Potential Urban Forest Carbon Sequestration and Storage Capacities in Burnside Industrial Park, Nova Scotia

by

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Signature of Author

For my mother

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LIST OF ABBREVIATIONS USED

AG	Above-ground
BG	Below-ground
BIP	Burnside Industrial Park
C	Carbon
CAD	Canadian Dollars
dbh	Diameter at breast height
DSF	David Suzuki Foundation
GHG	Greenhouse gas
GIS	Geographic information system
HRM	Halifax Regional Municipality
IPCC	Intergovernmental Panel on Climate Change
tCO_2e	Metric tonnes carbon dioxide equivalents
UFMP	Urban forest master plan
UHI	Urban heat island
USD	American Dollars
USGAO	United States Government Accountability Office

ABSTRACT

Urban and industrial settings represent potential areas for increased carbon (C) sequestration and storage through intensified tree growth. Consisting of an estimated 1270 ha of land once entirely forested, Burnside Industrial Park (BIP) in Dartmouth, Nova Scotia. Our study examines the degree to which intensified urban tree planting within the BIP ecosystem could enhance C sequestration and storage. This was achieved by conducting a geospatial analysis in combination with construction of a C model. Three scenarios urban forest development were examined. If all potential planting spots are filled with trees by 2020, an estimated 26,368 tC, at a sequestration rate of 635 tC/yr, could be achieved by 2050. Next, we explored the challenges and opportunities associated with pursuing C offset markets as a means for funding urban forest development within BIP. A basic framework from which a community-based C offset market could potentially be established was recommended.

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CHAPTER 1: INTRODUCTION

1.1 Problem Statement

In response to the growing concerns surrounding the relationship between anthropogenic greenhouse gas (GHG) emissions and the potential impacts of climate change, much time, energy, and effort in the realm of climate change research have been focused on determining the most logical and practical steps to mitigate potential impacts (IPCC, 2005). Carbon dioxide (CO_2) is a GHG of particular interest because of the degree to which anthropogenic activities, primarily fossil-fuel consumption and land-use change via deforestation, have been able to influence its presence within the atmosphere (IPCC, 2007; UNCCC, 2007; Sundquist et al., 2009). Upon compiling a special report outlining viable options for CO_2 capture and storage, the Intergovernmental Panel on Climate Change (IPCC) identified five technological options for mitigating atmospheric CO_2 levels. One of these options was enhancing biological absorption capacity of the earth's terrestrial carbon (C) stores (IPCC, 2005).

Trees, as the major biota within forest ecosystems, play a critical role within the global C cycle. The world's forests have potential to act as global C sinks because they directly sequester and store atmospheric CO_2 as biomass through biological processes (Ajtay et al., 1971; Kurz et al., 2002; Nieder and Benbi, 2008). As such, there has been a proliferation of research investigating the importance of preservation and enhancement of forest C sinks via conservation, afforestation, and reforestation efforts (Dixon et al., 1994; Kurz et al., 2002; Luyssaert et al., 2008; White et al., 2008). Traditionally, these efforts have been concentrated within the rural and hinterland settings. However, many other researchers have been examining the potential of improving urban forest structure as an additional and underexploited opportunity for enhancing biological C sequestration and storage specifically within urban landscapes (e.g. Rowntree and Nowak, 1991; McPherson, 1998; Brack, 2002; Nowak and Crane, 2002; Nowak et al., 2008).

For the first time in history, the majority of the world's population is currently estimated to reside within urban areas (UN-Habitat, 2009). This recent trend of rural-to-urban migration is one that is expected to continue into the future (Grimm et al., 2008; UN-Habitat, 2009). The process of urbanization is directly associated with the two primary anthropogenic activities contributing atmospheric CO_2 levels - fossil-fuel consumption and land-use change via deforestation (Pataki et al., 2006; Grimm et al., 2008). Fortunately, urban forest development can help mitigate atmospheric CO_2 levels through biological sequestration and storage, while also providing a number of other benefits to the community at large for the single cost of planting and maintaining a tree (Dwyer et al., 2000; Nowak, 2006; Carreiro, 2008). These benefits include improved air and water quality (Dwyer et al., 1992; Nowak, 1994; Yang et al., 2005), increased opportunities for recreation, leisure, and relaxation (Dwyer et al., 1992; Peckham, 2010), and reduced energy demands associated with heating and cooling of buildings (Heisler, 1986; Akbari et al., 1997). As such, much interest has been directed toward how communities could better understand the urban forest as a valuable resource, in addition to exploration of strategies to optimize benefits associated with urban forest maintenance and enhancement.

1.2 Project Overview

The primary purpose of this research is to examine the extent at which C sequestration and storage within an urbanized landscape might be enhanced under three scenarios of urban forest development. The study site, Burnside Industrial Park (BIP), located in Dartmouth, Nova Scotia, is a light industrial and commercial park that has been subject to intensified anthropogenic development pressure over the past forty years. The BIP landscape exhibits many characteristics of low-density urban sprawl pattern of development. Urbanization of this area has undoubtedly contributed to levels of atmospheric CO_2 through fossil-fuel-using activities, as well as land-use change via deforestation, as its continued development encroaches onto lands currently forested.

1.2.1 Research questions

The following research questions provided the guidance from which this study was conducted:

- How much C is stored by the BIP urban forest today (2010)?
- What is the potential for future C sequestration and storage in the 2050 BIP urban forest, under the following three urban-forest development scenarios:
    1. Maintenance of the 2010 urban forest population of trees;
    2. Maintenance of the 2010 urban forest in addition to planting 50% of all 2010 vacancies (i.e., plantable spot); and
    3. Maintenance of the 2010 urban forest in addition to planting 100% of all 2010 vacancies.
- To what extent might development of the BIP urban forest be financed through local businesses purchasing C credits through current C-offset markets?

1.2.2 Research objectives

Several research objectives were established and served as the stepping stones to support my approach in answering the previously identified research questions, and are as follows:

- Create an original land-cover classification system and subsequent land-cover map of the current BIP landscape to estimate capacity for future tree-planting scenarios.
- Develop and parameterize an original urban-forest C budget model to estimate current and future C sequestration and storage potentials of the BIP urban forest under three urban-forest development scenarios identified by the research questions.

- Through conducting an extensive literature review, assess the extent to which an intensified tree-planting program within BIP might be financed through local businesses purchasing C credits based on compliance with standards of current premier C offsets.

1.2.3 Structure of the thesis

This thesis has been divided into six chapters. *Chapter 2* explores and presents an overview of current literature to provide the contextual backdrop of this research, and focuses primarily on previous studies that assess C sequestration and storage potentials of urban forest development. *Chapter 3* provides a comprehensive overview of the methods chosen to satisfy the identified research questions and associated objectives. *Chapter 4* and *Chapter 5* are presented as stand-alone articles for submission to peer-reviewed journals, within which results and consequent discussions are found. *Chapter 6*, the final chapter, provides a summary of the primary conclusions of my research, as well as identifies venues and direction for future research efforts.

