act as greater carbon stores than young trees (Brack, 2002; Cox, 2012). However, forests can become sources of carbon if the rate of forest die-off or deforestation exceeds the growth rate (Ravin & Raine, 2007; Natural Resources Canada, 2016b); thus, proper management of forest ecosystems plays an important role in maintaining carbon stores.

In order to construct global and national forest carbon inventories, such as Canada's NFCMARS, the aboveground biomass density of forests must be measured and related proportionally to carbon content (Lambert, Ung & Raulier, 2005). Researchers are able to estimate the total amount of carbon stored in forest biomass through a process known as biomass allometry. This process allows for the biomass of each tree to be measured without having to physically harvest the tree and weigh it directly. Using non-linear regressions, researchers have related the diameter at breast height (DBH) of a tree to its dry weight to produce a series of standardized biomass equations for different species (Ter-Mikaelian & Korzukhin, 1997; Lambert, Ung & Raulier, 2005). By combining measurements of average DBH with estimates of forest cover and species composition, biomass equations can be used to determine the total dry volume of a forest, which is generally assumed to be approximately 50% carbon (Kurz & Apps, 1999). Biomass equations have been produced for numerous species across a wide geographic range, including Canada as a whole and for more specific regions (e.g., Nova Scotia) to account for local climate factors (Lambert, Ung & Raulier, 2005; Townsend, 2008).

The process of measuring biomass to estimate forest carbon stocks has, more recently, been used to quantify the amount of carbon stored in urban forest environments. Although definitions vary across the literature, urban forests are generally defined as all of the trees located within urbanized areas or urban clusters (Nowak et al., 2013). An increasing trend towards urbanization has led to a greater focus on the environmental benefits of urban forests and the role that they serve as carbon sinks in localized areas (Churkina, Brown & Keoleian, 2010). Municipalities frequently develop inventories of their urban forests to aid in forest management and planning, often including carbon storage and sequestration estimates as well. For example, the City of Toronto produced a report estimating that 1.1 million metric tonnes of carbon are stored in their urban forest, with an annual sequestration rate of 46 700 tonnes year^{-1} (City of Toronto, 2013). Halifax, similarly, has an Urban Forest Master Plan (UFMP) that includes estimates of carbon sequestration from its street trees (Halifax Regional Municipality, 2012).

While many studies have concentrated on national or city-wide forest inventories, university campuses are increasingly the focus of small-scale assessments. The University of Pennsylvania, for example, conducted a recent assessment of the environmental benefits of its on-campus trees, while California State University specifically quantified carbon sequestration by its trees to include in its GHG inventory (Bassett, 2015; Cox, 2012). Having campus-specific data benefits universities looking to implement specific forest management practices and informs their climate change policies and programs. Furthermore, previous research has shown the importance of higher education institutions (HEIs) in demonstrating leadership and initiative in sustainable issues (Walton & Galea, 2005). Climate change policies and planning, in particular, has been shown to be relevant in a university setting, adding value to pursuing this line of research (Lemons, 2010; Bowers, 2008).

Dalhousie University, located in downtown Halifax, is a higher education institution that was established in 1818 (Dalhousie University, 2016). The university places a strong emphasis on environmental education and sustainability and has signed on to a number of agreements (e.g., the University and College Presidents' Climate Change Statement of Action) to commit to becoming more sustainable (Smulders, 2009). Dalhousie actively tracks its annual GHG emissions and has implemented a Climate Change Plan in which it stresses the importance of the natural environment in offsetting carbon (Dalhousie Office of Sustainability, 2010). Furthermore, it published a Natural Environment Plan in 2014 that outlines strategies for tree management and establishes a tree diameter replacement policy (Dalhousie Office of Sustainability, 2014). However, Dalhousie has yet to quantify the relationship between carbon sequestration by on-campus trees and its annual GHG emissions.

This study examined the tree population on Dalhousie University's Halifax campuses and characterized it based on factors such as species, size distribution, and carbon storage and sequestration potential. The intent of the research was to determine both the total carbon pool and the rate of carbon sequestration across all trees on the campuses and to compare this value with Dalhousie’s current GHG emissions. In doing so, the relative importance of the trees to act as a local carbon sink was established, which allowed for possible recommendations for future on-campus tree management and climate change policies to be developed and presented.

The specific research question addressed by this study was:

What percentage of the total annual 2014-15 GHG emissions (in tonnes of equivalent carbon dioxide) from Dalhousie University’s Halifax campuses is represented by the total annual sequestration of carbon by trees located on the Halifax campuses?

The research question was addressed by applying allometric equations to an existing inventory of on-campus trees, using a forest inventory software application called i-Tree Eco. The application generated estimates of carbon stored in and sequestered by each tree, based on species, measurements of height, DBH and tree condition, and local climate (USDA Forest Service, 2016a). Estimates of total annual carbon sequestration were then compared to Dalhousie’s GHG inventory from the 2014-2015 fiscal year.

This study’s findings can be incorporated into future GHG inventories and used to inform updates to Dalhousie’s Climate Change and Natural Environment Plans (Dalhousie Office of Sustainability, 2010; 2014). Similarly, this study can inform future on-campus development, be integrated into existing sustainability policies like the tree diameter replacement policy, and act as a baseline for future assessments of the campus carbon sink.

2.0. Literature Review

While the importance of climate change mitigation has been well-established in the literature, an emerging focus in research is the role of individual institutions in mitigating and adapting to climate change. Localized businesses or organizations are driven to manage their GHG emissions by policies on carbon accounting and sustainability and by corporate social responsibility (Babiak & Trendafilova, 2010). These concepts have more recently been applied to higher education institutions (HEIs), with a newer body of research highlighting their importance in promoting sustainable behaviour and responding to climate change (Walton & Galea, 2005; Lemons, 2010). This review explores how and why HEIs take climate change-specific actions, including carbon accounting, and focuses on identifying key knowledge gaps within the literature. In particular, the role of urban forests as carbon sinks and their current inclusion within municipal- and university-level carbon accounting protocols is examined. The review aims to further delineate the scope of this project and provide greater context for its motivation by evaluating how universities currently incorporate carbon sinks into their greenhouse gas (GHG) inventories and by identifying a need for better inclusion of urban forests in these assessments.

2.1. Importance of scale in climate change mitigation

Anthropogenic influences on the climate system are well-documented, with abundant evidence suggesting on-going climatic warming will have significant impacts on both human health and the environment (IPCC, 2014; Karl & Trenberth, 2003). As a result, global collaboration to mitigate anthropogenic GHG emissions has become a key part of the climate change narrative and is well-established on both international and national scales. On a global scale, multinational agreements (e.g., the 2015 Paris Agreement) emphasize the need for increased global collaboration and highlight economic imbalances between developed and developing nations (UNFCCC, 2015; IPCC, 2014). Developed nations are often considered to have both a social and environmental responsibility to take a leadership role in climate change issues and to provide support to other countries where needed (Council of the Federation, 2015). Similarly, the implementation of climate change policies on a national scale often requires collaboration between federal governments and their constituent state- or provincial-level authorities (Council of the Federation, 2015; Rabe, 2007). These policies suggest that coordination across different jurisdictions plays a key role in climate change mitigation, with these smaller-scale groups providing the framework for implementing broader plans.

Research has also shown that there are additional benefits to implementing mitigation strategies on regional or even local scales; urban environments (i.e., cities) and municipalities are likewise thought to have a critical role in climate change mitigation (Okereke, Bulkeley & Schroeder, 2009; Wilbanks & Kates, 1999; Measham et al., 2011). For example, local governments control land-use planning, waste management and aspects of transportation such as public transit, all of which provide opportunities to moderate and reduce municipal GHG emissions (Betsill & Bulkeley, 2006; Betsill, 2001). Implementing localized mitigation strategies also helps drive local sustainability and can contribute to a more prosperous economy (Lambright, Changnon & Harvey, 1996; NSE, 2009; Council of the Federation, 2015). Recent years have seen an increase in the number of municipalities taking steps towards mitigating climate change, including tracking and recording initiatives to reduce GHG emissions and implementing climate change-specific plans or strategies (Federation of Canadian Municipalities, 2015). In fact, the International Council for Local Environmental Initiatives (ICLEI) has recently developed protocols for completing local GHG inventories, including emissions from buildings, fleet vehicles, lighting and waste (ICLEI, 2009). The protocol provides further support for individual municipalities characterizing their emissions under a city-specific lens, suggesting that adopting a localized, or bottom-up, approach allows for effective climate change mitigation.

An integral part of the bottom-up approach to mitigation is implementing policies at an institutional level, with individual businesses now implementing their own climate change mitigation policies and strategies. In many cases, corporate social responsibility may be the key driver in the upsurge in attention towards sustainability; studies have shown that businesses now view adopting sustainable practices as the “social norm”, and that doing so can have both economic and social benefits (Babiak & Trendafilova, 2010). For example, businesses that are more sustainable may receive more attention from prospective consumers who are concerned with environmental reputation (Ganescu & Dindire, 2014). Unsworth, Russell and Davis (2016) suggest that climate change, specifically, should be considered by businesses that are perceived by the public as being larger GHG contributors, and thus they may have added responsibility to mitigate in the eyes of the consumer. Additionally, climate change has the potential to negatively impact companies (e.g. fuel and energy costs, supply chain) and therefore mitigation and adaptation strategies suit their economic needs (Lingl & Carlson, 2010). Localized businesses and institutions are therefore individually driven, through a combination of social and economic considerations, to consider their impact on the climate and account for or reduce their emissions.

The wide range of mitigation strategies that have been implemented to date therefore provides substantial support for considering climate change across multiple scales. While multinational agreements allow for nations to share responsibilities and collaborate on a global issue (UNFCCC, 2015; Council of the Federation, 2015), these agreements rely on the support of regional and local initiatives (Measham et al., 2011; Federation of Canadian Municipalities, 2015). The bottom-up approach of these initiatives allows individual institutions to play a key role in mitigation; while businesses may primarily be driven to act sustainably by socioeconomic considerations, their influence on the resolution of a global problem is nonetheless substantial.

2.2. Carbon accounting

Carbon accounting refers to the way in which entities (e.g., federal governments or local institutions) track carbon emissions and removals associated with their operational activities, including from both direct and indirect sources (Hespenheide et al., 2010). Carbon accounting is not limited by scale and can be considered for individual products, organizations, projects, or even nations as a whole (Stechemesser & Guenther, 2012; Ascui & Lovell, 2011). The process of carbon accounting plays a vital role in climate change mitigation, because it helps ensure that these entities meet their reduction targets, whether nationally mandated or set by company policy (Ascui & Lovell, 2011). Carbon accounting is also a key component of climate change economics; the process allows for trading carbon credits (i.e., buying and selling quantified emissions) to help meet targets and is necessary for demonstrating accountability (Kolk et al., 2008; Schaltegger & Csutora, 2012). This last point is particularly relevant as countries begin implementing carbon pricing policies. For example, Canada recently announced that all provinces or territories must have a “floor price” on carbon of at least 10 dollars tonne^{-1} by 2018 (Campion-Smith, 2016); businesses would therefore be taxed, or have to pay more, for each tonne of carbon consumed or emitted by their operations. Carbon accounting, then, is crucial in allowing institutions to quantify their individual contributions to climate change, holding them accountable both to their mitigation policies and to carbon tax legislation.

2.2.1. Greenhouse gas inventories

For carbon accounting to be used effectively and accurately in trading carbon credits or following the implementation of a carbon tax, institutions need a standardized means of quantifying their GHG emissions. Most organizations produce carbon accounts in the form of annual GHG inventories, for which a number of standard protocols have been established to ensure consistency (Ranganathan et al., 2013). These protocols include the International Organization for Standardization (ISO)'s GHG protocol (ISO 14064) and The Climate Registry (TCR) General Reporting Protocol (Ranganathan et al., 2013; TCR, 2013). Although there is some variation between different protocols, most typically divide inventory emissions into three scopes: Scope 1 emissions – direct GHG emissions from owned or controlled sources; Scope 2 emissions – indirect GHG emission from purchased electricity; and Scope 3 emissions – indirect GHG emissions from upstream production of materials and from transport-related activities. The protocols also generally include some instruction on consideration of biomass combustion and incorporation of carbon sinks into the inventories (Ranganathan et al., 2013). These protocols can be applied to almost any institution, with individual cities, projects and universities opting to develop inventories using these methods; for example, Dalhousie University releases an annual GHG inventory in accordance with the TCR General Reporting Protocol (Dalhousie Office of Sustainability, 2015).

In order to account fully for all carbon, however, some consideration should be given to the role of carbon offsets in GHG inventories. Carbon offsetting refers to efforts made by an organization or project to reduce its emissions, often achieved through purchasing credits from a third party that is implementing a specific reduction project (Lingl & Carlson, 2010). A variety of different projects are considered to offset emissions, including renewable energy and energy efficiency projects, artificial carbon capture and storage, and afforestation or reforestation projects (Peskett & Brown, 2010). Forestry projects, in particular, are often implemented because of the ease with which they can be completed and their ability to be applied in underdeveloped and rural areas, including both planting seedlings and conserving existing forests (i.e., avoided deforestation) (Peskett & Brown, 2010; Rowntree & Nowak, 1991).

There is also a growing interest in being able to account for the carbon that is stored naturally by terrestrial ecosystems in the form of carbon sinks (Ravin & Raine, 2007). Forests specifically are often considered in research for their ability to sequester and store carbon; a number of studies have attempted to quantify the amount of carbon stored in forest ecosystems, both at a local scale (e.g., within a municipality) and across wide regions (Walsh, 2012; Kurz & Apps, 1999). On a national scale, forests have been incorporated into carbon accounts through programs such as Canada's National Forest Carbon Monitoring, Accounting and Reporting System (NFCMARS), which tracks changes in Canada's forest carbon stocks (Natural Resources Canada, 2016a). NFCMARS uses an accounting tool called the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) to predict these changes and allow forest managers to assess how development project might impact the carbon stocks (Natural Resources Canada, 2016b). Forest management strategies that enhance the potential of forests to act as sinks are therefore a key component of mitigation, and may serve as effective carbon offsets if properly managed.

2.2.2. Inclusion of urban forests

While the bulk of literature on carbon sinks has focused on traditional forests, urban trees have also been considered in research for their ability to sequester and store carbon (Rowntree & Nowak, 1991; Nowak & Crane, 2002; McPherson, 1998; Nowak et al., 2013; Pasher et al., 2014). Numerous studies have attempted to quantify direct carbon storage across cities in Canada and the United States, including city-specific assessments (e.g. Sacramento) (McPherson, 1998) and comprehensive multi-city inventories (Nowak & Crane, 2002; Nowak et al., 2013; Pasher et al., 2014). Additionally, novel technologies have been applied to estimate carbon storage over large urban areas by means of field data and modelling; for example, Pasher et al. (2014) demonstrated how high-resolution aerial photography can be used to estimate forest cover and, subsequently, carbon storage in Canada's urban forests. These trends suggest the role of urban forests as carbon sinks is becoming a greater focus in forestry research.