1.3 References

Ajtay, G.L., Ketner, P., & Duvigneaud, P. (1977). Terrestrial primary production and phytomass. In B. Bolin, E.T. Degens, S. Kempe, & P. Ketner (Eds.), *The global carbon cycle* (pp. 129-236). New York, NY: John Wiley & Sons.

Akbari, H., Kurn, D.M., Bretz, S.E., & Hanford, J.W. (1997). Peak power and cooling energy savings of shade trees. *Energy and Buildings, 25*, 139-148.

Brack, C. (2002). Pollution mitigation and carbon sequestration by an urban forest. *Environmental Pollution, 116*, S195-S200.

Carreiro, M.M. (2008). Introduction: The growth of cities and urban forestry. In M.M. Carreiro, Y.-C. Song, & J. Wu (Eds.), *Ecology, planning, and management of urban forests* (pp. 3-9). New York, NY: Springer Science.

Dixon, R.K., Brown, S., Houghton, R.A., Solomon, A.M., Trexler, M.C., & Wisniewski, J. (1994). Carbon pools and flux of global forest ecosystems. *Science, 263*, 185-191.

Dwyer, J.F., McPherson, E.G., Schroeder, H.W., & Rowntree, R.A. (1992). Assessing the benefits and costs of the urban forest. *Journal of Arboriculture, 15*, 247-252.

Dwyer, J.F., Nowak, D.J., Noble, M.H., & Sisinni, S.M. (2000). Connecting people with ecosystems in the 21st century: An assessment of our nation's urban forests (General Technical Report PNW-GTR-490). Retrieved from United States Forest Service: http://www.treesearch.fs.fed.us/pubs/29448

Ewing, R.H. (2008). Characteristics, causes, and effects of sprawl: A literature review. In Marzluff, J.M., Shulenberger, E., Endlicher, W., Alberti, M., Bradley,G., Ryan, C., … & Simon, U., *Urban ecology: An international perspective on the interaction between humans and nature* (pp. 519-535). New York, NY: Springer Science.

Grimm, N.B., Faeth, S.H., Golubiewski, N.E., Redman, C.L., Wu, J., Bai, X., & Briggs, J.M. (2008). Global climate change and the ecology of cities. *Science, 319*, 756-560.

Heisler, G.M. (1986). Energy savings with trees. *Journal of Arboriculture, 12*(5), 113-125.

Intergovernmental Panel on Climate Change (IPCC). (2005). *IPCC special report on carbon dioxide capture and storage.* London, UK: Cambridge University Press.

Intergovernmental Panel on Climate Change (IPCC). (2007). Climate change 2007: The physical science basis. In S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor & H.L. Miller (Eds.), *Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change.* Cambridge, UK: Cambridge University Press.

Kurz, W.A., Apps, M., Banfield, E., & Stinson, G. (2002). Forest carbon accounting at the operational scale. *The Forestry Chronicle, 78*(5), 672-679.

Luyssaert, S., Schulze, E.-D., Börner, A., Knohl, A., Hessenmöller, D., Law, B.E., … & Grace, J. (2008). Old-growth forests as global carbon sinks. *Nature, 455*, 213-215.

McPherson, E.G. (1998). Atmospheric carbon dioxide reduction by Sacramento's urban forest. *Journal of Arboriculture, 24*(4), 215-223.

Nieder, R., & Benbi, D.K. (2008). Carbon and nitrogen pools in terrestrial ecosystems. In R., Nieder, & D.K. Benbi (Eds.), *Carbon and nitrogen in the terrestrial environment* (pp. 5-43). New York, NY: Springer.

Nowak, D.J. (1994). Atmospheric carbon dioxide reduction by Chicago's urban forest. In E.G. McPherson, D.J. Nowak, & R.A. Rowntree (Eds.), *Chicago's urban forest ecosystem: Results of the Chicago urban forest climate project* (pp. 83-94) (General Technical Report NE-186). Retrieved from United States Forest Service: http://www.treesearch.fs.fed.us/pubs/4285

Nowak, D.J. (2006). Institutionalizing urban forestry as a "biotechnology" to improve environmental quality. *Urban Forestry & Urban Greening, 5*, 93-100.

Nowak, D.J., & Crane, D.E. (2002). Carbon storage and sequestration by urban trees in the USA. *Environmental Pollution, 116*(3), 381-389.

Nowak, D.J., Crane, D.E., Stevens, J.C., Hoehen, R.E., Walton, J.T., & Bond, J. (2008). A ground-based method of assessing urban forest structure and ecosystem services. *Arboriculture and Urban Forestry, 34*(6), 347-358.

Pataki, D.E., Alig, R.J., Fung, A.S., Golubiewski, N.E., Kennedy, C.A., McPherson, E.G., … & Lankao, P.R. (2006). Urban ecosystems and the North American carbon cycle. *Global Change Biology, 12*(11), 2092–2102.

Peckham, S. (2010). *Nature in the city: Ecological consciousness development associated with naturalized urban spaces and urban forest values in Calgary, AB and Halifax, NS* (Unpublished master's thesis). Dalhousie University, Canada.

Rowntree, R.A. (1984). Ecology of the urban forest: Introduction to part I. *Urban Ecology, 8*, 1-11.

Sundquist, E.T., Ackerman, K.V., Parker, L., & Huntzinger, D.N. (2009). An introduction to global carbon cycle management. In B.J. McPherson & E.T. Sundquist (Eds.), *Carbon sequestration and its role in the global carbon cycle* (pp. 1-23). Washington, DC: American Geophysical Union.

United Nations Climate Change Conference (UNCCC). (2007). *Uniting on climate change*. Retrieved April 13, 2011 from http://unfccc.int/resource/docs/publications/unitingonclimate_eng.pdf

United Nations-Habitat (UN-Habitat). (2009). *Planning sustainable cities: Global report on human settlements 2009*. Sterling, VA: Earthscan.

White, T., Luckai, N., Larocque, G.R., Kurz, W.A., & Smyth, C. (2008). A practical approach for assessing the sensitivity of the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3). *Ecological Modelling, 219*, 373-382.

CHAPTER 2: LITERATURE REVIEW

2.1 Global Climate Change, Atmospheric Carbon Dioxide, and People

The threat of global climate change is a serious and pending issue for 21st century society. Although fluctuations of the earth's climate are known to occur naturally, it is now a widely accepted notion that anthropogenic activities are a primary force driving new, threatening, and dramatic alterations to the earth's climate (IPCC, 2007a; UNCCC, 2007). Observed changes in surface air temperatures, arctic temperatures, precipitation patterns, ocean salinity, and occurrences of extreme weather events are examples of ways the earth's climate has already began to transform (IPCC, 2007a; UNCCC, 2007). Some anticipated future impacts of climate change identified by Working Group II of the Fourth Assessment Report produced by the IPCC include increased global mean temperatures, sea-level rise, decreased access to freshwater resources (particularly within coastal zones), extinction of climatically sensitive biota, and continued intensification of extreme weather events (IPCC, 2007b).