Increased urbanization has led to more research on environmental impacts in urban areas (e.g., habitat loss and deforestation) and has helped highlight the environmental and climate change-specific benefits of maintaining and planting urban trees (Churkina, Brown & Keoleian, 2010). In fact, urban forests are thought to have a greater per-tree impact on reducing atmospheric carbon dioxide than traditional forests; although less carbon is physically stored in urban trees, they also play a role in indirect energy savings by moderating the heating and cooling needs of buildings (ICLEI, 2006; McPherson & Rowntree, 1993). The increased availability of modelling tools and region-specific biomass equations has allowed inventorying urban forests to extend beyond the realm of academic research, with municipalities and local governments now considering the direct and indirect benefits of urban trees in their city plans. Cities such as Toronto and Halifax have already begun estimating the amount of carbon stored in trees under their jurisdictions and have included these values in city-wide urban forest master plans (City of Toronto, 2015; Halifax Regional Municipality, 2012). Guidance is also available for municipalities to develop forest inventories. For example, the *Urban Forestry Toolkit*, developed by the ICLEI, discusses the benefits of urban forests, including carbon storage, and provides a rationale for including the effects of carbon sinks within the municipality's forest management policies, climate change plans, and GHG inventories (ICLEI, 2006).

2.2.3. Modelling carbon storage in urban environments

Biomass allometry is the process of estimating the total amount of carbon stored in forest biomass (Lambert, Ung & Raulier, 2005). Researchers have traditionally relied on allometric techniques to convert estimates of forest cover into biomass and, subsequently, into carbon storage (Nowak & Crane, 2002; Kurz & Apps, 1999). The process can be conducted by directly measuring the dry weight of trees, or by using standardized equations that relate the diameter at breast height (DBH) of a tree to its total aboveground biomass. Some studies may also apply conversion factors to convert from fresh to dry biomass and to incorporate underground biomass into estimates as well (Scharenbroach, 2012). These values can then be converted to carbon based on the commonly accepted assumption that dry biomass is 50% carbon (Nowak et al., 2013; Kurz & Apps, 1999). Biomass equations specific to different species and to different climatic regions have been developed and compared in numerous studies, including those that are specific to Canada and to Nova Scotia (Ter-Mikaelian & Korzukhin, 1997; Lambert, Ung & Raulier, 2005; Townsend, 2008). These equations are generally applied in both traditional and urban forest settings. Although some evidence suggests that equations developed for traditional forests incorrectly estimate carbon storage in urban trees (McHale et al., 2009), most allometric methods established in the literature have been well-verified by repeated research and apply correction factors to account for differences between urban and traditional forests (Aguaron & McPherson, 2012).

Increasing interest in modelling urban forest inventories has led to the development of software applications that allow researchers and municipalities to directly calculate the environmental benefits of urban forests, including carbon storage and sequestration potential (Aguaron & McPherson, 2012). Commonly used tools include: i-Tree Eco, an application developed by the United States Department of Agriculture (USDA) Forest Service to estimate environmental benefits of urban forest populations from sample plots or complete inventories (USDA Forest Service, 2016a; Nowak et al., 2008); i-Tree Streets, another USDA application that allows the user to focus more specifically on individual street tree populations (USDA Forest Service, 2016b); and the Center for Urban Forest Research (CUFR) Tree Carbon Calculator, a Microsoft Excel-based spreadsheet that similarly calculates carbon sequestration and storage in individual trees (USDA Forest Service, 2016c). These types of modelling software have been reviewed in the literature and applied extensively in urban environments. Aguaron and McPherson (2012) evaluated the difference in estimates of carbon storage in Sacramento's urban forest using these models. While there were differences between the models, these differences were not significant when compared with the differences observed between Sacramento and other cities (Aguaron & McPherson, 2012). The models all rely on biomass equations derived from peer-reviewed literature (Nowak et al., 2002; Cairns et al., 1997; Nowak, 1994), suggesting these applications are an effective, reliable means of determining carbon storage in urban environments. A number of cities in Canada, such as both Halifax and Toronto, have also relied on modelling software (i.e., i-Tree Eco) to develop their urban forest plans (City of Toronto, 2013; Halifax Regional Municipality, 2012).

2.3. Higher education institutions

2.3.1. Relevance of HEIs in sustainability

Higher education institutions are considered to play a positive role in fostering innovation and in the development and sharing of new knowledge through learning and research. Many studies highlight the importance of HEIs specifically in promoting sustainability, both through research and by encouraging new generations of students to assume leadership roles in environmental issues (Stephens et al., 2008; Walton & Galea, 2005; Betzbatchenko, 2010). For example, Stephens et al. (2008) argue that HEIs can act as agents of change and have the ability to model sustainability by promoting environmentally-friendly, or “green”, practices on campus. Evidence of university-led green initiatives can also lead to increased student response to environmental issues and to more widespread sustainable behaviour (Figueredo & Tsarenko, 2013; Eagle et al., 2015). In much the same way that businesses adopt green practices to demonstrate corporate social responsibility, HEIs can apply similar techniques to elevate their commitment to sustainability (Walton & Galea, 2005). In fact, many HEIs already address this commitment by signing sustainability agreements or declarations, such as the Talloires Declaration (1990), the Swansea Declaration (1993), and the University Presidents’ Climate Commitment (2007) (Betzbatchenko, 2010). Furthermore, HEIs may participate in community initiatives and partnerships that drive innovation and reward positive sustainable thinking; for example, the Association for the Advancement of Sustainability in Higher Education (AASHE), established in 2005, allows colleges and universities to self-report their sustainable goals and achievements, and shares best practices through annual reviews of these goals (AASHE, 2014).

For similar reasons, HEIs may also serve as leaders and innovators in actions taken specifically to mitigate and adapt to climate change. Lemons (2010) and Bowers (2008) advocate for greater incorporation of climate change into university curriculums, emphasizing the need for an interdisciplinary approach. They argue that discussion of the broader implications of climate change (e.g., its social and economic impacts) is relevant in all degree programs, rather than just sustainability or environmental studies (Lemons, 2010; Bowers, 2008). Furthermore, considering climate change at a university-level may have benefits that extend beyond education. Some research suggests that university-led actions and research may play a role in policymaking at regional and national levels (Walton, 2009). Institutional leaders are now more commonly adopting commitments, such as the University and College Presidents' Climate Change Statement of Action for Canada, that stress the importance they place on climate change issues (Toope et al., 2008). The commitment outlines specific actions to be taken with respect to university policy and planning (e.g., implementing a plan to reduce GHG emissions) to respond to climate change. The commitment also stresses the importance of exercising leadership in reducing emissions within the community, again emphasizing the role of HEIs in contributing to more sustainable behaviour (Toope et al., 2008).

2.3.2. Tools used to record sustainability

To demonstrate how they are integrating sustainability into their curriculums and institutional policies, HEIs frequently seek additional means to report and publicize their actions. Over the past few decades, a number of different tools have been established as a means for HEIs to report their actions, including internationally-recognized tools such as the College Sustainability Report Card and the UI GreenMetric World University Sustainability Ranking (Suwartha & Sari, 2013; College Sustainability Report Card, 2011). Some universities also implement their own means of assessing on-campus sustainability, such as the University of Waterloo's WATgreen Advisory Committee and Concordia University's Campus Sustainability

Framework (Legacy, 2004). However, the most commonly recognized and most well-established tool within North America is the Sustainability Tracking, Assessment and Rating System (STARS), created by AASHE in 2009 (AASHE, 2015). STARS is one of the leading standard metrics for measuring sustainability in HEIs, with more than 790 schools enrolled (AASHE, 2015). It provides an effective means for universities to hold themselves accountable to their goals/targets, while also allowing them to share best practices and earn public recognition for their achievements (AASHE, 2015; Urbanksi & Filho, 2014).

Many HEIs also establish policies and strategies that are specific to climate change mitigation and adaptation, including self-reported GHG inventories and climate change action plans (Button, 2009; Cleaves et al., 2009). A number of climate change plans aim specifically for HEIs to have net zero emissions (i.e., to be carbon “neutral”). For example, Central Connecticut State University committed itself to achieving carbon neutrality after signing the American College and University Presidents Climate Commitment in 2007, and has since implemented strategies, including joining AASHE, to meet that goal (Button, 2009). GHG inventories are a key component of many climate change action plans, with institutions using established methodologies to ensure consistent reporting. The University of New Hampshire partnered with a local non-profit, Clean Air-Cool Planet, to develop a tool called the Campus Carbon Calculator; the tool allows university campuses to easily develop standard GHG inventories and has been widely used across the United States (Cleaves et al., 2009). Others, such as Dalhousie University, rely on the methodology established by The Climate Registry to calculate and report their emissions (Dalhousie Office of Sustainability, 2014). Increasing recognition of the importance of HEIs in responding to climate change, as well as a greater availability of tools for producing GHG inventories, has therefore led to more widespread development of climate change policies and plans in recent years.

2.3.3. Previous campus tree studies

The role of urban forests at the level of university campuses is an emerging area of research within HEI-specific climate change mitigation policy, with only a limited number of universities having conducted complete on-campus tree inventories and quantified carbon storage. Several recent studies at the University of Pennsylvania and California State University used i-Tree Eco and the CCTC respectively to quantify the environmental benefits of their urban forests (Bassett, 2015; Cox, 2012); however, there is no indication that the results of these studies have been incorporated into the universities' climate change actions (Penn Green Campus Partnership, 2014; California State University, 2014). On the other hand, the University of Windsor has a comprehensive tree management plan which provides an average annual carbon sequestration rate for on-campus trees (68.7 tonnes CO_2 $year^{-1}$), determined using i-Tree Streets (Davey Resource Group Canada, 2011). The relatively small number of universities that have completed this research suggests that HEIs, as a whole, have not yet seriously considered the role of on-campus trees in carbon storage and sequestration.

2.4. Summary of knowledge gaps

Despite an increasing trend toward sustainable policy development and using self-reporting tools to manage sustainability, some evidence suggests that there are still gaps in how HEIs address climate change. Urbanski and Filho (2014) examined the degree to which institutions registered under STARS incorporated climate change into their self-reports, and noted that only 64% of rated institutions had some form of climate change or GHG mitigation plan. Additionally, a wide variation in scores reported for GHG emissions management suggests that, while some universities may have adopted comprehensive mitigation plans and policies, a considerable number of HEIs have not done so (Urbanksi & Filho, 2014). Participation in STARS provides an opportunity for many universities to identify best practices and collaborate on future research (AASHE, 2015), which may be beneficial for HEIs that are lacking in appropriate climate change policy and management. However, it is apparent that this remains a gap within university policies in general that needs to be addressed through future research and collaboration.

Within the STARS reporting tool, universities are able to self-report their total emissions, including a break-down of GHGs into Scopes 1, 2, and 3 (AASHE, 2016). Universities can also include carbon offsetting from a number of sources, including: third-party verified and purchased carbon offsets; institution-catalyzed (local) carbon offsets; land-based carbon sequestration (as documented in university land management policies); and carbon storage from on-site composting (AASHE, 2016). A feature of the AASHE website – the STARS Report Content Analyzer – allows reporting institutions to be compared across different elements of their self-reports, including their reported carbon offsets and, more specifically, their land-based carbon sequestration. However, less than 10% of the Reporting Institutions (and none within Canada) have reported any procedures or quantified values for carbon sequestration. This observation suggests an additional gap where universities are not considering carbon sequestration from a local perspective (i.e., within the bounds of their campuses). Most universities have not integrated information they may have from on-campus tree inventories into their carbon accounts, despite the role it may play as a carbon sink (AASHE, 2016).

Dalhousie University, despite being an AASHE member and having a clear interest in promoting sustainability, does not currently account for carbon sequestered by and stored in university-owned trees. Although the university does note in its Climate Change Plan that the natural environment will be incorporated in future years, no carbon sinks (either third-party credits or local carbon stocks) are quantified or described in the plan (Dalhousie Office of Sustainability, 2010). Furthermore, Dalhousie’s Natural Environment Plan identifies maximizing carbon removal through on-campus vegetation as being a future goal of the university (Dalhousie Office of Sustainability, 2014). It describes a diameter replacement policy, whereby trees removed during construction are replaced by planting a sufficient number of trees to offset the loss; however, this policy relies on using DBH as a proxy for biomass measurements and does not actually quantify biomass, or carbon storage, directly (Dalhousie Office of Sustainability, 2014). A study that quantifies the amount of carbon stored and sequestered by trees on Dalhousie’s Halifax campuses therefore provides information that can enhance its GHG emission reduction strategies and the management of its natural environment, particularly within the framework of existing policies. Additionally, it helps meet the objective of the Natural Environment Plan to maximize carbon removal by providing concrete data that can be used in future planning.

2.5. Conclusions

This literature review has explored climate change mitigation within the context of localized action to offset GHG emissions through urban forest sinks. Research has shown a clear need to consider land use and carbon sinks in constructing GHG inventories, in order to account fully for all carbon emitted and stored by an institution. In particular, this review has examined the role of higher education institutions in mitigating climate change. As leaders in sustainability research, HEIs have well-developed means of participating in climate change-specific initiatives. However, many are still lacking comprehensive GHG inventories, and fewer still fully incorporate on-campus carbon sinks into their inventories. To date, there has been limited research in terms of quantifying carbon sequestration and storage in on-campus trees. Dalhousie University, specifically, is lacking in a quantified relationship between its natural environment and carbon sink potential. These knowledge gaps provide sufficient justification to suggest the need for a study to quantify the carbon sequestration capacity and storage potential of trees on the Dalhousie Halifax campuses. This research therefore contributes to Dalhousie's on-going efforts to manage its natural environment, reduce its carbon footprint, and continue promoting sustainable actions.

3.0. Methods

3.1. Overview of methods

This study quantified the carbon storage pool and the annual carbon sequestration rate of trees located on Dalhousie University's Halifax campuses, in order to evaluate and characterize the contribution of the local urban forest to offsetting Dalhousie's greenhouse gas emissions. Data used in the analysis were obtained from a complete inventory of woody plants growing on the Halifax campuses, originally collected beginning in 2009. The inventory contained both qualitative and quantitative characteristics for individual trees and shrubs, including species, DBH, and crown light exposure. These characteristics were used to describe the on-campus urban forest in terms of species profile and size structure. Additionally, the software suite i-Tree Eco v6 beta was used to convert the inventory characteristics into an estimate of the total carbon storage capacity and annual sequestration rate of the on-campus trees. The model estimates allowed for comparative analyses between on-campus carbon sequestration and annual GHG emissions.

3.2. Study area

Dalhousie University is a research institution based primarily in Nova Scotia, with three campuses located in downtown Halifax, an agricultural campus located in Bible Hill, Nova Scotia, and medical teaching facilities in Saint John, New Brunswick (Dalhousie University, 2016). The university was founded in 1818 and currently has over 18,500 students enrolled across a wide range of undergraduate and graduate programs, the majority of which take place in Halifax. The largest of the Halifax campuses, Studley campus (Figure 1), houses most of the university's main buildings and resources, including the Faculties of Science, Management, Computer Science, Law, and Arts and Social Sciences (Dalhousie University, 2016). Other notable features include the Central Services Building, which houses Facilities Management and the Office of the Sustainability, and the central heating plant. The other two campuses, Carleton campus (Figure 2) and Sexton campus (Figure 3), house the Faculties of Medicine and Dentistry, and the Faculties of Engineering and Architecture respectively (Dalhousie University, 2016). This study focused exclusively on the Halifax campuses.

The three Halifax campuses have a combined area of ~38 hectares and are a mixture of different landscape types, including impervious surfaces (e.g., buildings, pavement), naturalized areas, open greenspace, tree-lined streets, and tree stands (Dalhousie Office of Sustainability, 2014). Dalhousie University's Natural Environment Plan details the university's policies and plans for managing its natural environment, including green spaces, gardens, shrubs, and trees on its Halifax and agricultural campuses. The plan distinguishes between privately-owned university vegetation (915 trees, 980 shrubs), which falls under the scope of the plan, and municipally owned trees alongside roads (>300 trees) (Dalhousie Office of Sustainability, 2014).

Figure 1. Dalhousie University’s Studley campus, located in Halifax, NS. Area is approximately equal to 30 hectares. Retrieved February 25, 2017 from Google Maps.

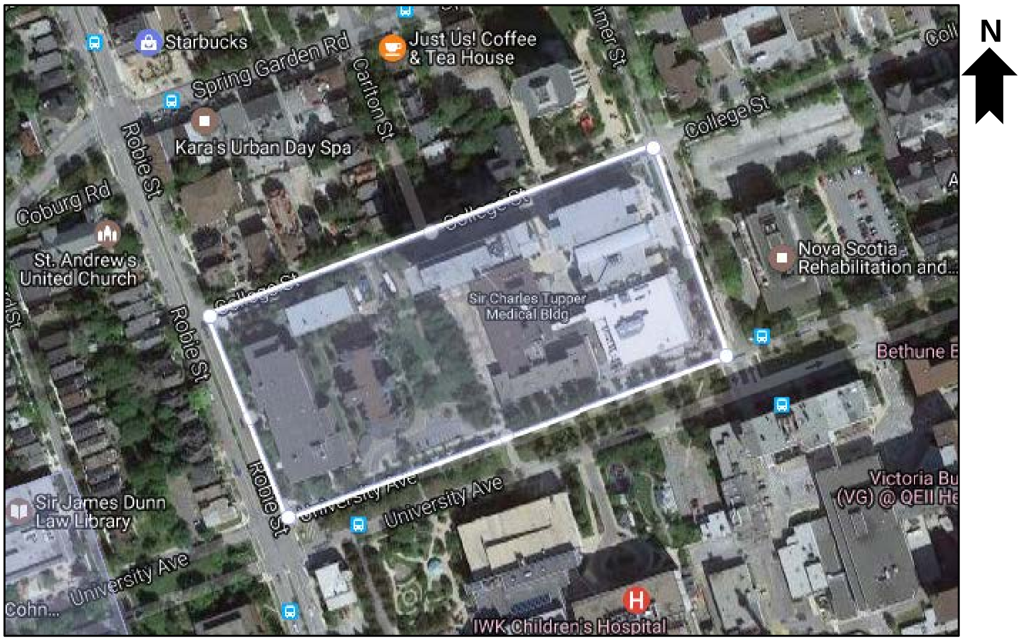

Figure 2. Dalhousie University’s Carleton campus, located in Halifax, NS. Area is approximately equal to 3.6 hectares. Retrieved February 25, 2017 from Google Maps.

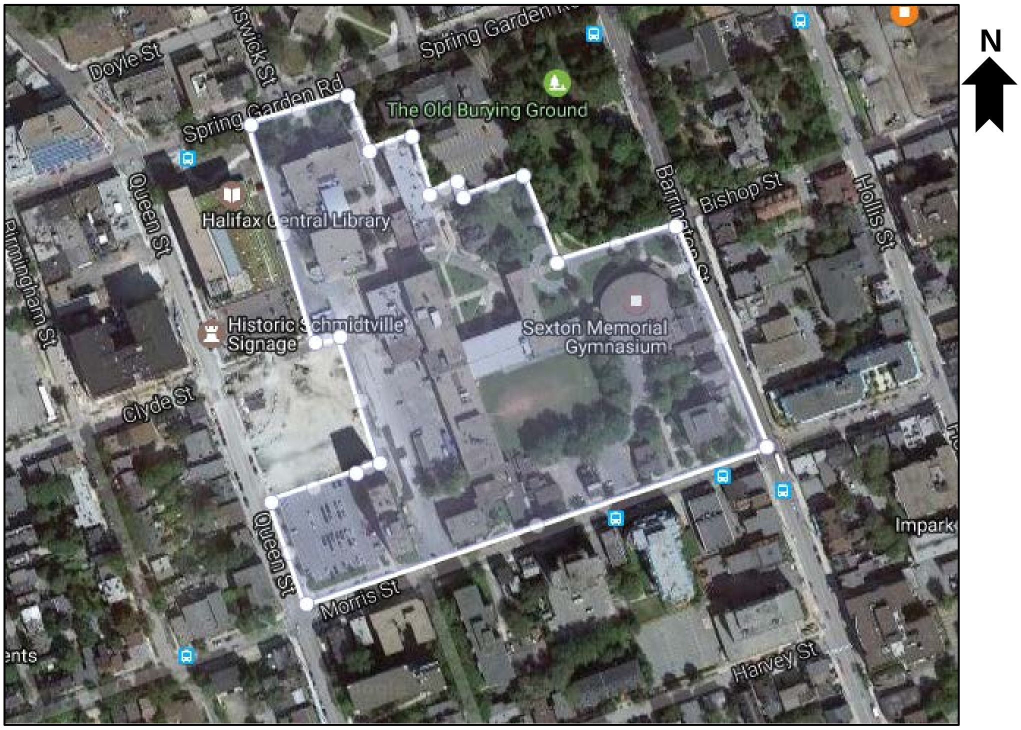

Figure 3. Dalhousie University's Sexton campus, located in Halifax, NS. Area is approximately equal to 4.8 hectares. Retrieved February 25, 2017 from Google Maps.

3.3. Data collection

Starting in 2009, an inventory of all woody plants on the Halifax campuses was conducted, with several updates in subsequent years (i.e., 2011 and 2013) as vegetation was planted or removed. Since its conception, the inventory has been used to inform the development of Dalhousie's Natural Environment Plan and was originally intended to be used as a baseline for future assessments (Dalhousie Office of Sustainability, 2014). The inventory served as the basis for determining the carbon storage and sequestration rates for the individual trees on the Halifax campuses. Using information collected on species, DBH, and tree condition, the biomass and, subsequently, carbon storage and sequestration of individual trees was subsequently calculated (Section 3.4), as in Nowak et al. (2002; 2008).

Data were collected using an established methodology outlined in the i-Tree Eco Field Guide (USDA Forest Service, 2016a). The i-Tree methodology establishes specific measurements to be taken for individual plants, such as species, DBH, total height, light exposure, wood and leaf condition, and % crown loss and % die-off (USDA Forest Service, 2016a). The inventory also distinguishes between trees and shrubs, and native and non-native vegetation. All three of the Halifax campuses were inventoried and stored separately in Microsoft Excel spreadsheets for ease of input into i-Tree software applications.

3.4. Data analysis

3.4.1. Tools

Data analysis was primarily conducted using the software suite i-Tree Eco v6 beta. i-Tree Eco was developed by the United States Department of Agriculture (USDA) Forest Service, and is originally adapted from the Urban Forest Effects (UFORE) model (USDA Forest Service, 2016a). The software has been peer-reviewed (Nowak et al., 2008; Aguaron & McPherson, 2012), and has undergone extensive updates since its initial release in 2006. These updates have included expanding the functionality of the model to areas beyond the United States (including Canada, Australia and the United Kingdom) by incorporating local climate data into the model; this process was facilitated by local collaboration (e.g., from university researchers) with members of the USDA Forest Service (USDA Forest Service, 2016a). The functionality of i-Tree Eco is therefore greater than that of other tools such as the CCTC, which has been peer-reviewed and applied successfully in the United States but has not been applied in other areas (USDA Forest Service, 2016c).

i-Tree Eco is able to estimate carbon storage for individual trees using a combination of measurements, including species, DBH, height, and crown light exposure. The biomass of each tree is estimated using literature-derived allometric equations, as well as conversion factors to determine the root-to-shoot ratio, moisture content, and carbon content of each tree (Nowak et al., 2008). Carbon sequestration rates are determined based on an assumed average annual diameter growth rate of 0.84 cm year^{-1}, which is adjusted based on the crown light exposure (i.e., growing conditions) and number of frost free days in the study area (Nowak et al., 2008; USDA Forest Service, 2016d).

i-Tree Eco has been used previously in other university campus studies, providing justification for its use here. For example, the University of Pennsylvania completed an inventory of its on-campus urban forest, and implemented i-Tree Eco in order to calculate the environmental benefits of the trees (Bassett, 2015). Although less research is available in Canada, a number of municipalities across Canada have also relied on i-Tree Eco to assess urban forest structure and develop their urban forest master plans, including Oakville, Toronto, Edmonton and Kelowna (USDA Forest Service, 2016b). Halifax, specifically, has implemented an urban forest master plan that outlines its previous use of UFORE (the precursor to i-Tree Eco) and made use of i-Tree applications to assess the urban forest structure, including carbon storage (Halifax Regional Municipality, 2012; Foster & Duinker, 2017). Finally, as outlined in the Natural Environment Plan, Dalhousie University has previously set a precedent for using i-Tree by describing its objective to maximize carbon removal, in which i-Tree will be used to establish a baseline (Dalhousie Office of Sustainability, 2014). These all lend support to the use of i-Tree Eco to conduct the analyses outlined below.

3.4.2. Analysis process

Prior to data entry into the i-Tree Eco software interface, data were pre-processed to make the database current to 2016-17. Given that most of the trees were originally measured in 2009, new DBH values were needed to estimate carbon storage more accurately. In order to establish the approximate current size of the trees, a base growth rate derived from the literature was applied to the existing DBH values (Nowak et al., 2008; USDA Forest Service, 2016d). Standardized growth (SG) was calculated as SG = 0.83 cm year^{-1} x (number of frost free days)/153, where the number of frost free days for Halifax was 167 (Veseys, 2017). Base growth (BG) was then estimated as: BG = SG/2.26, where crown light exposure (CLE) is 0 or 1; BG = SG/1.78, where CLE is 2 or 3; or BG = SG where CLE is 4 or 5 (Nowak et al., 2008). The base growth rate was also adjusted based on % die-off (multiplied by 0.76 if between 25 and 50%, by 0.42 if between 50 and 75%, by 0.15 if between 75 and 99%, or by 0 if 100%) as a proxy for tree condition (Nowak et al., 2008). Finally, the new DBH value was calculated as the existing DBH plus the base growth rate multiplied by the number of years of growth. For example, trees originally measured in 2009 were adjusted for seven years, while trees measured in 2013 were adjusted for three years.

Adjustments to the tree height were not made, as it was assumed that any vertical growth would be relatively small and within the error bounds of the initial height measurement (i.e., to the nearest 0.5 metres). Conversely, DBH is measured in centimetres and so was expected to have changed significantly from 2009 to the present year, justifying the need to apply a growth rate. All other characteristics, including crown light exposure and % die off, were assumed to be the same as when initially estimated.

Other basic data formatting was completed, such as: filtering out shrub data so that only trees were included in the analysis; sorting data by campus, species, and identification number; and identifying any gaps or missing data. For example, trees numbered 58-131 in the Carleton campus database were missing DBH values (due to construction in the area during the time the original inventory was completed); therefore, ground-truthing was conducted to determine the current DBH of these trees. Additionally, a number of trees with data missing for multiple characteristics were removed from the database prior to completing the i-Tree analysis process; these trees were generally small enough that DBH could not be measured (i.e., trees were less than 1.37 m tall) and accounted for less than 3% of the total number of trees on the campuses. Finally, a list of trees that had been removed due to construction on campus was procured from the Office of Sustainability; where possible, these trees were removed from the database.

Data were uploaded into the i-Tree Eco interface in separate files for each of the three campuses, including columns with species, DBH, total height, crown light exposure, and % die-off (all of which were required values for calculating carbon sequestration and/or storage). Specific information, including the local climate region (identified as specifically as the city of Halifax) and current year, were also recorded for each uploaded file. If measurements for crown light exposure (measured on a scale of 0-5) were missing, a default value of 3 (representing three exposed sides) was assumed (USDA Forest Service, 2016a). Similarly, an assumed die-off of 13% was used where values had not been recorded (USDA Forest Service, 2016a). i-Tree Eco then ran each database file through the model on an external server and generated reports with individual carbon sequestration and storage values.

Further calculations done at this time included estimating species diversity, which was calculated using the Shannon Diversity Index (H’) (Shannon, 1948), for the urban forest as a whole and for each campus individually. Subsequent estimates of evenness ($E = H'/\ln(S)$, where S = species richness) were made as well.

3.5. Potential limitations

There were several potential limitations associated with this study, primarily from relying on a secondary data source to complete the analysis. The measurements included in the inventory were primarily collected in 2009; although standard growth rates were applied to estimate the current DBH of the trees, all of the other measurements (including height, light exposure, and % die-off) were assumed to be the same. This assumption has the potential to introduce error into the analysis, as changes in conditions since 2009 are possible. Another source of error may be the growth rate calculations applied during data analysis, which were not species-specific and therefore may over- or underestimate changes in DBH. Given time constraints of this study, it was not practical to re-measure all of the trees, which would essentially amount to redoing the inventory completely; the method applied here was therefore deemed an acceptable alternative.

Furthermore, the information stored in the database does not distinguish between privately-owned university trees and trees that are managed by HRM (e.g., those planted along roadways), which may result in an overestimation of total carbon storage by Dalhousie-owned trees. Inclusion of these trees in the database was expected to represent a small proportion of the total data, but may be a source of error nonetheless. The same is true of trees that were excluded from the database because they had been planted after the most recent inventory update in 2013; however, given their expected small DBH, these were not expected to contribute substantially to carbon storage estimates for the current year.

Other minor limitations were likely introduced through modelling errors associated with using i-Tree Eco v6 to estimate carbon sequestration and storage. While the model has been widely used in both the United States and Canada, Aguaron and McPherson (2012) have observed minor variations between different model estimates, suggesting a potential margin for error. The model is also limited by the number of literature-derived allometric equations for different species; where a species-specific equation does not exist, i-Tree applies either an equation from the same genus, or a more generic equation for either hardwoods or softwoods (USDA Forest Service, 2016a). In this study, all of the identified species were listed in i-Tree Eco's database; however, it is unknown whether or not specific allometric equations are actually included for these species. These limitations have the potential to introduce error, but are expected to have minimal impact on the overall validity, given the well-established precedence for using i-Tree software.

4.0. Results

4.1. Forest species and age structure

A total of 1537 trees were documented across all three of Dalhousie University's Halifax campuses. Studley campus, the largest of the three campuses, hosted the majority of trees, with 1254, while Sexton and Carleton campuses had 158 and 125 trees respectively. The approximate density of trees on each campus was 42 trees ha^{-1} (Studley), 35 trees ha^{-1} (Carleton) and 33 trees ha^{-1} (Sexton), based on the areas shown in Figures 1-3. A total of 71 distinct tree species were identified across the campuses, with the ten most frequently occurring species making up 67% of the forest community (Figure 4). Norway maple (*Acer platanoides*) was the most dominant, accounting for 18% of the trees, more than double that of the second most abundant species.