Although life on earth depends on the presence of atmospheric GHGs for maintaining a habitable climate, relatively recent increasing atmospheric GHG levels associated with human activities have been recognized as a driver of global climate change (Keeling, 1973; Gouldie and Viles, 1997; UNCCC, 2007; UNFCCC, n.d.). There are several GHGs of climatic concern; CO_2 is of particular interest because of the extent to which human activities have been able to influence its presence within the atmosphere (IPPC, 2005; IPCC, 2007a; UNCCC, 2007; Sundquist et al., 2009). Strong relationships have been established between increasing atmospheric CO_2 levels and Earth's rising surface air temperature – a pattern that has only become increasingly more apparent since the mid 19th century (Keeling, 1973; IPCC, 2007a; Vitousek et al., 1997; UNFCCC, n.d.). The two principal ways people are augmenting atmospheric CO_2 levels are through: 1) the combustion of fossil fuels; and 2) land use and land-use change, primarily via deforestation (Dixon et al., 1994; UNCCC, 2007; Sundquist et al., 2009). Both of these activities are innately associated with urbanizing landscapes (Pataki et al., 2006; Grimm et al., 2008).

2.1.1 Living in an urban era

Today's global population resides predominately in urban areas. This is a trend the world has not seen before. Approximately 50% of the earth's human inhabitants are estimated to live in cities, a figure that is only expected to increase years to come (Grimm et al., 2008; UN-Habitat, 2009). The same trend of urban migration also exists in Canada. This is demonstrated by the results of the 2006 Canadian census, where approximately 80% (~25,000,000) of all Canadians were estimated to reside within urban areas (Statistics Canada, 2009). Urbanization entails the concentration of people into smaller areas of land (Tisdale, 1942). In Canada, an urban area is officially defined by Statistics Canada (2007) as having "… a minimum population concentration of 1,000 persons and a population density of at least 400 persons per square kilometre, based on the current census population count" (para. 2).

How an urban area is developed and arranged spatially will subsequently influence how it will affect levels of CO_2 (Pataki et al., 2006). Although there is a lack of consensus as to what, precisely, low-density urban sprawl is, there are several common characteristics associated with this type of urban development pattern that frequently emerge from the literature. For the purpose of this research, I am choosing to define low-density urban sprawl using the following three predominant characteristics: 1) distinct segregation of land uses; 2) low-density development; and 3) dependence on automobiles for movement within the area identified as low-density sprawl (Sierra Club, 1998; Johnson, 2000; Frumkin, 2002; Squires, 2002; Kahn, 2006; Pataki et al., 2006).

Aside from the climate-change implications related to atmospheric CO_2 levels, there are other environmental impacts associated anthropogenic activities, regardless of their geographic location. Examples of environmental impacts associated with urbanization include decreased air and water quality, disruption of natural ecological cycles (e.g. biogeochemical, hydrological), as well as loss of wildlife habitat and native plant biodiversity (Raedeke and Raedeke, 1995; VanMetre et al., 2000; McKinney, 2002; Duh et al., 2008; Ewing, 2008; Grimm et al., 2008). Cities also impose a number of environmental impacts upon themselves, as inherently related to the urbanization process. Examples of these impacts include increased volume and pollutant loading of stormwater runoff, creation of urban heat islands, and amplified concentrations of heavy metals, including (but not limited to) mercury, lead, and zinc (Oke, 1995; Tsihrintzis and Hamid, 1997; Sieghardt et al., 2005). Patterns of low-density urban sprawl are of concern because they encourage the use of private automobiles as a primary source of transportation and movement between land-use zones (resulting in increased fossil-fuel combustion (Frumkin, 2002; Kahn, 2006)), and encourage the transformation of large amounts of land, resulting in CO_2 release via deforestation via land-use change (Ajtay, et al., 1977; Watson et al., 2000; Kahn, 2006).

2.2 What is an Urban Forest?

Although varying throughout the literature, the term *urban forest* generally refers to all trees, both naturally occurring and purposefully planted, found within an urban area (Rowntree, 1984; Randrup et al., 2005; Ordóñez and Duinker, 2010). Past and current research efforts dedicated to enhancing the understanding of urban forests within communities have helped reveal their implications within environmental, social, and economic realms, which are discussed within *Section 2.3* and *Section 2.4* (McPherson et al., 1994; McPherson and Simpson, 1999; Dwyer et al., 2000; Nowak et al., 2006; Nowak and Dwyer, 2007). Urban forests possess many characteristics that ultimately influence the degree to which a community experiences their effects.

As such, each urban forest is unique to the community it is a part of (Peckham, 2010). However, before discussing the characteristics and associated effects of urban forests, it is important to establish how they differ from their rural and hinterland counterparts.

2.2.1 Urban versus rural forests

I have chosen to compare and contrast urban and rural forests from a structural standpoint, because forest structure influences essentially all services, functions, and characteristics associated with forests, regardless of their location (Sanders, 1984; Nowak, 1994a; Zipperer et al., 1997; Pickett and Cadenasso, 2008; Ordóñez and Duinker, 2010). Forest structure is influenced by three basic factors: 1) area available for tree growth; 2) natural and environmental conditions; and 3) anthropogenic management systems (Sanders, 1984; Nowak, 1994a; Zipperer et al., 1997; Pickett and Cadenasso, 2008). These factors are discussed below.

1) Area available for tree growth

The physical morphology of urban and rural landscapes is an important factor influencing forest structure because it directly dictates the amount and type of land on which trees could potentially grow. Urban landscapes are highly heterogeneous, as they are composed of a wide diversity of natural and anthropogenic land cover types (Cadenasso et al., 2007; Pickett et al., 2011). The presence of urban infrastructures (e.g. buildings, transportation networks) effectively limit the total physical space available for tree planting in urban areas (Nowak, 1994a; Bradley, 1995a; 1995b; Pauliet and Duhme, 2000). As a result, the density of trees within urban forests is substantially lower than those within surrounding rural and hinterland forest settings (McDonnell and Pickett, 1990; McDonnell et al., 2008).

2) Natural and environmental conditions

Differences in both abiotic and biotic environmental conditions in urban and rural forest settings influence subsequent forest structure (McDonnell and Pickett, 1990;

Sieghardt et al., 2005; Tello et al., 2005; Pickett et al., 2011). The density at which trees are able to grow affects the physical structure of the trees themselves. As a result, trees grown in more open, urban areas at lower densities, although generally shorter, tend to develop larger, denser above-ground (AG) biomass than those found in a rural forest setting, where trees tend to have larger proportions of below-ground (BG) biomass (Spurr and Barnes, 1980; McPherson, 1993; McHale et al., 2009). Urban forests also tend to be highly fragmented, as landscape fragmentation and ecosystem disruption are two impacts directly associated with urbanization (LaPaix and Freedman, 2010).