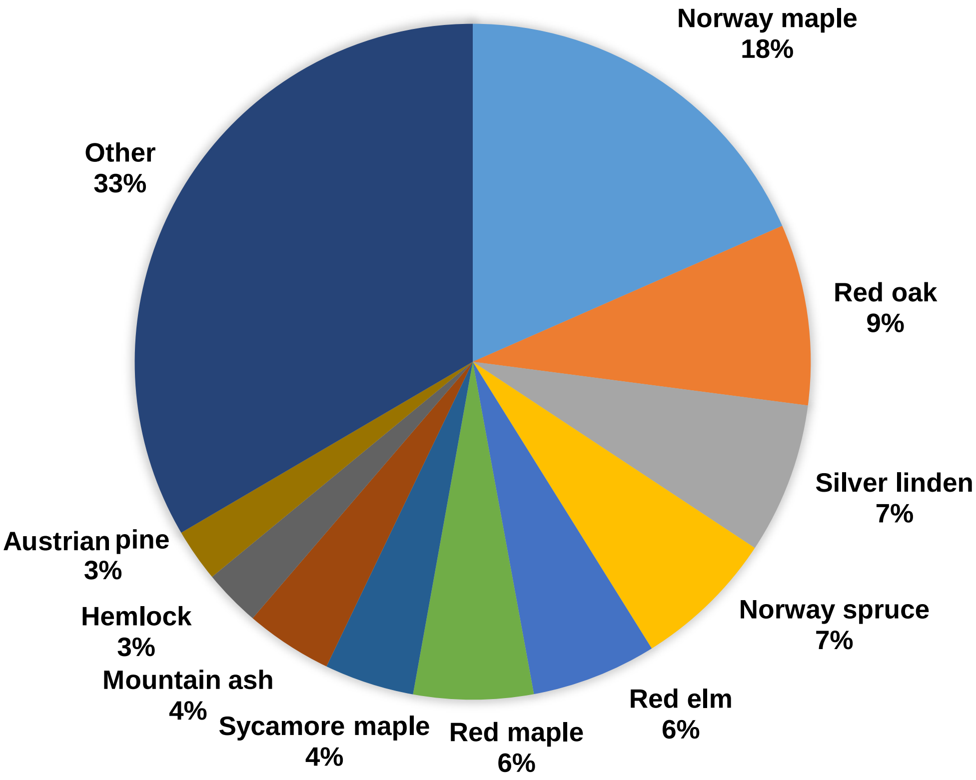

Figure 4. Relative proportion of species identified on Dalhousie University's Halifax campuses, based on the total number (N = 1537) of trees for which complete results were obtained.

The species diversity (H’) of the urban forest as a whole was H’ = 3.27; for the individual campuses, scores varied, with H’ = 3.25 for Studley, H’ = 2.37 for Sexton and H’ = 2.28 for Carleton. The Evenness scores (E), however, were relatively consistent across the campuses, with E = 0.79 for Sexton campus, and E = 0.77 for each of Studley, Carleton and three campuses combined.

The size distribution of the trees (Figure 5) also varied considerably within the Dalhousie tree population. The largest individual tree, a red oak (*Quercus rubra*) located on the Studley campus, had a DBH of 171 cm and was more than 20 cm larger than the next biggest tree. A total of 17 trees (1% of the population) had a DBH greater than 100 cm, 14 of which were found on the Studley campus and three on the Sexton campus. The majority of trees (56.8%) were between 10 and 40 cm in diameter. However, the size distribution also varied considerably across different species (Table 1). Additionally, the distribution by 10 cm DBH classes is also shown for the three most populous species, Norway maple, red oak, and silver linden (*Tilia tomentosa*) in Figure 6a-c; supplementary figures for species with abundances greater than 30 individuals are included in Appendix A.

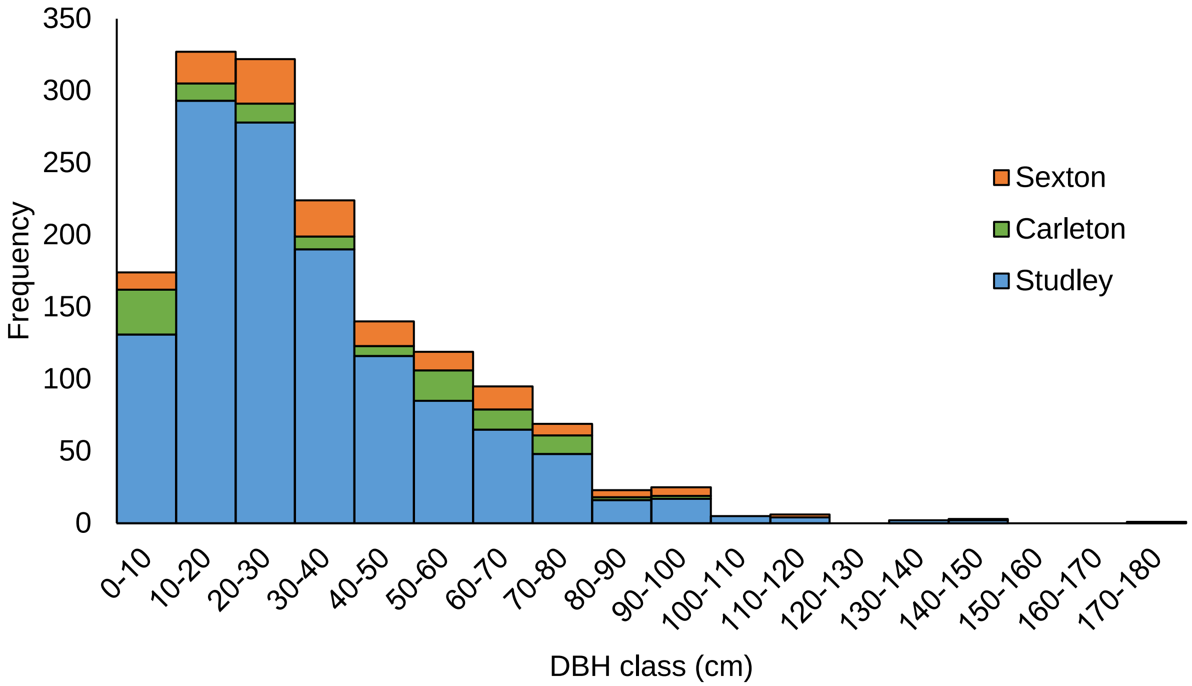

Figure 5. Size class distribution of trees by diameter at breast height (DBH) on Dalhousie University's Sexton, Carleton and Studley campuses, where N_{Sexton} = 158, N_{Carleton} = 125, and N_{Studley} = 1254.

Table 1. Descriptive statistics of the diameter at breast height (DBH) of the ten most abundant species on Dalhousie University's Halifax campuses, including the average and standard deviation (SD) and the maximum values for individual trees.

Species	**N**	**Average ± SD (cm)**	**Maximum (cm)**
Norway maple (*Acer platanoides*)	283	39.8 ± 20.9	140.3
Red oak (*Quercus rubra*)	133	36.0 ± 20.9	170.6
Silver linden (*Tilia tomentosa*)	111	55.3 ± 23.9	111.4
Norway spruce (*Picea abies*)	105	22.7 ± 11.2	51.8
Red elm (*Ulmus rubra*)	92	65.1 ± 25.9	143.3
Red maple (*Acer rubrum*)	88	23.2 ± 13.0	66.3
Sycamore maple (*Acer pseudoplatanus*)	66	37.3 ± 23.4	119.3
Mountain ash (*Sorbus aucuparia*)	64	19.7 ± 10.6	58.3
Hemlock (*Tsuga canadensis*)	42	23.9 ± 8.5	48.8
Austrian pine (*Pinus nigra*)	39	36.0 ± 14.7	75.8
Other species	514	38.6 ± 21.5	133.3

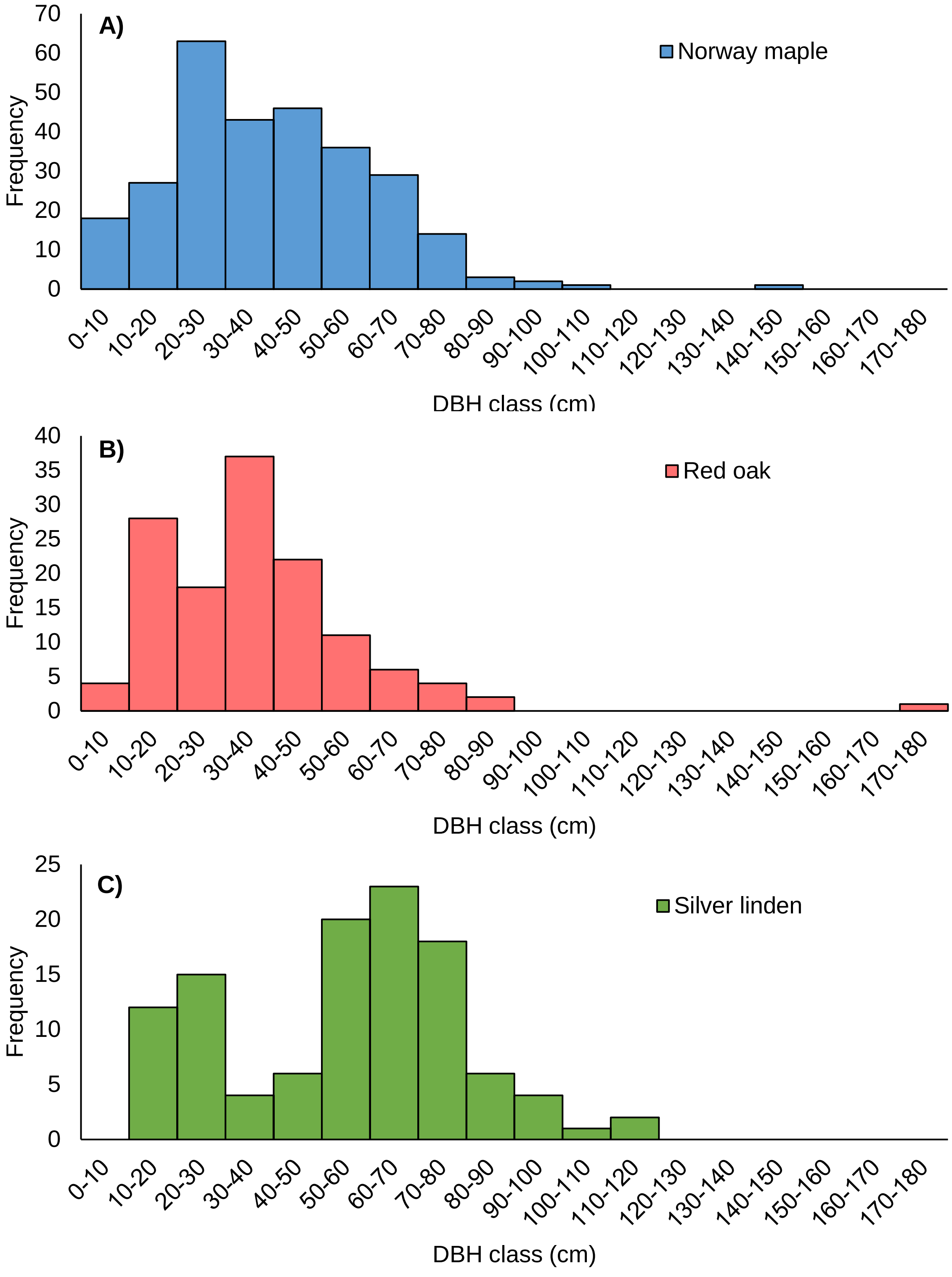

Figure 6. Size class distribution of trees by diameter at breast height (DBH) on Dalhousie University's Sexton, Carleton and Studley campuses, for a) Norway maple (N = 283), b) red oak (N = 133) and c) silver linden (N = 111).

Of the 71 tree species identified on the Halifax campuses, only fifteen of these are native to Nova Scotia (Saunders, 1996). Three of these species, red oak, red maple (*Acer rubrum*), and hemlock (*Tsuga canadensis*), were in the top ten most abundant species. Other species included green ash (*Fraxinus pennsylvanica*), white elm (*Ulmus americana*), and white birch (*Betula papyifera*), making up 2.1%, 1.8% and 1.6% of the population respectively. The remaining species were classified in the original inventory as either native to North America or as introduced but non-invasive (i.e., are considered naturalized or unlikely to harm native species). The exception was Norway maple which, in addition to being the most abundant species on the campuses, is considered an invasive species. The *Crimson King* variety of Norway maple, of which there were 18 on the Studley campus, was included as a separate species in the inventory and is also invasive. Appendix B shows a complete list of the tree species coded on the campuses, as well as their origin classifications based on the original inventory.

4.2. Carbon sequestration and storage

The total amount of carbon stored by all the trees on campus was approximately 600 metric tonnes, with 454 tonnes, 87 tonnes and 59 tonnes stored by Studley, Sexton and Carleton campuses respectively (Figure 7). Carbon storage varied both with DBH and with species (Figures 7 and 8). On average (based on the most abundant trees), red elm trees stored the most carbon per tree, followed by silver linden (Figure 8); however, these species also had the two highest average DBH values (Table 1). In general, red oak and red maple showed the greatest increase in carbon storage amongst individual trees with increasing DBH, while species such as silver linden, hemlock and Austrian pine stored noticeably less with increasing DBH.

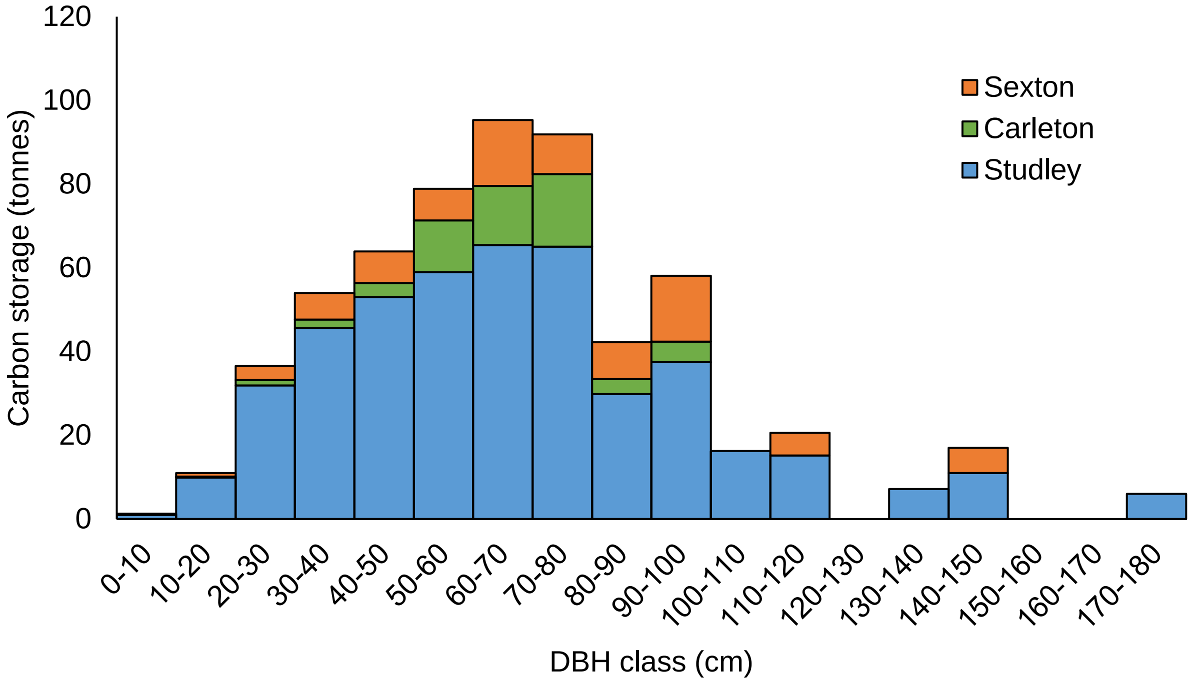

Figure 7. Carbon storage (tonnes) by diameter at breast height (DBH) classes for all trees on Dalhousie University's Sexton, Carleton and Studley campuses, where $N_{Sexton} = 158$, $N_{Carleton} = 125$, and $N_{Studley} = 1254$. Values shown are the total amount of carbon stored within each size class, where the number of individual trees in each size class is shown in Figure 5.