3) Management systems

Various goals and objectives of forest management programs inform decisions surrounding the structural management of urban and rural forests. Rural forests are traditionally managed in one of two ways: 1) to satisfy industrial production needs (e.g. timber), or 2) to enhance non-industrial forest values, such as wildlife habitat or environmental services (Costanza et al., 1987; Freedman and Keith, 1995). Conversely, the goal of an urban forest management plan may be to enhance the aesthetic and recreational value of a particular area (Schroeder and Green, 1985; Nowak, 1994a), or to fulfil a biophysical need, such as enhancing C sequestration and storage, or reducing volumes of stormwater runoff (Dwyer et al., 2000; Nowak and Dwyer, 2007). Each forest's management program is unique and is tailored to meet specific objectives, and thereby influences the structure of the landscape under management.

Based on the preceding three factors, resulting structures of urban and rural forests influence how they are able to interact and subsequently affect their surrounding environments and inhabitants. According to Dwyer et al (2000), "The connections among vegetation configurations on different land uses at the local level, and between urban and rural vegetation configurations at the regional scale, can affect the movement of wildlife, people, insects, and diseases and the distribution of social and physical benefits provided by alternative vegetation structures" (p. 7). It is therefore important to appreciate and understand the role of biophysical forest structure from this fundamental standpoint.

Urban and rural forests are capable of providing surrounding communities a wide variety of environmental, social, and economic benefits. However, for the purpose of this thesis, close attention will be directed toward examining the C associated benefits provided by urban forests. *Section 2.3* and *Section 2.4* discuss non-C and C benefits of urban forests, respectively.

2.3 Non-Carbon Benefits of Urban Forests

Because the world's population continues to become more urban, there is an increasing need to understand the impacts associated with urbanization of landscapes (Grimm et al., 2008; UN-Habitat, 2009). Maintaining and improving upon existing urban forest structure has been well documented as providing multiple benefits to urban communities, many of which help offset impacts associated with urbanization (Carreiro, 2008). Subsequently, much research has been completed to document and enhance our comprehension of urban forest benefits. These efforts have been focused, to a large extent, towards exploring various strategies to maximize the provision of urban forest benefits to communities (Bradley, 1995b; Dwyer et al., 2000; Konijnendijk et al., 2005; Nowak and Dwyer, 2007; Carreiro et al., 2008). Although perhaps an infinite list could be created to describe all the benefits associated with urban forests, the benefits are organized and discussed, beginning with non-C related benefits, into three categories: 1) environmental; 2) social; and 3) economic. C sequestration and storage has been purposefully omitted as a benefit from this section. A detailed discussion of C sequestration and storage associated with urban forests is found within *Section 2.4*.

1) Environmental benefits

Urban trees, as major biota within urban ecosystems, have a number of direct and indirect impacts on the environment in which they grow, many of which result in the provision of valuable functions and services. Urban forests have been shown to have positive impacts on air and water quality (Dwyer et al., 1992; Nowak, 1994c; Yang et al., 2005; Nowak et al., 2006; Nowak and Dwyer, 2007). They are also capable of reducing levels of air pollution in urban areas directly via dry deposition, and indirectly through reducing emissions associated with energy consumption (Yang et al., 2005).

In 1994, the United States Department of Agriculture Forest Service published an extensive report profiling the wide range of services and benefits provided by Chicago's urban forest ecosystem (McPherson et al., 1994). In chapter five of this report, the findings indicated trees in Chicago improved air quality through the removal of various gaseous (carbon monoxide (CO), nitrogen dioxide (NO_2), ozone (O_3), sulphur dioxide (SO_2)) and particulate pollutants (PM_{10}) through dry deposition (Nowak, 1994c). These trees removed an estimated 590 metric tons of pollutants during 1991. The air pollution removal services provided by small trees assigned a monetary value of \$0.04/year, while larger trees were valued at \$2/year (value estimates expressed in United States Dollars).

Stormwater runoff is a non-point source of pollution in urban areas (Duh et al., 2008). As such, it contains an array of pollutants that are, by their nature, extremely difficult to trace, and typically include contaminants such as lead, zinc, and excess nutrients, including nitrogen and phosphorous (Duh et al., 2008). Stormwater runoff subsequently degrades water quality in urban areas. Urban forests affect hydrological cycling in urban areas; Dwyer and Miller (1999) established a positive relationship between the percentage of canopy cover and the volume and rate of stormwater runoff in a study conducted in Stevens Point, Wisconsin. They concluded if tree canopy cover is increased, pollutant loading in urban water (as is attributable to stormwater runoff) could be decreased.

The process of urbanization inevitably results in a loss of and subsequent fragmentation of natural habitat for any and all species residing within the area that becomes developed. As a result, there is a decline in species richness, as the biotic diversity of an area is highly dependent on the type, presence, and composition of the vegetation within the developed area (Raedeke and Raedeke, 1995; McKinney, 2002; Alvey, 2006). Improving urban forest structure is an effective strategy to mitigate habitat losses associated with urban development, and promotes biodiversity in urban areas (Rowntree, 1986; Bradley, 1995a; Botkin and Beveridge, 1997; McKinney, 2002; Alvey, 2006; Yue, 2010).

2) Social benefits

Although social benefits provided by urban forests are difficult to assess and quantify, evidence supported by many research efforts continues to accumulate supporting the significance of direct and indirect social and psychological benefits urban forests provide to communities (Ulrich, 1984, 1986; Dwyer et al., 1992; Kuo and Sullivan, 2001; Peckham, 2010). Urban forests provide many opportunities for recreation, leisure, and relaxation for urban residents, most identifiably in park-like settings (Dwyer et al., 1992; Dwyer et al., 2000; Peckham, 2010), in addition to the connections people feel with the natural environment (Dwyer et al., 1992). Ulrich (1984; 1986) advocates that the benefits provided by urban forests contribute towards improving human health through elevating positive emotional and psychological conditions through reduction of stress and anxiety.

3) Economic benefits

One prevalent economic benefit associated with urban forests is savings associated with reducing energy consumption of buildings (Heisler, 1986; McPherson et al. 1995; Akbari et al., 1997, 2001; Akbari, 2002). Urban trees reduce heating and cooling demands of buildings through influencing local microclimates. When strategically placed, trees provide much-appreciated shade on a hot summer's day, and thereby contribute to negating the degree of urban heat islands (UHI). In the winter, properly planted trees block harsh and prevailing winds. Decreased energy consumption directly translates into monetary savings, but also simultaneously reduces levels of GHG emissions used to generate energy. Other economic benefits provided by urban forests include increased property and real estate values (Anderson and Cordell, 1988; Tyrväinen and Miettinen, 2000; Nowak and Dwyer, 2007), as well as improved positive consumer-merchant interactions within commercial areas (Wolf, 2003).