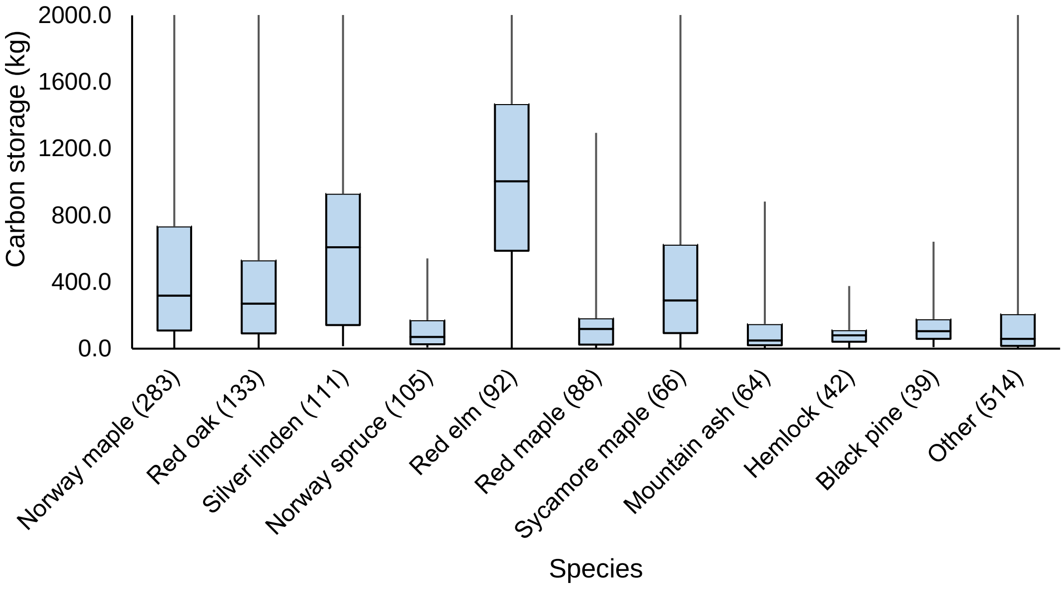

Figure 8. Carbon storage (kg tree^{-1}) for the ten most abundant tree species on Dalhousie University's Halifax campuses. Boxplot bounds represent the 25th, 50th and 75th percentiles of the data. The y-axis is limited to 2000 kg, although for some species with larger trees, maximum storage ≈ 6000 kg.

Carbon sequestration also varied with DBH and with species. The annual sequestration rate of the urban forest as a whole was 16.6 tonnes of carbon year^{-1}, equivalent to 60.9 tonnes of CO_2 year^{-1}. For the individual campuses, sequestration rates were estimated to be 12.9 tonnes of carbon year^{-1} on the Studley campus (47.3 tCO_2e yr^{-1}), 2.1 tonnes of carbon year^{-1} on the Sexton campus (7.7 tCO_2e yr^{-1}), and 1.6 tonnes of carbon year^{-1} on the Carleton campus (5.9 tCO_2e yr^{-1}) (Figure 9). As with carbon storage, red elm and silver linden trees had the highest average sequestration rates of the ten most populous species (Figure 10). However, individual trees showed greater sequestration rates with increasing DBH in particular for species like red maple and red oak. Austrian pine and hemlock again demonstrated a substantially lower sequestration rate with increasing DBH. Interestingly, most species demonstrated multiple linear trends, suggesting a role of other variables included in the model, i.e., crown light exposure and % die-off (Section 4.3). Additionally, although there were few trees with a diameter greater than 100 cm, these trees reflected considerably lower sequestration rates. For example, the largest red oak tree (171 cm in diameter) was estimated to sequester 10 kg C yr^{-1}, while the red oak tree estimated to sequester the most carbon (61.8 kg C yr^{-1}) was 87 cm in diameter.

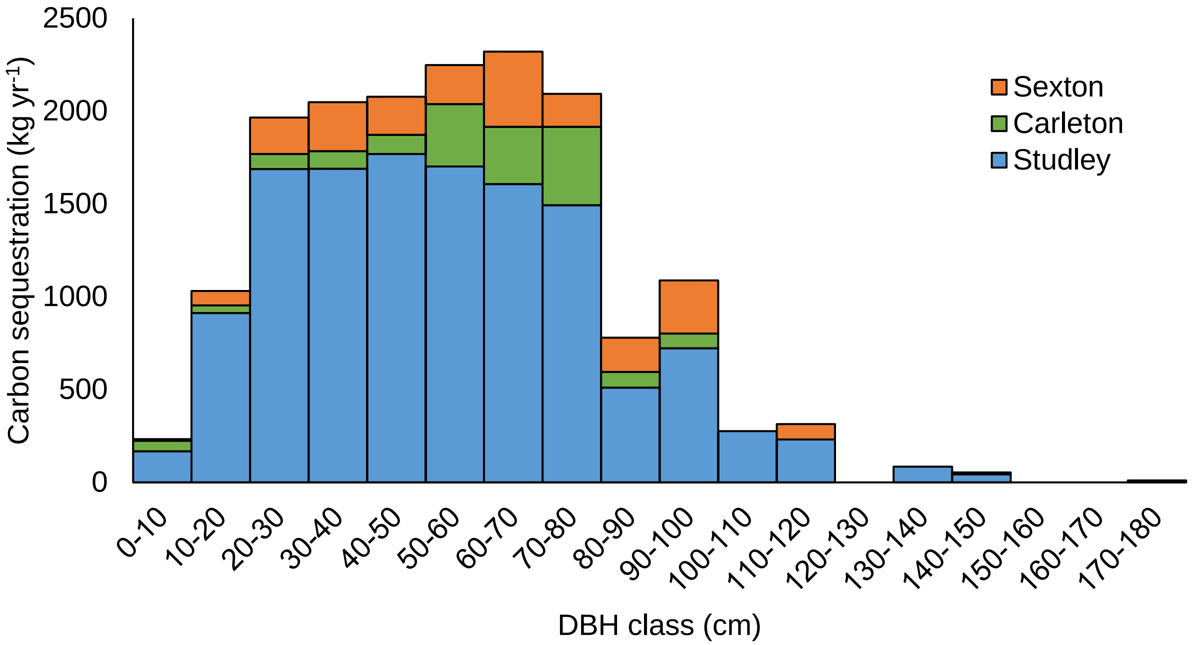

Figure 9. Carbon sequestration (kg yr^{-1}) by diameter at breast height (DBH) classes for all trees on Dalhousie University's Sexton, Carleton and Studley campuses, where N_{Sexton} = 158, $N_{Carleton}$ = 125, and $N_{Studley}$ = 1254. Values shown are the total annual amount of carbon sequestered within each size class, where the number of individual trees in each class is shown in Figure 5.

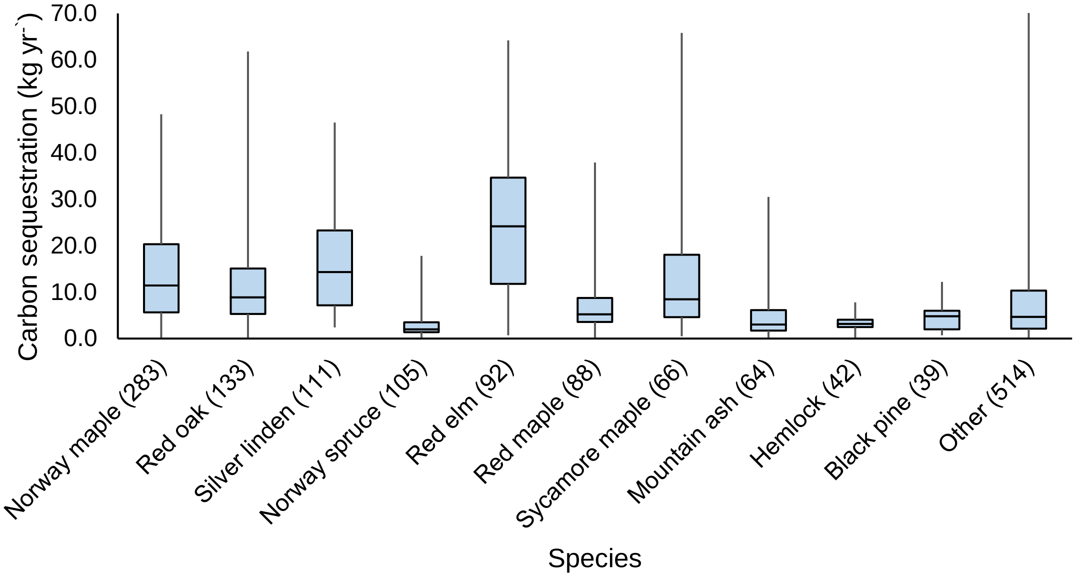

Figure 10. Carbon sequestration (kg yr^{-1} tree^{-1}) for the ten most abundant tree species on Dalhousie University's Halifax campuses. Boxplot bounds represent the 25th, 50th and 75th percentiles of the data. The y-axis is limited to 70 kg yr^{-1}, although for the "other species" category, the maximum value exceeds 90 kg yr^{-1}.

The total amount of carbon stored by species yielded a slightly different ranking than the most common species (Table 2). For example, although Norway maple, the most abundant species, stored the most carbon (24%), the next greatest carbon store was red elm, which ranked fifth in terms of abundance. Conversely, red oak trees were second most abundant but only ranked fourth in terms of carbon storage. This trend was also apparent in terms of carbon sequestration by species, although tree species did not always share the same ranking for both storage and sequestration (for example, red maple ranked sixth in terms of sequestration but seventh in terms of storage).

Other notable results include species such as wild cherry (*Prunus avium*) and Siberian elm (*Ulmus pumila*), which yielded the highest sequestration rates per individual tree, with 47.1 kg yr^{-1} and 40.0 kg yr^{-1} respectively. Each also had high carbon storage values, with 2.4 tonnes and 2.3 tonnes per individual tree for wild cherry and Siberian elm respectively. However, there were a limited number of individuals of these species, with each only having two trees, all located on the Studley campus. The two wild cherry trees had DBH values of 16 cm and 106 cm, while the Siberian elm trees had DBH values of 53 cm and 116 cm.

Table 2. Descriptive characteristics for the top 15 most abundant species on Dalhousie University's Halifax campuses, including the rank value for each species in terms of abundance, total carbon sequestration (tonnes yr^{-1}), and total carbon storage (tonnes).

Species	**N**	**Rank**	**Carbon sequestration (tonnes yr^{-1})**	**Rank**	**Carbon storage total (tonnes)**	**Rank**
Norway maple (*Acer platanoides*)	283	(1)	3.98	(1)	140.3	(1)
Red oak (*Quercus rubra*)	133	(2)	1.69	(4)	61.7	(4)
Silver linden (*Tilia tomentosa*)	111	(3)	1.80	(3)	74.0	(3)
Norway spruce (*Picea abies*)	105	(4)	0.33	(10)	12.3	(8)
Red elm (*Ulmus rubra*)	92	(5)	2.25	(2)	114.9	(2)
Red maple (*Acer rubrum*)	88	(6)	0.66	(6)	14.5	(7)
Sycamore maple (*Acer pseudoplatanus*)	66	(7)	0.77	(5)	32.0	(5)
Mountain ash (*Sorbus aucuparia*)	64	(8)	0.28	(11)	6.3	(12)
Hemlock (*Tsuga canadensis*)	42	(9)	0.13	(14)	3.7	(15)
Austrian pine (*Pinus nigra*)	39	(10)	0.19	(13)	6.7	(11)
Green ash (*Fraxinus pennsylvanica*)	32	(11)	0.09	(15)	3.7	(14)
English oak (*Quercus robur*)	32	(12)	0.46	(8)	11.4	(9)
White elm (*Ulmus americana*)	27	(13)	0.47	(7)	20.2	(6)
White birch (*Betula papyrifera*)	25	(14)	0.34	(9)	8.2	(10)
Sugar maple (*Acer saccharum*)	24	(15)	0.21	(12)	4.2	(13)

4.3. Crown light exposure and % die-off

Carbon storage and sequestration metrics calculated by i-Tree also relied on estimates of crown light exposure (CLE) and % die-off as a proxy for estimating growth rates. Variations in either CLE or % die-off may therefore help account for the variation observed in changes in carbon storage and sequestration with increasing DBH. Crown light exposure is categorized in six different groups, dependent on how many sides of the tree are exposed, where 0 represents minimal light exposure and 5 represents maximum light exposure. Figure 11 shows the percentage of trees assigned each CLE classification for the top ten most abundant species. Most species showed relatively even distributions across the six categories; however, species such as red elm and silver linden tended to have a greater percentage with 4-5 sides exposed. Norway spruce, in particular, had a greater percentage of 0-1 sides exposed, followed by mountain ash.

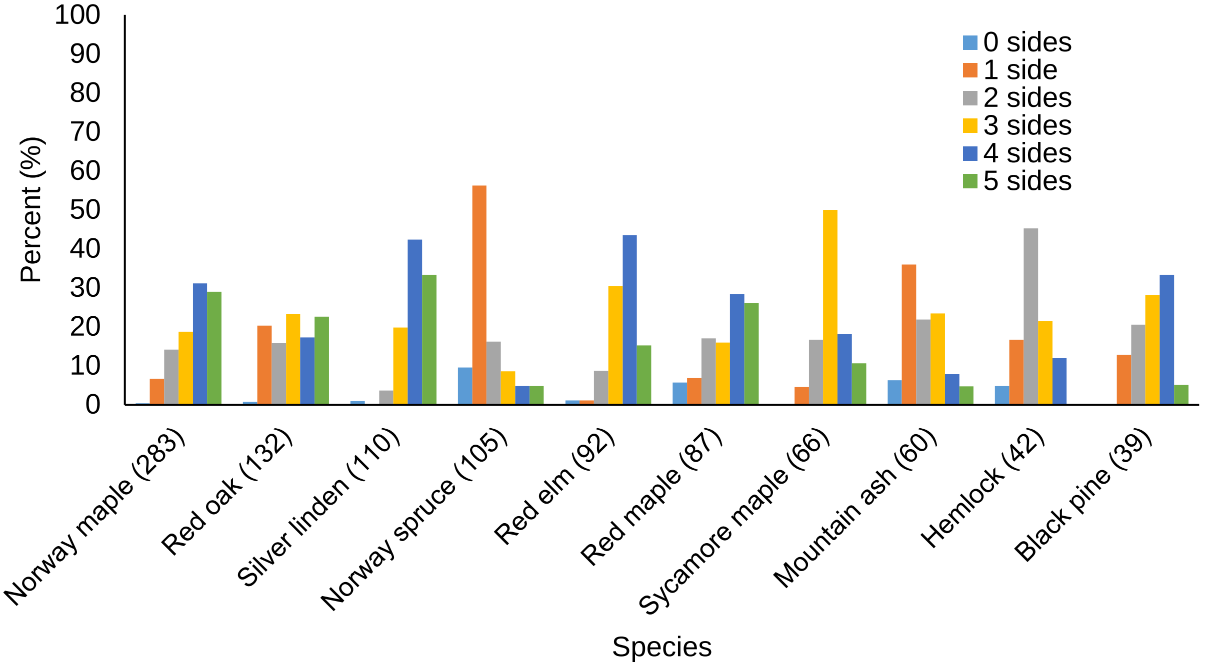

Figure 11. Percent distribution of crown light exposure (CLE) classifications for individual trees of the ten most abundant species on Dalhousie University's Halifax campuses. CLE is characterized on a scale of 0-5, with values representing the number of sides unobstructed to light.

Percent die-off represents an estimate of the total crown cover made up of dead terminal twigs and is likewise assigned to different categories to estimate tree condition. i-Tree Eco assigns percentage values into the following categories: excellent condition (0% die-off), good condition (1-10% die-off), fair condition (10-25% die-off), poor condition (25-50% die-off), critical condition (50-75% die-off), dying (75-99% die-off) and dead (100% die-off). Figure 12 shows the percentage of trees assigned to each tree condition categories for the top ten most abundant species. Nearly all of the species had the majority of trees classified as either in excellent condition or in fair condition, with lower percentages of good or poor condition trees. Exceptions included red elm and Norway spruce, with only 16% and 14% in excellent condition respectively; Norway spruce also had the highest proportion of poor or critical condition trees (36% and 10% respectively).

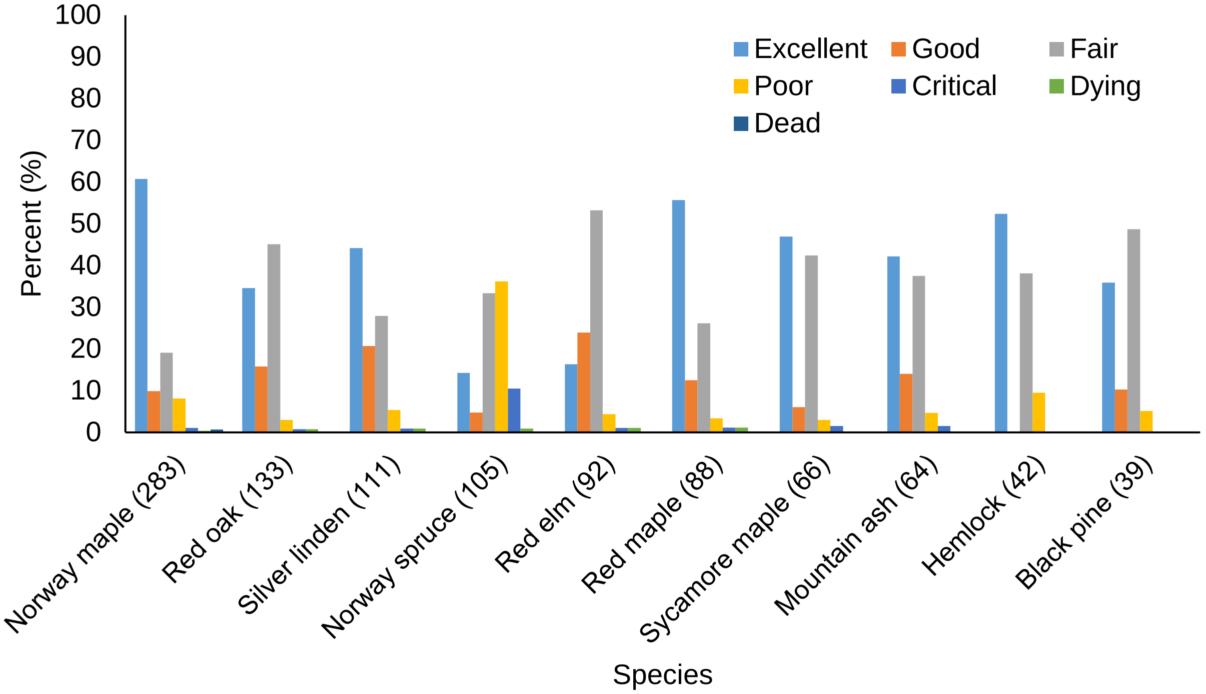

Figure 12. Percent distribution of tree condition classifications for individual trees of the ten most abundant species on Dalhousie University's Halifax campuses. Tree condition is characterized based on estimates of % die-off of crown cover, where excellent = 0%, good = 1-10%, fair = 10-25%, poor = 25-30%, critical = 50-75%, dying = 75-99% and dead = 100%.

4.4. Relation to Dalhousie GHG emissions

The most recent GHG emissions report published by Dalhousie University defines the Scope 1, 2, and 3 emissions released during the 2014-15 fiscal year (April 1, 2014 – March 31, 2015) (Dalhousie Office of Sustainability, 2015). Total GHG emissions from the Halifax campuses were determined to be 86,077 tCO_2e; these were further divided into 28,602 tCO_2e (33.2%) from Scope 1 emissions, 48,840 tCO_2e (56.7%) from Scope 2 emissions, and 8,635 tCO_2e (10.0%) from Scope 3 emissions. In contrast, the annual sequestration rate from the Halifax campuses' urban forest was 60.9 tCO_2e, 0.071% of the total annual emissions.

The Dalhousie GHG inventory provides a further breakdown of the sources of on-campus emissions, with a particular focus on Scope 1 emissions (Dalhousie Office of Sustainability, 2015). For example, GHG emissions from distinct fuel sources used in stationary combustion have been calculated, including furnace oil, propane and natural gas. The majority of emissions are from natural gas; however, the usage of diesel (58.9 tCO_2e) and propane (29.6 tCO_2e) are both less than the campus urban forest sequestration rate. Similarly, the use of refrigerants on Halifax campuses results in 579.13 tCO_2e, of which forest sequestration accounts for approximately 10%. Sequestration could also be considered to offset approximately 37% of Dalhousie's Halifax fleet vehicles emissions (162.42 tCO_2e). Figure 13 summarizes the amount of carbon sequestered or emitted by the urban forest and several minor sources of GHG emissions (refrigerants, diesel, propane and fleet emissions).

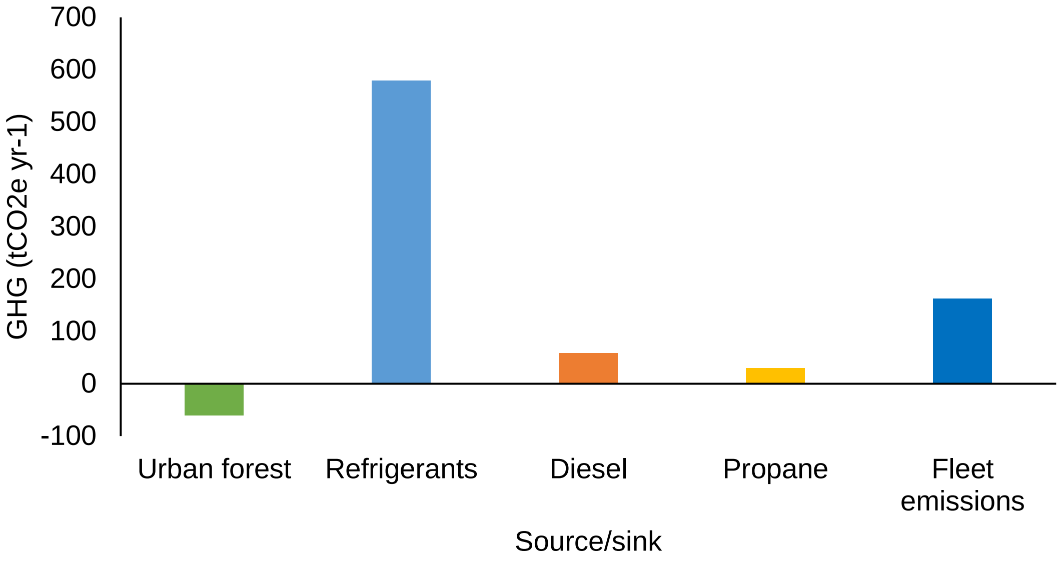

Figure 13. Annual amount of carbon dioxide equivalent (CO_2e) sequestered or emitted by local sinks and sources on the Dalhousie University Halifax campuses. The urban forest sink estimate is based on carbon sequestration values approximated for 2016; sources are taken from Dalhousie University's GHG Inventory Report for the 2014-2015 fiscal year.

5.0. Discussion

The results from this study help characterize the urban forest located on Dalhousie University's Halifax campuses, providing details on species distribution, diversity, size structure, and carbon storage and sequestration. Overall, the three Halifax campuses – Studley, Carleton, and Sexton – showed similar species richness and diversity, but Studley campus had considerably more individual trees (given its larger area) and a higher tree density, resulting in a greater carbon pool. The campuses' urban forest was dominated primarily by Norway maple, an invasive species. Norway maple not only accounted for the majority of trees in terms of abundance, but was also the greatest contributor to carbon sequestration and storage out of any species on the campuses. However, the total amount of carbon sequestered annually by this species, and by the urban forest as a whole, paled in comparison to Dalhousie's annual GHG emissions. This section highlights some of the key trends identified in this study and draws comparisons to similar regional and campus-specific studies, ending with possible recommendations for updating Dalhousie's sustainability policies.

5.1. General data trends

Dalhousie's urban forest profile is similar with respect to species and size structure to other research conducted in the area, both within Halifax specifically (Walsh, 2012; Turner et al., 2005; Nitoslawski & Duinker, 2016) and Nova Scotia as a whole (Saunders, 1996). In general, many of the tree species identified on the campuses are common to the Acadian forest. The Acadian forest is defined as the forest ecoregion covering most of Nova Scotia, New Brunswick, Prince Edward Island, and parts of the northeastern United States, serving as a transition zone between boreal and deciduous forests (Mosseler et al., 2003). Species such as red oak, red maple and hemlock, which were found in high abundance across the Halifax campuses, are widespread across Nova Scotia (Saunders, 1996).

Furthermore, although Norway maple trees are considered to be an invasive species, their dominance on campus is mirrored by their dominance in Halifax as well (Halifax Regional Municipality, 2012; Turner et al., 2005; Nitoslawski & Duinker, 2016). Apart from Norway maple (and the *Crimson King* variety of this species), no other tree on campus was considered to be invasive. However, many were considered to be “naturalized”, meaning they are not indigenous but do not cause ecological harm to native species and are self-sustaining (Turner et al., 2005). Turner et al. (2005) noted that residential neighbourhoods in Halifax tend to have higher species richness than natural forests due to planting and management of species by local residents; similarly, Nitoslawski and Duinker (2016) found that streetscapes in newer neighbourhoods (<15 years) tended to exhibit greater species richness. These observations may help account for the high richness observed on the campuses, which is likely more similar to residential areas than to a natural forest. Apart from Norway maple, other non-native species like silver linden, Austrian pine, and tree lilac (*Syringa reticulata*), which were present in neighbourhoods observed by Nitoslawski and Duinker (2016), were also relatively common within Dalhousie’s tree population.

In terms of the size structure of the urban forest, the majority of the trees on campus were between 10 and 40 cm in diameter, suggesting that the existing forest is relatively young. Different species and growing conditions may support different growth rates, which can make the average age of the forest difficult to determine without direct measurements (Nix, 2016). However, based on estimates of DBH-to-age conversions from the literature (Walsh, 2012), it is likely that most trees on campus are generally less than 50 years old. The presence of a few larger individuals indicate some older trees; for example, the red oak tree with a DBH of 171 cm is located in a remnant oak stand behind Shirreff Hall on the Studley campus and is estimated to be between 250 and 300 years old (Dalhousie Office of Sustainability, 2014). Turner et al. (2005) note that older trees have a higher basal area and therefore have greater biomass and carbon storage. This observation accounts for the differences in distribution between Figures 5 and 7, where most carbon storage occurs in trees between 50 and 80 cm in diameter.

Additionally, it is worth noting that the number of trees recorded in the smallest DBH class (0-10 cm) may not reflect the exact number of saplings present on campus. Although the current size of trees was estimated using literature-derived average growth rates (Nowak et al., 2008), measurements of new trees planted since 2013 were generally not included (Section 3.5). However, the relatively small basal area of these trees suggests a minimal contribution, at least in the current year, to the overall carbon storage and sequestration on campus (Turner et al., 2005). Trees less than 10 cm in diameter sequestered only 1% of the total amount of carbon sequestered by all the trees on campus, despite accounting for 11% or more of the campus urban forest by abundance; furthermore, the total amount stored by these trees was approximately 0.2% of the campus total. These trees are expected to represent a larger proportion of the campus carbon sink in future years, provided they are well maintained and grow to a large size.

5.2. Carbon storage and sequestration

Overall, the total amount of carbon stored by the urban forest on campus was 600 tonnes, with an annual sequestration rate of 16.6 tonnes year^{-1} of carbon. Given an approximate size of 38 hectares (Figures 1-3), the campus carbon pool is therefore approximately 15.7 tonnes ha^{-1} and campus sequestration is approximately 0.437 tonnes ha^{-1} year^{-1}. Nowak et al. (2010)

compared estimates of carbon storage and sequestration for 17 urban forests across North America, with values ranging from 4.9 to 37.7 tonnes ha^{-1} for storage and from 0.202 to 1.233 tonnes ha^{-1} year^{-1}. These findings suggest that Dalhousie University's urban forest fits within the range of typical carbon storage and sequestration values, but the campuses' values are still below the average of the 17 cities (Nowak et al., 2010a; Scharenbroach, 2012). However, the two Canadian cities included in the study, Toronto and Calgary, both had below-average values for carbon storage and sequestration as well (Nowak et al., 2010a). Furthermore, despite having a greater density of trees, Calgary sequestered and stored less carbon per hectare than Toronto (Nowak et al., 2010a). Variations in the local climate (e.g., temperature, precipitation, etc.) as well as differing capacities to manage urban trees may play a role in dictating the maximum storage and sequestration possible in an area.

Carbon storage and sequestration also showed considerable variation between different species. Figure 8 for carbon storage and Figure 10 for carbon sequestration highlight the variation between different species, indicating in particular that dominant species like red elm and silver linden store and sequester more carbon on average than species like Norway spruce or Austrian pine. Other species, like red oak and red maple, showed the greatest increase in carbon sequestration and carbon storage with increasing DBH. Although it is worth noting that the particular trends identified in the figures are a product of the i-Tree Eco model, the findings still help to illustrate the importance of species selection in maximizing carbon sequestration.

Scharenbroach (2012) evaluated the carbon sequestration potential of 145 urban tree species commonly found across North America, using literature-derived growth rates, lifespans, and average tree sizes to estimate maximum carbon storage and annual sequestration rates. Although many of the species evaluated were not found on the Halifax campuses, several of those included in the top 15 most abundant species (Table 2) were considered to have high carbon storage potential (e.g., hemlock and Norway spruce). Overall, however, cedar and larch trees were considered to have the greatest urban tree carbon sequestration and storage potential; additionally, spruce and pine ranked more highly than hardwoods such as maple and oak (Scharenbroach, 2012). These differences may be accounted for by model variation between the methodology used by the i-Tree Eco model and by Scharenbroach (who also included estimates of avoided emissions through energy reduction and emissions from maintenance) (Nowak et al., 2008; Scharenbroach, 2012). Moreover, variation in local climate conditions (where Scharenbroach (2012) focused on Illinois in the United States) or tree health (e.g., most Norway spruce on campus were considered to be in fair or poor condition) may be responsible for the observed differences as well.

The results from this study provide a rationale for maintaining the existing trees on campus, particularly larger trees. Nowak et al. (2010b) note that carbon storage values represent how much carbon is released back to the atmosphere when a tree dies and decomposes; therefore, preventing decomposition through maintenance and selecting long-lived trees should be prioritized (Nowak et al., 2010b; Rostami, 2011). The findings of this study support these statements and illustrate the possible implications on the local carbon sink of removing larger trees (i.e., during construction of new buildings). Despite the majority of trees on campus being between 10 and 40 cm in diameter, the bulk of carbon storage occurred in trees larger than 50 cm in diameter. This result suggests that it may not be sufficient to simply replace larger trees with a set number of smaller trees, which may have implications for the university’s tree maintenance and replacement policies (discussed further in Section 5.4).