2.4 Biological Carbon Sequestration and Storage within Urban Forest Landscapes

In addition to the provision of a myriad of environmental, social, and economic benefits, urban trees also mitigate levels of atmospheric CO_2 directly, through biological sequestration and storage of C as biomass (Rowntree and Nowak, 1991; Nowak, 1993; Nowak, 1994b; Jo and McPherson, 1995; McPherson, 1998; Nowak and Crane, 2002; Nowak et al., 2002; Brack, 2002; Jo, 2002; Myeong et al., 2006), or indirectly, by influencing local microclimatic conditions which thereby reduces energy demands and subsequent consumption of fossil fuels (Heisler, 1986; McPherson, 1993; Akbari et al., 1997, 2001; Akbari, 2002; Simpson, 2002; Gill et al., 2007). Although the indirect influence of urban trees on atmospheric CO_2 levels is arguably more significant than C sequestration and storage capabilities of urban trees, this thesis focuses on enhancement of the direct biological C sequestration and storage potential via urban forest development.

2.4.1 Differentiating between biological carbon sequestration and storage

While closely related, and sometimes haphazardly synonymously referenced, C sequestration and storage are terms that embody distinct definitions. C sequestration refers to the rate at which C is stored as biomass per year (McPherson and Simpson, 1993), while C storage is the total amount of C within a tree's biomass at a single point in time (McPherson, 1998; Nowak et al., 2002). Generally, C sequestration is commonly expressed as an annual rate, in kilograms (kg) or tonnes (t) per unit time (typically one year), while C storage is expressed as a total amount, also in kg or t.

Forests, urban and non-urban alike, can be considered as C sources or sinks. Forests become net C sinks when carbon is taken from the atmosphere at a greater rate than carbon is released (Birdsey, 2006). Trees have a finite lifespan; therefore C sequestered and stored over the duration of a given tree's life is temporary. Upon tree death and decomposition, the sequestered and stored C stored as biomass is returned to the atmosphere (Nowak and Crane, 2002; Nowak and Dwyer, 2007). Many factors influence C sequestration and storage potentials of any one tree, and thereby inform the C dynamics of a given forest as an entity. Such factors ultimately determine if a forest is a net sink or source of CO_2, and are discussed within the following section.

2.4.2 Quantifying urban forest carbon sequestration and storage

2.4.2.1 Carbon models

Urban forest C resources are commonly estimated by constructing C models that mimic primary factors dictating urban forest C sequestration and storage potentials. Examples of such factors include species composition (which also informs other factors, such as individual tree size at maturity, growth rate, and longevity), age structure, diameter at breast height (dbh; i.e. 1.37m) distribution, population density, as well as local climatic and environmental conditions (Rowntree and Nowak, 1991; Nowak, 1993; Nowak, 1994a; McPherson, 1998; Nowak and Crane, 2002; Nowak et al., 2002; Sieghardt et al., 2005; Tello et al., 2005; Yang et al., 2005).

Although our understanding of factors influencing urban forest C dynamics continues to improve, quantification of this resource is complicated, and it is inherently impossible to construct a C model that could possibly account for every factor influencing C sequestration and storage within an urban forest ecosystem

(Starfield, 1997; Jackson et al., 2000; Birdsey, 2006). Rather, C models are constructed to fulfill objectives of a specific research question(s), and strive to provide a simplified representation of the elements, processes, and factors influencing C sequestration and storage potentials the urban forest of interest.

Much research has been completed in an effort to estimate C sequestration and storage within urban forest settings (e.g. Rowntree and Nowak, 1991; Nowak, 1993; Nowak, 1994b; McPherson, 1998; McPherson and Simpson, 1999; Brack, 2002; Nowak and Crane, 2002; Nowak et al., 2002; McHale et al., 2009), and the notion of modeling CO_2 dynamics within the urban forest setting is not a new one. There are several existing models designed to quantify C dynamics within these ecosystems (Rowntree and Nowak, 1991; Nowak, 1994b; Nowak and Crane, 2000; Nowak et al., 2002; Nowak and Crane, 2002; McPherson, 1998; McPherson et al., 2010; American Forests, n.d.). When considering the research questions and objectives of this project, it was important to recognize that although previously developed urban-forest C models may be widely used, peer-reviewed, and of high calibre, they may not necessarily be suitable for application within the context of a site-specific forest landscape; in this instance the BIP urban forest landscape (Carreiro and Zipperer, 2008).

There are a number of limiting factors associated with using previously developed models to estimate C sequestration and storage potentials within the BIP urban forest landscape. These factors include reliance on geographically distant biomass equations and climatic data for tree biomass and C estimates (e.g. McPherson et al., 2010), inability to project urban forest growth over time (e.g. Nowak and Crane, 2000), and dependence on data that are too coarse for application within a given project (e.g. Rowntree and Nowak, 1991). As such, constructing an original C was deemed the most viable option to fulfill the objectives of this thesis; doing so afforded the opportunity to select the most appropriate assumptions and parameters under which the model could generate BIP urban forest C sequestration and storage potentials (discussed in depth within *Chapter 3*).

2.4.2.2 Integration of land cover classification and a geographic information system

Despite a myriad of other capabilities, remote sensing and geographic information system (GIS) technologies have been used in traditional silvicultural applications primarily as mapping tools (Landsberg, 2003). Carreiro and Zipperer (2008) identify a major advantage to conducting spatial analysis using GIS helps with the strategic selection of tree locations to optimize multiple benefits provided by trees. Many land cover classification systems and subsequent maps are used today, each designed with their own purpose, application and utility. Land cover classification systems and associated maps are common and critical information resources for governments, businesses, researchers, natural resource managers, and policy-makers alike (NRCan, 2009; Homer et al., 2004). Land cover classification criteria and maps have been produced on many scales, ranging from global, national, to regional and local applications, all fulfilling unique purposes and through their defining characteristics (e.g. Anderson et al., 1976; McPherson, 1998; Homer et al., 2004; NRCan, 2009; NASA, 2011).

Urban landscapes are highly heterogeneous by nature (Zipperer et al., 1997; Cadenasso et al., 2007; Pickett and Cadenasso, 2008), and as such, their heterogeneity can be classified in a number of ways, depending on a project's objective (Cadenasso, 2008). Classifying urban heterogeneity is a technique used by urban forest researchers. Previous works have created an original or selected a suitable existing land cover classification system that aligned with the project's objectives (e.g. Dwyer and Miller, 1999; Dwyer et al., 2000; Pauleit and Duhme, 2000; Myeong et al., 2006). Integration of a land cover classification system in conjunction with a GIS can help improve knowledge, conception, and overall comprehension of the urban forest resource for scholars and practitioners alike.

2.5 Potential Urban Forest Development via Carbon Offset Markets

While some urban-forest benefits are easily quantified, others are extraordinarily difficult or simply impossible to quantify. Quantifiability aside, several functions, services, and benefits provided by urban forests remain unnoticed to planners, decision-makers and everyday passersby alike, because they are intrinsically inconspicuous and intangible (e.g. C sequestration) (Chen and Jim, 2008). For this reason, it is important to continue to improve our perception and understanding of the full spectrum of functions and services provided by urban forests through additional research if we are to maximize the potential benefits they could provide to their respective communities (Carreiro and Zipperer, 2008).