Additional characteristics beyond those discussed in this study may also play a role in determining the effectiveness of trees as carbon sinks. Although crown light exposure and % die-off were evaluated for each species (with healthier/more light-exposed trees sequestering more carbon due to better growth conditions), a number of other factors were not considered. These factors include presence of diseases and pests, such as the spruce budworm (*Choristoneura fumiferana*) and the emerald ash borer (*Agrilus planipennis*), which may increase susceptibility of certain species (Nowak et al., 2010b; Department of Natural Resources, 2013); ability to resist climatic changes (Rostami, 2011); and tolerance of urban stressors like poor soil conditions and contamination (Scharenbroach, 2012).

5.3. Comparison to other studies

Several previous studies have also conducted similar inventories of trees on urban university campuses, including the University of Pennsylvania, California State University, and the University of Windsor (Bassett, 2015; Cox, 2012; Davey Resource Group Canada, 2011). Of these universities, the University of Windsor was perhaps the most similar to Dalhousie, with an estimated 1634 trees of 71 species and an estimated sequestration rate of 68.7 tonnes of carbon dioxide year^{-1} (Davey Resource Group Canada, 2011). Located in Southern Ontario, the campus does not fall within the Acadian forest ecoregion (Mosseler et al., 2003); however, similar non-native species, such as Norway maple and Austrian pine, were also dominant (Davey Resource Group Canada, 2011). The University of Windsor campus is approximately 51 hectares, suggesting a lower average tree density than Dalhousie; however, its average per-tree sequestration rate is slightly higher (42 kg CO_2 tree^{-1} year^{-1} versus 39.6 kg CO_2 tree^{-1} year^{-1} at Dalhousie) (Davey Resource Group Canada, 2011).

In comparison, both California State University (CSU) and the University of Pennsylvania ("Penn") sequester considerably more carbon than Dalhousie, with 154 and 125 tonnes of CO_2 year^{-1} respectively. This difference is in large part due to the size of their campuses; both universities have campuses larger than Dalhousie's Halifax campuses (64.7 ha at Penn and 142 ha at CSU) and a greater total number of trees (4086 at Penn and 3900 at CSU) (Bassett, 2015; Cox, 2012). Differences in campus size and tree number help account for the difference in sequestration rates between Dalhousie and CSU; in fact, Dalhousie actually has a higher tree density and per-hectare sequestration rate than CSU. However, Penn shows a greater per-hectare rate of carbon sequestration than Dalhousie. With an average tree density of 63 trees ha^{-1} (compared to Dalhousie's 40 trees ha^{-1}), Penn sequesters 1.9 tonnes CO_2 ha^{-1} year^{-1}, slightly more than the 1.6 tonnes CO_2 ha^{-1} year^{-1} at Dalhousie (Bassett, 2015).

Although local climate, average tree size and species all play a role in determining the carbon sequestration and storage capacity of these campuses, university policies and management may also contribute to the relative success of urban forests as a carbon sink. For example, Penn has made a number of commitments towards increasing its urban tree cover, including participating in an annual "Creating Canopy" tree giveaway program beginning in 2011 and outlining specific initiatives in its Climate Action Plan (Bassett, 2015; University of Pennsylvania, 2014). The Climate Action Plan describes a number of actions related to urban trees, noting in particular the importance of tree planting and increasing tree canopy; the Plan also makes mention of a Campus Tree Care Plan, which details proper maintenance of the trees (University of Pennsylvania, 2014; 2017). Moreover, it references the study by Bassett (2015), although it does not elaborate on how to increase carbon storage (University of Pennsylvania, 2017). Both plans are similar to Dalhousie University's Climate Change Plan and Natural

Environment Plan respectively (Dalhousie Office of Sustainability, 2010; 2014). Similarly, the University of Windsor's Campus Tree Management Plan includes a detailed characterization of the urban forest, including its carbon sequestration and storage estimates, as well as best management practices (Davey Resource Group Canada, 2011). The existence of plans similar to Dalhousie's, particularly those that quantify campus carbon sinks, may be useful in helping to inform updates to best practices.

5.4. University policy and management implications

As discussed in Section 2.3, higher education institutions are considered to play an important role in promoting sustainable education and management (Walton & Galea, 2005; Lemons, 2010). Developing policies that outline climate change-specific mitigation strategies is one way that HEIs can promote sustainability; these strategies are often included in GHG inventories or in climate change action plans (Button, 2009; Cleaves et al., 2009). Dalhousie University, like many other universities, has demonstrated its commitment to climate change action by signing onto agreements such as the University and College Presidents' Climate Change Statement of Action (Smulders, 2009) and by releasing annual GHG inventories (Dalhousie Office of Sustainability, 2015). Additionally, Dalhousie has published several relevant policies pertaining to sustainability, including its Climate Change Plan and its Natural Environment Plan (Dalhousie Office of Sustainability, 2010; 2014). However, as noted in Section 2.4, the university does not currently include a quantified estimate of the carbon stored in its urban forest in its Climate Change Plan, nor does it discuss the potential to incorporate sinks into a carbon offset or crediting scheme.

This study provides information that can be used to update and inform the university's sustainability policies, particularly with respect to urban forest management. The Natural Environment Plan notes that maximizing carbon removal through on-campus vegetation is a university goal; this goal is also listed as a climate action in the Climate Change Plan (Dalhousie Office of Sustainability, 2010; 2014). The results from this study provide a preliminary estimate of on-campus carbon removal, establishing a baseline for future studies and suggesting areas for improvement. In comparing the carbon storage pool and annual sequestration by the campus urban forest to Dalhousie's GHG inventory, the results suggest that the amount of carbon sequestered is almost negligible in comparison to the amount emitted annually. Based on this finding, this study recommends that the university consider expanding its urban forest by planting more trees to increase the current density of the tree population and that it prioritize maintenance of existing large trees on campus.

This study's characterization of the urban forest can help inform strategies for planting new trees and maintaining existing trees, including prioritizing certain species. Several studies outline the importance of selecting species with longer lifespans and fast growth rates to maximize carbon removal (Rostami, 2011; Nowak et al., 2010b). Trees with longer lifespans retain carbon in their tissues for a longer period of time, suggesting a more enduring carbon pool, while faster growing species accumulate more biomass (and thus more carbon) per year (Turner et al., 2005; Scharenbroach, 2012). Although this study did not specifically examine growth rates, it did identify which trees species on campus were storing and sequestering more carbon than average; for example, of the ten most abundant species, red elm sequestered an average of 24.4 kg yr^{-1} $tree^{-1}$, compared to 16.6 kg yr^{-1} $tree^{-1}$ for silver linden and 14.1 kg yr^{-1} $tree^{-1}$ for Norway maple. Red elm trees were on average larger than the other abundant species, which may account for their above-average sequestration rate. Trees such as wild cherry and Siberian elm, which sequestered an average of 47.1 kg yr^{-1} $tree^{-1}$ and 40.0 kg yr^{-1} $tree^{-1}$ respectively, may also be worth considering when expanding the urban forest, given their low abundance on campus.

On the other hand, species like red oak, although sequestering less than the aforementioned species, are native to Nova Scotia and may warrant consideration due to their high adaptability to local conditions and ability to contribute to gene flow (Dalhousie Office of Sustainability, 2014). Red oak also showed the greatest increase in carbon storage and sequestration with increasing DBH of any of the ten most abundant species. They were second-most abundant but had an average DBH of only 36 cm, suggesting a considerable potential for continued growth on campus. Further research should evaluate their contribution to other environmental benefits (e.g., pollution control) and susceptibility to pressures like climate change or disease; however, based on the results from this study, red oak is recommended as a good option for future plantings.

In 2018, the Faculty of Management at Dalhousie is leading a project to plant 200 new trees as part of a celebration of the university's 200th anniversary (P. Duinker, personal communication, March 27, 2017); this study may provide useful considerations for selecting appropriate species for planting, including red oak, as mentioned above. This type of project is crucial for expanding the existing urban forest and improving campus tree density. However, as shown in Figures 7 and 9, small trees (i.e., between 0 and 10 cm in diameter) do not sequester and store much carbon compared to larger trees. These results suggest the importance of continuous planting of seedlings or other young trees over an extended period of time. While projects such as the proposed planting of 200 trees are important, these plantings should be repeated frequently in order to maintain an even size structure of trees on campus and continue developing the campus carbon sink potential. Location of the plantings is also an important consideration (discussed below). Furthermore, efforts to maintain newly planted and existing trees are similarly important. Maintaining existing trees not only allows smaller trees to yield more significant carbon sequestration values as they grow larger, but prevents additional carbon from being released into the atmosphere if large carbon stores are destroyed. In particular, this study recommends implementing protection around the largest trees on campus (e.g., the 171 cm red oak tree behind Shirreff Hall, which stores approximately 6 tonnes of carbon) and limiting development to areas with few large trees so as not to reduce the existing carbon pool.

Dalhousie's Natural Environment Plan also outlines a tree diameter replacement policy, in which any trees removed due to construction must be replaced by a number of smaller trees equivalent in DBH to the size of the tree lost. That is, if a tree with a trunk diameter of 50 cm is removed, ten 5-cm trees must be planted to replace it (Dalhousie Office of Sustainability, 2014). However, the results from this study indicate that the resulting carbon lost during tree removal is not offset by planting numerous smaller trees of an equivalent combined diameter. For example, the average storage per tree for the 0-10 cm DBH class was 7.1 kg C tree^{-1}, compared to 456.4 kg C tree^{-1} for the 40-50 cm DBH class. Although over time each tree may eventually reach the size of the original tree prior to its removal (provided it is maintained well and is not removed in turn), the required amount of growth would likely take several decades. In order to immediately replace the amount of lost carbon sequestration potential, the university should consider an alternative strategy for tree replacement that does not rely on DBH as a proxy for biomass. Instead, a strategy that uses basal area of the trees as a proxy for biomass would provide a better estimate of the amount of tree foliage, and thus carbon sequestration potential, that needs to be replaced through new planting.

By implementing these changes, the university would have the potential to increase the significance of the on-campus vegetation as a carbon sink. Doing so would help fulfil the goals outlined in the Natural Environment and Climate Change Plans (Dalhousie Office of Sustainability, 2010; 2014). Additionally, Dalhousie could increase its standing as an AASHE member, adding further support to its reputation and its role as a leader in sustainability. In the AASHE STARS rating system, universities are able to report their efforts to offset their GHG emissions through a number of sources, including land-based carbon sequestration (AASHE, 2016). Although existing trees would not necessarily count, additional plantings for the specific purpose of offsetting GHG emissions would count towards carbon offset credits and allow Dalhousie to include these values in their reports. This would help address a key knowledge gap, wherein less than 10% of Reporting Institutions had reported any procedures or quantified carbon sequestration, and allow Dalhousie to demonstrate leadership on this issue.

Finally, the university ought to consider additional means of offsetting emissions (e.g., through purchasing third-party credits or developing an external forest plot) in order to have a more significant and quantifiable effect on its annual carbon footprint and to improve its AASHE STARS rating (Ravin & Raine, 2007; AASHE, 2016). Although expanding the urban forest on campus would increase the carbon pool contained within the boundaries of the university, a more immediate and greater impact would be seen if tree planting occurred over a larger area. Previous research has shown the potential for forests to act as considerable carbon sinks on regional and global scales (Natural Resources Canada, 2016a; Canadell & Raupach, 2008; Kurz & Apps, 1999), suggesting that universities could develop more meaningful carbon sinks if they participated in afforestation projects off-campus. Continuous planting, as well as selecting numerous native and fast-growing species (as mentioned above), would ensure even diversity and size structure. Dalhousie, specifically, may also consider the potential for the agricultural campus in Truro to be used for this purpose. The agricultural campus has approximately 183 hectares of green space (e.g., pasture land, greenhouses, and an orchard) (Dalhousie Office of Sustainability, 2014) and would perhaps have potential to be used for an afforestation project. Further research would be needed to evaluate the campus's ability to support this type of project.

5.5. Future work

This study has limited its scope to focusing on the carbon storage benefits of urban forests. There is a considerable body of research that expands on the importance of accounting for additional environmental benefits of trees, including abating energy use, improving air and water quality, enhancing wildlife biodiversity, and providing aesthetic value (Nowak et al., 2010b; Bassett, 2015; Pothier & Millward, 2013). Moreover, cost-benefit analyses can be completed for these additional environmental benefits, as well as for carbon storage and sequestration (Pothier & Millward, 2013). These benefits can be calculated using i-Tree Eco; in fact, estimates of avoided runoff, pollution removal and energy savings are included with the reports generated for annual carbon sequestration and carbon storage (USDA Forest Service, 2016a). Many of the data used in this study could therefore be re-applied to expand the scope to include a greater number of environmental benefits. Doing so may better inform decisions regarding species selection, so that new trees can be chosen to maximize benefits, rather than just carbon storage and sequestration.

Although this study serves as an effective baseline for determining the carbon pool in the on-campus urban forest, future research would benefit from considerable updates to the inventory. This study was primarily limited by use of a secondary data source and uncertainties in the database, including the geographic location of the trees, which made it difficult to re-measure characteristics like height or DBH. Geo-referencing the data would increase the usability of the database and make repeated measurements much easier to complete. Moreover, the inclusion of HRM trees within the original inventory may overestimate the amount of carbon stored by university-owned trees; although the exact number of HRM trees was unknown, they may account for as much as 25% of the inventory. The inventorying process should be completed again with these considerations in mind, so that the database solely reflects Dalhousie's tree population, increasing its relevance as a potential mechanism for determining carbon offset credits in the future. The inventory would also benefit from being updated more consistently (e.g., on an annual basis) to include the planting of new trees and the removal of existing trees. Due to time constraints, it was not possible to include all newly-planted trees since 2013 and it is likely that trees have been removed on campus while still being included in the original inventory.

Applying a consistent methodology as outlined in the i-Tree Eco guide (USDA Forest Service, 2016a) would allow biases in the inventorying processes to be reduced. For example, estimates of % die-off in the existing inventory tended to show a bimodal distribution, with most trees classified as being in excellent condition (0% die-off) or fair condition (10-25%). Although not all measurements would need to be repeated annually, the inventory should be reassessed in its entirety approximately every 10 years to ensure that estimates of height, % die-off and other characteristics remain accurate. Maintenance of the inventory could be an ongoing student project (e.g., for an Environmental Science field school), under supervision of an individual with forestry experience. Furthermore, to account for the full scope of its GHG emission and sinks, Dalhousie University's agricultural campus in Truro should also be inventoried. The agricultural campus emits substantially less GHGs annually than the Halifax campuses, but may yield a greater carbon sink due to its focus on gardening and naturalized landscapes (Dalhousie Office of Sustainability, 2010; 2014). Including this campus in the inventory could also be the first step in evaluating its potential for an afforestation project, as outlined in Section 5.4.

Finally, maintaining the database regularly and evaluating the carbon sequestration rates on an annual basis could yield information on important trends or changes in the carbon sink from year to year. This information could also be used to support the broader framework of urban forest management within HRM. Given the precedence for using i-Tree to calculate the environmental benefits of trees within HRM, as noted in Halifax's Urban Forest Master Plan (HRM, 2012), Dalhousie's inventory and subsequent calculations of carbon sequestration could be incorporated into city-wide estimates of the urban forest carbon sink. As mentioned above, Dalhousie's role as an HEI also suggests a leadership role for implementing sustainability initiatives. If Dalhousie incorporates recommendations from this study into its university policies and continues maintenance of its campus tree inventory, it may set a precedent for improved urban forest management and climate change mitigation on a wider scale.