The C sequestration and storage potentials of a given tree constitute a biophysical attribute that is measurable. However, incorporating every factor influencing the C sequestration and storage potential of a given tree into a C model is inherently impossible to do. The primary objective of this thesis is to estimate the C sequestration and storage potential of the BIP urban forest under various future development scenarios. Therefore, questions then turn towards those of practicality and applicability; how might this information be utilized in a productive manner to improve upon existing urban forest structure? And does this information present a unique vantage that may aid in enhancing benefits provided by urban forests?

Enhancing urban forest structure is one of several CO_2 mitigation strategies, because trees sequester and store C as biomass (Freedman and Keith, 1995). Advancements made within the realm of C offsetting seem to present themselves as a potential opportunity for obtaining funds to support forest development, rural and urban alike, while also enhancing biological C sequestration and storage within trees (Freedman and Keith, 1995; McPherson and Simpson, 1999; IPCC, 2005; Birdsey, 2006; McHale et al., 2007; McPherson et al., 2007; DSF, 2008; Bayon et al., 2009). As such, the third and final objective of this thesis is to assess the extent to which urban forest development within BIP may be financed through local businesses purchasing C offsets using current standards within C offset markets (explored within *Chapter 5*). The remainder of this section is devoted to introducing basic definitions and concepts as well as prevalent issues associated with pursuing C offsets as a potentially viable option for urban forest development.

2.5.1 Overview of current carbon offsets standards and markets in North America

As an emerging concept driven by increasing pressure and desire to mitigate potential and undesirable impacts of global climate change, North American C markets are not without flaws, controversies, challenges, barriers, and limitations (e.g. LeBlanc, 1999; IPCC, 2005; Sovacool, 2011). Although perhaps perceived by some as a complete solution to the pressing threats of climate change, more realistically, the role of C offsets is actually only one segment of a larger, more holistic approach to mitigating the impacts of a changing climate which possesses multiple facets (IPCC, 2005; DSF, 2008). Kirschbaum and Cowie (2004) advocate the importance of integrating emissions avoidance strategies with enhancing biological C sequestration and storage as two important platforms for mitigating atmospheric CO_2 levels.

For application within the BIP setting, C offsets would be based solely on the future potential of trees within developed portions of the park to sequester and store C as above-ground (AG) dry-weight biomass. However, this approach fails to acknowledge other factors influencing C dynamics within BIP. For example, substantial stores of C are actually found within below-ground (BG) biomass (approximately 20%) in addition to soil and organic matter (Ajtay et al., 1977). Other factors influencing C dynamics in a setting such as BIP include land use and land-use change, emissions related to energy consumption that are conserved or consumed to meet the demands of everyday energy use (varying with project scope and objectives) (Heisler, 1986; Akbari et al. 1997, 2001; Côté and Smolenaars, 1997; Vitousek et al., 1997), as well as choice of implementation and maintenance techniques used to sustain urban forest structure (Nowak et al., 2002; McPherson et al., 2007).

2.5.1.1 Carbon offsets vs. carbon credits

The terms *C offset* and *C credit*, albeit similar, actually embody two distinct concepts. A technical report produced by the David Suzuki Foundation (DSF) in 2008 distinguished the two terms; a *C offset* refers to the measurement of the reduction of GHGs that are declared by, but not necessarily achieved by, the offset claimants. In contrast, the term *C credit* is typically referenced in an economic context, and is assigned a monetary or market value, expressed as \$/tonne of CO_2 equivalents (tCO_2e) (Environment Canada, 2008; Ristea and Maness, 2009). C credits are tradable entities within a C market. Both terms refer to the quantification of CO_2 reductions, but C credits simply represent the value of the C offsets in an economic context (McHale et al., 2007; DSF, 2008).

2.5.1.2 Mandatory vs. voluntary carbon markets

There are two markets in which those wishing to achieve C offsets can participate: 1) mandatory (also referred to as regulatory or compliance) and 2) voluntary. Mandatory and voluntary markets, although both represent platforms for C creating offsets, differ in some fundamental ways. Mandatory C offset markets operate under a cap-and-trade mechanism. One prevalent example of a mandatory C market is the Kyoto Protocol, which came into effect in February 2005 (McHale et al., 2007). The Kyoto Protocol is the first internationally recognized offset trading market, and establishes “specific, legally-binding targets” (Kirschbaum and Cowie, 2004, p 417) to which participating parties must adhere. Since its inception, mandatory C offset markets have experienced rapid growth. This escalation has resulted in tremendous variance in prices per tCO_2e. Bayon et al. (2009) noted extreme price fluctuations, ranging between £7 and £32 pounds/tCO_2e.

Voluntary markets quantify C offsets that are project-based. The scenario under which the project is implemented must demonstrate a reduction in CO_2 emissions from the non-project scenario. An overarching, governing body does not regulate voluntary markets, and as such, voluntary markets lack universally applicable standards, guidelines, conventions, and/or regulations (Ristea and Maness, 2009; Bayon et al., 2009). The DSF suggests that the fast-paced growth of voluntary offset markets have been driven by the growing concern and general awareness of severity of impending threats related to global climate change (DSF, 2008).

2.6 References

Ajtay, G.L., Ketner, P., & Duvigneaud, P. (1977). Terrestrial primary production and phytomass. In B. Bolin, E.T. Degens, S. Kempe, & P. Ketner (Eds.), *The global carbon cycle* (pp. 129-236). New York, NY: John Wiley & Sons.

Akbari, H. (2002). Shade trees reduce building energy use and CO_2 emissions from power plants. *Environmental Pollution, 116,* S119-S126.

Akbari, H., Kurn, D.M., Bretz, S.E., & Hanford, J.W. (1997). Peak power and cooling energy savings of shade trees. *Energy and Buildings, 25*, 139-148.

Akbari, H., Pomerantz, M., & Taha, H. (2001). Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. *Solar Energy, 70*(3), 295-310.

Alig, R.J., Adams, D., & McCarl, B. (2002). Projecting impacts of global climate change the US forest and agricultural sectors and carbon budgets. *Forest Ecology and Management, 169*(1-2), 3–14.

Alig, R.J., & Butler, B.J. (2004). Projecting large-scale area changes in land use and land cover for terrestrial carbon analyses. *Environmental Management, 33*, 443–456.

Alvey, A.A. (2006). Promoting and preserving biodiversity in the urban forest. *Urban Forestry & Urban Greening, 5*(4), 195-201.

American Forests. (n.d.). *CITYgreen.* Retrieved May 9, 2011 from http://www.americanforests.org/productsandpubs/citygreen/

Anderson, L.M., & Cordell, H.K. (1988). Influence of trees on residential property values in Athens, Georgia (USA): A survey based on actual sales prices. *Landscape and Urban Planning, 15,* 153-164.

Anderson, J.R., Hardy, E.E., Roach, J.T., & Witmer, R.E. (1976). A land use and land cover classification system for use with remote sensor data (US Geological Survey Professional Paper 964). Retrieved from United States Geological Survey: http://landcover.usgs.gov/pdf/anderson.pdf

Bayon, R., Hawn, A., Hamilton, K. (2009). *Voluntary carbon markets: An International business guide to what they are and how they work* (2nd ed.). London, UK: Earthscan.

Birdsey, R.A. (2006). Carbon accounting rules and guidelines for the United States forest sector. *Journal of Environmental Quality, 35*, 1518-1524.

Botkin, D.B., & Beveridge, C.E. (1997). Cities as environments. *Urban Ecology, 1*, 3-19.

Brack, C. (2002). Pollution mitigation and carbon sequestration by an urban forest. *Environmental Pollution, 116*, S195-S200.

Bradley, G. (1995a). Urban forest landscapes: Integrating multidisciplinary perspectives. In G. Bradley (Ed.), *Urban forest landscapes: Integrating multidisciplinary perspectives* (pp. 3-11). Seattle, WA: University of Washington Press.

Bradley, G. (Ed.). (1995b). Urban forest landscapes: *Integrating multidisciplinary perspectives*. Seattle, WA: University of Washington Press.

Cadenasso, M.L., Pickett, S.T.A., & Schwarz, K. (2007). Spatial heterogeneity in urban ecosystems: Reconceptualizing land cover and a framework for classification. *Frontiers in Ecology and the Environment, 5*(2), 80-88.

Carreiro, M.M. (2008). Introduction: The growth of cities and urban forestry. In M.M. Carreiro, Y.-C. Song, & J. Wu (Eds.), *Ecology, planning, and management of urban forests* (pp. 3-9). New York, NY: Springer Science.

Carreiro, M.M., Song, Y.-C., & Wu, J. (Eds.). (2008). *Ecology, planning, and management of urban forests – International perspectives.* New York, NY: Springer Science.

Carreiro, M.M. & Zipperer, W.C. (2008). Urban forestry and the eco-city: Today and tomorrow. In M.M. Carreiro, Y.-C. Song, & J. Wu (Eds.), *Ecology, planning, and management of urban forests* (pp. 435-456). New York, NY: Springer Science.

Chen, S.S., & Jim, C.Y. (2008). The urban forest management of Nanjing city: Key characteristics and management assessment. In M.M. Carreiro, Y.-C. Song, & J. Wu (Eds.), *Ecology, planning, and management of urban forests* (pp. 259-278). New York, NY: Springer Science.

Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., … & van den Belt, M. (1987). The value of the world's ecosystem services and natural capital. *Nature, 387*(15), 253-260

Côté, R.P., & Smolenaars, T. (1997). Supporting pillars for industrial ecosystems. *Journal of Cleaner Production, 5*(1-2), 67-74.

Dalhousie University. (2001). *Industrial parks and climate change with a case study of Debert, Nova Scotia.* Retrieved April 15, 2012 from http://sres.management.dal.ca/Files/eco-debert/climatechangefinal.pdf

David Suzuki Foundation. (2008). Credit check: A comparative evaluation of tree-planting and fossil-fuel emission reduction offsets (A David Suzuki Foundation Technical Paper). Retrieved from David Suzuki Foundation: http://www.davidsuzuki.org/publications/downloads/2008/Credit_Check_080701.pdf

Dixon, R.K., Brown, S., Houghton, R.A., Solomon, A.M., Trexler, M.C., & Wisniewski, J. (1994). Carbon pools and flux of global forest ecosystems. *Science, 263*, 185-191.

Duh, J.-D., Shandas, V., Chang, H., & George, L.A. (2008). Rates of urbanization and the resiliency of air and water quality. *Science of the Total Environment, 400*, 238-256.

Dwyer, J.F., McPherson, E.G., Schroeder, H.W., & Rowntree, R.A. (1992). Assessing the benefits and costs of the urban forest. *Journal of Arboriculture, 15*, 247-252.

Dwyer, J.F., Nowak, D.J., Noble, M.H., & Sisinni, S.M. (2000). Connecting people with ecosystems in the 21st century: An assessment of our nation's urban forests (General Technical Report PNW-GTR-490). Retrieved from United States Forest Service: http://www.treesearch.fs.fed.us/pubs/29448

Dwyer, M.C., & Miller, R.W. (1999). Using GIS to assess urban tree canopy benefits and surrounding greenspace distributions. *Journal of Arboriculture, 25*(2), 102-107.

Dwyer, J.F., McPherson, E.G., Schroeder, H.W., & Rowntree, R.A. (1992). Assessing the benefits and costs of the urban forest. *Journal of Arboriculture, 15*, 247-252.

Dwyer, J.F., Nowak, D.J., Noble, M.H., & Sisinni, S.M. (2000). Connecting people with ecosystems in the 21st century: An assessment of our nation's urban forests (General Technical Report PNW-GTR-490). Retrieved from United States Forest Service: http://www.treesearch.fs.fed.us/pubs/29448

Dwyer, M.C., & Miller, R.W. (1999). Using GIS to assess urban tree canopy benefits and surrounding greenspace distributions. *Journal of Arboriculture, 25*(2), 102-107.

Environment Canada. (2008). *Turning the corner: Canada's offset system for greenhouse gasses*. Retrieved December 8, 2011 from http://www.ec.gc.ca/doc/virage-corner/2008-03/526_eng.htm

Ewing, R.H. (2008). Characteristics, causes, and effects of sprawl: A literature review. In Marzluff, J.M., Shulenberger, E., Endlicher, W., Alberti, M., Bradley,G., Ryan, C., … & Simon, U., *Urban ecology: An international perspective on the interaction between humans and nature* (pp. 519-535). New York, NY: Springer Science.

Freedman, B., & Keith, T. (1995). *Planting trees for carbon credits: A discussion of the issues, feasibility, and environmental benefits.* Ottawa, ON: Tree Canada Foundation.

Frumkin, H. (2002). Urban sprawl and public health. *Public Health Reports, 117*(3), 201-217.

Gill, S.E., Handley, J.F., Ennos, A.R., & Pauleit, S. (2007). Adapting cities for climate change: The role of the green infrastructure. *Built Environment, 33*(1), 115-133.

Gouldie, A., & Viles, H.A. (1997). *The earth transformed: An introduction to human impacts on the environment*. Oxford, UK: Blackwell.

Grimm, N.B., Faeth, S.H., Golubiewski, N.E., Redman, C.L., Wu, J., Bai, X., & Briggs, J.M. (2008). Global climate change and the ecology of cities. *Science, 319*, 756-560.

Heisler, G.M. (1986). Energy savings with trees. *Journal of Arboriculture, 12*(5), 113-125.

Homer, C., Huang, C., Yang, L., Wylie, B., & Coan, M. (2004). Development of a 2001 National land-cover database for the United States. *Photogrammetric Engineering & Remote Sensing*, *70*(7), 829–840.

Intergovernmental Panel on Climate Change (IPCC). (2005). *IPCC special report on carbon dioxide capture and storage.* London, UK: Cambridge University Press.

Intergovernmental Panel on Climate Change (IPCC). (2007a). Climate change 2007: Synthesis report. In R.K. Pachauri & A. Reisinger (Eds.), *Contribution of working groups I, II and III to the fourth assessment report of the Intergovernmental Panel on Climate Change*. Geneva, Switzerland: IPCC.