6.0. Conclusions

This study has examined the importance of urban forests within the context of localized climate change mitigation. The management of carbon sinks is considered to be a key aspect of mitigation strategies, and considerable research has therefore examined the capacity of forest ecosystems to offset GHG emissions (Canadell & Raupach, 2008; Nowak & Crane, 2002). Increased urbanization and potential for habitat loss justify considering the role of urban forests, particularly how these forests may be managed to protect carbon sinks (Churkina, Brown & Keoleian, 2010). Additionally, this study has considered how local organizations, with a particular emphasis on higher education institutions, can support broader frameworks for mitigation and improve their sustainability reputations through managing their own carbon sinks (Measham et al., 2011; Babiak & Trendafilova, 2010). This research therefore aimed to determine the relationship between Dalhousie University’s annual GHG emissions and its urban forest carbon sink.

Through the use of modelling software, carbon sequestration and storage values were determined for each individual tree on Dalhousie’s three Halifax campuses. The existing inventory of all woody plants on these campuses also allowed the urban forest to be characterized in terms of species composition and tree-size distribution. In comparison with Dalhousie’s total annual GHG emissions reported in the 2014-2015 fiscal year, the urban forest sequestration rate represents an almost negligible amount. The findings from this study suggest that Dalhousie still needs to further develop or expand its urban forest, in order to increase the relevance of its on-campus trees to act as a local carbon sink. However, differences in sequestration and storage rates based on species types and size classes will be relevant in managing future forest development. For example, although Norway maple trees were the most abundant and stored the most carbon, red oak trees showed the fastest increase in carbon storage and sequestration with increasing DBH. Red oak also had the added benefit of being native to Nova Scotia, and are therefore the top recommended species for planting. Additionally, although the majority of trees were between 10 and 40 cm in diameter, the bulk of carbon storage was in larger trees (i.e., between 50 and 80 cm), suggesting the importance of maintaining existing trees on campus and limiting destructive development.

Results from this study provide a preliminary baseline for future assessments of the campus urban forest and can be useful in evaluating existing university policies. This study has made recommendations for Dalhousie’s policies pertaining to climate change mitigation and urban forest management, particularly the tree diameter replacement policy, which may be useful for other higher education institutions considering similar management strategies. Further areas of research could focus on updating the existing inventory, including confirming the validity of growth rates used in this project, and on expanding the inventory to include Dalhousie’s agricultural campus in Truro. In particular, the potential of the agricultural campus to be used for a larger afforestation project should be considered. Additional research in this area would allow Dalhousie to expand on and develop the existing work done in urban forest management, meet key university goals pertaining to carbon sequestration, and further strengthen its reputation as a leader in sustainability.

7.0. References

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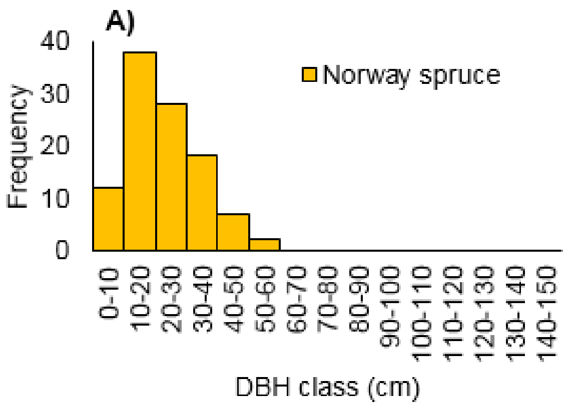
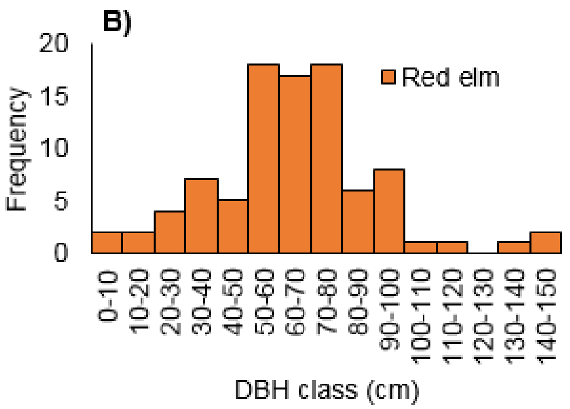
Appendix A


A)
🟨 Norway spruce
Frequency
0
10
20
30
40
0-10
10-20
20-30
30-40
40-50
50-60
60-70
70-80
80-90
90-100
100-110
110-120
120-130
130-140
140-150
DBH class (cm)


B)
🟧 Red elm
Frequency
0
5
10
15
20
0-10
10-20
20-30
30-40
40-50
50-60
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90-100
100-110
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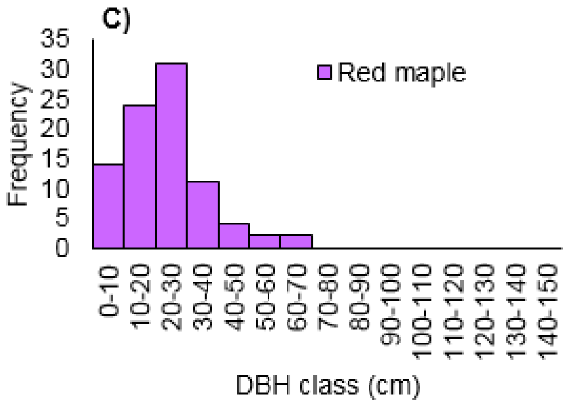
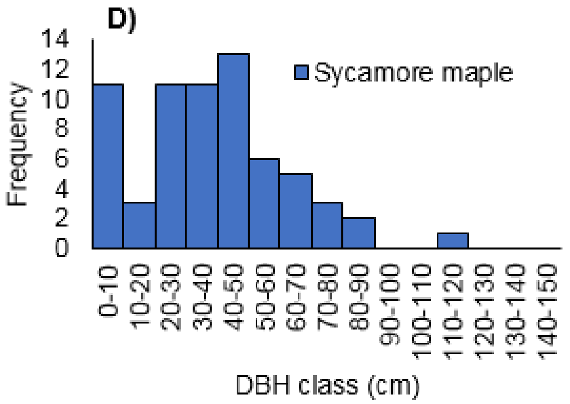
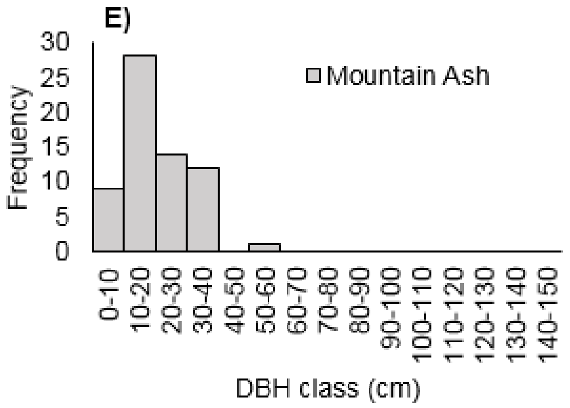
120-130
130-140
140-150
DBH class (cm)


C)
🟪 Red maple
Frequency
0
5
10
15
20
25
30
35
0-10
10-20
20-30
30-40
40-50
50-60
60-70
70-80
80-90
90-100
100-110
110-120
120-130
130-140
140-150
DBH class (cm)


D)
🟦 Sycamore maple
Frequency
0
2
4
6
8
10
12
14
0-10
10-20
20-30
30-40
40-50
50-60
60-70
70-80
80-90
90-100
100-110
110-120
120-130
130-140
140-150
DBH class (cm)


E)
⬜ Mountain Ash
Frequency
0
5
10
15
20
25
30
0-10
10-20
20-30
30-40
40-50
50-60
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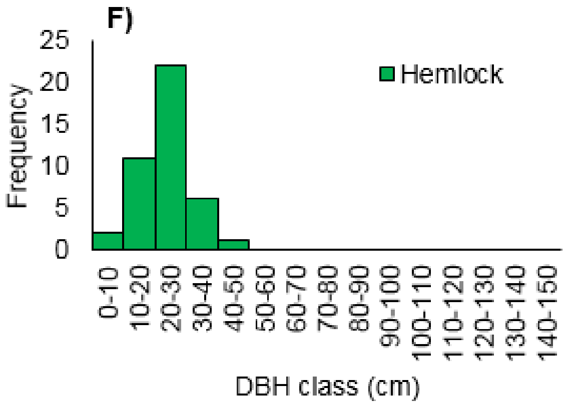
120-130
130-140
140-150
DBH class (cm)


F)
🟩 Hemlock
Frequency
0
5
10
15
20
25
0-10
10-20
20-30
30-40
40-50
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140-150
DBH class (cm)

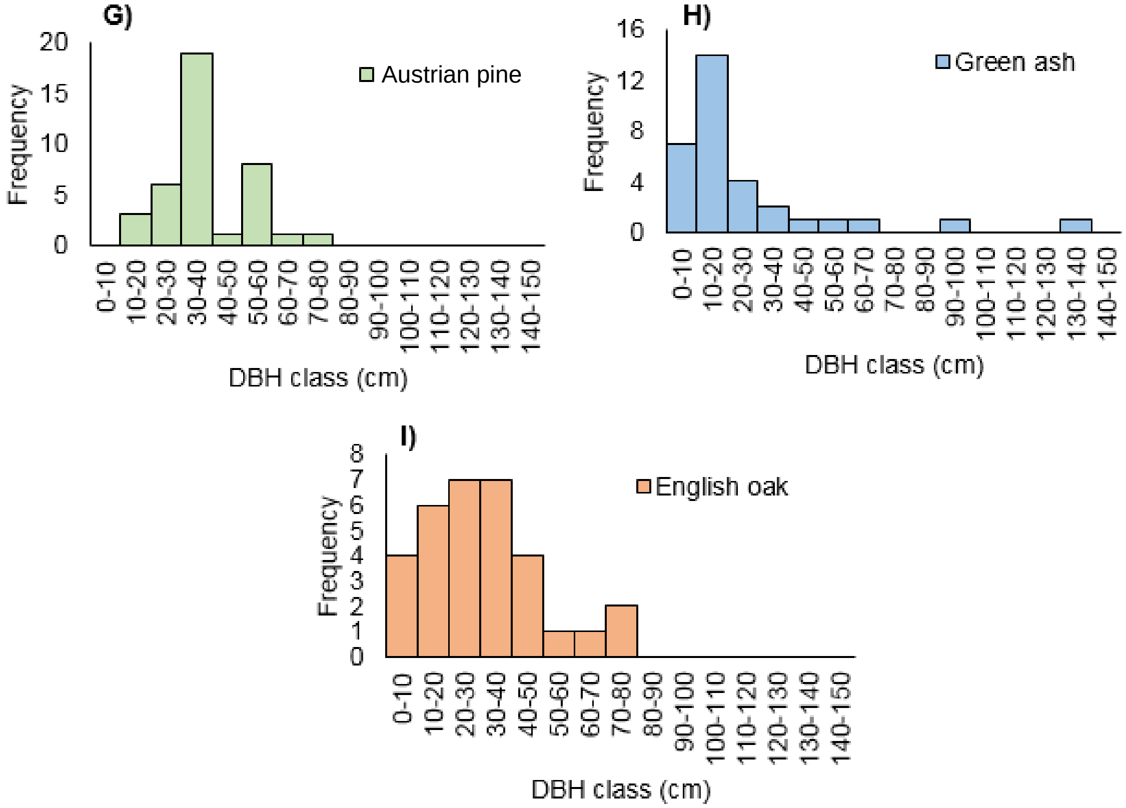

Figure 14. Size class distribution of trees by diameter at breast height (DBH) on Dalhousie University’s Sexton, Carleton and Studley campuses, for a) Norway spruce (N = 105), b) red elm (N = 92), c) red maple (N = 88), d) sycamore maple (N = 66), e) mountain ash (N = 64), f) hemlock (N = 42), g) Austrian pine (N = 39), h) green ash (N = 32) and i) English oak (*Quercus robur*) (N = 32).

Appendix B

Table 3. Trees species coded on Dalhousie University's Halifax campuses (N = 71). Origin is coded as follows: 1 = native to Nova Scotia; 2 = native to North America; 3 = introduced and naturalized; 4 = introduced but not naturalized; and 5 = invasive. Origin classifications are from the original tree inventory collected in 2009-10.

Botanical name	Common name	Origin
Abies balsamea	Balsam fir	1
Abies concolor	White fir	2
Acer amurense	Amur maple	4
Acer campestre	Hedge maple	4
Acer griseum	Paper bark maple	4
Acer negundo	Box elder	2
Acer palmatum	Japanese maple	4
Acer platanoides	Norway maple	5
Acer platanoides 'Crimson King'	Crimson King	5
Acer pseudoplatanus	Sycamore maple	3
Acer rubrum	Red maple	1
Acer saccharinum	Silver maple	2
Acer saccharum	Sugar maple	1
Aesculus glabra	Buckeye	2
Aesculus hippocastanum	Horse chestnut	4
Betula papyrifera	White birch	1
Betula pendula	Silver birch	4
Betula populifolia	Grey birch	1
Castanea dentata	American chestnut	2
Celtis occidentalis	Hackberry	2
Chamaecyparis pisifera	False cypress	4
Cladrastis lutea	Yellowwood	2
Crataegus monogyna	European hawthorn	4
Fagus sylvatica	European beech	4
Fraxinus americana	White ash	1
Fraxinus pennsylvanica	Green ash	1
Gingko biloba	Gingko	4
Gleditsia tricanthos	Honey locust	2
Juniperus scopulorum	Rocky Mountain juniper	4
Juniperus virginiana	Eastern red cedar	2
Larix decidua	European larch	4
Lirodendron tulipifera	Tulip tree	2
Magnolia soulangeana	Saucer magnolia	4

Magnolia stellata	Star magnolia	4
Malus domestica	Apple tree	3
Malus sp.	Crab-apple	3
Metasequoia glyptostroboides	Dawn redwood	4
Morus alba	Weeping white mulberry	4
Phellododendron amurense	Cork tree	4
Picea abies	Norway spruce	4
Picea glauca	White spruce	1
Picea pungens	Colorado spruce	2
Picea rubens	Red spruce	1
Pinus banksiana	Jack pine	1
Pinus mugo	Mugo pine	4
Pinus nigra	Austrian pine	4
Pinus resinosa	Red pine	1
Pinus sylvestris	Scotch pine	4
Platanus x acerifolia	Plane tree	4
Populus x canadensis	Carolina poplar	3
Prunus avium	Mazzard cherry	3
Prunus serrulata	Japanese cherry	4
Pyrus sp.	Pear tree	4
Quercus palustris	Pin oak	2
Quercus robur	English oak	4
Quercus rubra	Red oak	1
Quercus veluntina	Black oak	2
Robinia pseudoacacia	Black locust	2
Salix alba	White willow	3
Sorbus aucuparia	Mountain ash	4
Syringa reticulata	Tree lilac	4
Thuja occidentalis	White cedar	1
Tilia americana	Redmond linden	2
Tilia cordata	Little leaf linden	4
Tilia tomentosa	Silver linden	4
Tsuga canadensis	Hemlock	1
Ulmus americana	White elm	1
Ulmus glabra	Scotch elm	4
Ulmus pumila	Siberian elm	3
Ulmus rubra	Red elm	2
Zelkova serrata	Japanese elm	4