Intergovernmental Panel on Climate Change (IPCC). (2007b). Climate change 2007: Impacts, adaptation, and vulnerability. In M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, & C.E. Hanson (Eds.), *Fourth assessment report of the Intergovernmental Panel on Climate Change, 2007*. Cambridge, UK: Cambridge University Press.

Jackson, L.J., Trebitz, A.S., & Kottingham, K.L. (2000). An introduction to the practice of ecological modelling. *BioScience, 50*(8), 694-706.

Jo, H.-K. (2002). Impacts of urban greenspace on offsetting carbon emissions for middle Korea. *Journal of Environmental Management, 64,* 115-126.

Jo, H.K., & McPherson, E.G. (1995). Carbon storage and flux in urban residential greenspace. *Journal of Environmental Management, 45*, 109-133.

Johnson, M.P. (2000). Environmental impacts of urban sprawl: A survey of the literature and proposed research agenda. *Environment and Planning, 33*, 717-735.

Kahn, M.E. (2006). *Green cities: Urban growth and the environment.* Washington, DC: Brookings Institution Press.

Keeling, C.D. (1973). Industrial production of carbon dioxide from fossil fuels and limestone. *Tellus, XXV*(2),174-198.

Kirschbaum, M.U.F., & Cowie, A.L. (2004). A practical method to distinguish between human and natural factors in carbon accounting. *Climatic Change*, *67,* 417–436.

Konijnendijk, C.C., Nilsson, K., Randrup, T.B. & Schipperijn, J. (Eds). (2005). *Urban forests and trees*. New York, NY: Springer Science.

Kuo, F. E., & Sullivan, W. C. (2001). Environment and crime in the inner city: Does vegetation reduce crime? *Environment and Behavior, 33*(3), 343-365.

Landsberg, J. (2003). Physiology in forest models: History and the future. *Forest Biometry, Modelling and Information Sciences, 1,* 49-63.

LaPaix, R., & Freedman, B. (2010). Vegetation structure and composition within urban parks of Halifax Regional Municipality, Nova Scotia, Canada. *Landscape and Urban Planning, 98,* 124-135.

LeBlanc, A. (1999). Issues related to including forestry-based offsets in a GHG emissions trading system. *Environmental Science & Policy, 2,* 199-206.

McDonnell, M.J., & Pickett, S.T.A. (1990). The study of ecosystem structure and function along urban-rural gradients: An unexploited opportunity for ecology. *Ecology, 71,* 1231–1237.

McDonnell, M.J., Pickett, S.T.A., Groffman, P., Pouyat, R.V., Zipperer, W.C., Parmelee, R.W. … & Medley, K. (2008). Ecosystem processes along an urban-to-rural gradient. In J.M. Marzluff, E. Shulenberger, W. Endlicher, M. Alberti, G. Bradley… & U. Simon (Eds.), *Urban ecology - An international perspective on the interaction between humans and nature* (pp. 299-313). New York, NY: Springer Science.

McHale, M.R., McPherson, E.G., & Burke, I.C. (2007). The potential of urban tree plantings to be cost effective in carbon credit markets. *Urban Forestry & Urban Greening, 6,* 49-60.

McHale, M.R, Burke, I.C., Lefsky, M.A., Peper, P.J., & McPherson, E.G. (2009). Urban forest biomass estimates: Is it important to use allometric relationships developed specifically for urban trees? *Urban Ecosystems, 12*, 95-113.

McKinney, M.L. (2002). Urbanization, biodiversity, and conservation. *BioScience, 52*(10), 883-890.

McPherson, E.G. (1993). Evaluating the cost effectiveness of shade trees for demand-side management. *The Electricity Journal, 6*(9), 57-65.

McPherson, E.G. (1998). Atmospheric carbon dioxide reduction by Sacramento's urban forest. *Journal of Arboriculture, 24*(4), 215-223.

McPherson, E.G., Nowak, D.J., & Rowntree, R.A. (Eds.). (1994). Chicago's urban forest ecosystem: Results of the Chicago urban forest climate project. (General Technical Report NE-186). Retrieved from United States Forest Service: http://www.treesearch.fs.fed.us/pubs/4285

McPherson, E.G., Rowntree, R.A., & Wagar, J.A. (1995). Energy-efficient landscapes. In G. Bradley (Ed.), *Urban forest landscapes: Integrating multidisciplinary perspectives* (pp. 150-160). Seattle, WA: University of Washington Press.

McPherson, E.G., Simpson, J.R., Peper, P.J., Gardner, S.L., Vargas, K.E., & Xiao, Q. (2007). Northeast community tree guide: Benefits, costs, and strategic planting (General Technical Report PSW-GTR-202). Retrieved from United States Forest Service: http://www.treesearch.fs.fed.us/pubs/28759

McPherson, E.G., & Simpson, J.R. (1999). Carbon dioxide reduction through urban forestry: Guidelines for professional and volunteer tree planters. (General Technical Report PSW-GTR-171). Retrieved from United States Forest Service: http://www.treesearch.fs.fed.us/pubs/6779

McPherson, E.G., Simpson, J., Marconett, D., Peper, P., & Aguaron, E. (2010). *Urban forests and climate change.* Retrieved May 9, 2011 from http://www.fs.fed.us/ccrc/topics/urban-forests/

Myeong, S., Nowak, D.J., & Duggin, M.J. (2006). A temporal analysis of urban forest carbon storage using remote sensing. *Remote Sensing of Environment, 101*, 277-282.

National Aeronautics and Space Administration (NASA). (2011). *NASA's Terra satellite refines map of global land cover.* Retrieved April 29, 2011 from http://earthobservatory.nasa.gov/Newsroom/view.php?id=22585

Natural Resources Canada (NRCan). (2009). *The atlas of Canada – Land cover.* Retrieved April 29, 2011 from http://atlas.nrcan.gc.ca/site/english/maps/environment/land/landcover/1

Nowak, D.J. (1993). Atmospheric carbon reduction by urban trees. *Journal of Environmental Management, 37*, 207-217.

Nowak, D.J. (1994a). Understanding the structure of urban forests. *Journal of Forestry, 92,* 42–46.

Nowak, D.J. (1994b). Atmospheric carbon dioxide reduction by Chicago's urban forest. In E.G. McPherson, D.J. Nowak, & R.A. Rowntree (Eds.), *Chicago's urban forest ecosystem: Results of the Chicago urban forest climate project* (pp. 83-94) (General Technical Report NE-186). Retrieved from United States Forest Service: http://www.treesearch.fs.fed.us/pubs/4285

Nowak, D.J. (1994c). Air pollution removal by Chicago's urban forest. In E.G. McPherson, D.J. Nowak, & R.A. Rowntree (Eds.), C*hicago's urban forest ecosystem: Results of the Chicago urban forest climate project* (pp. 63-81) (General Technical Report NE-186). Retrieved from United States Forest Service: http://www.treesearch.fs.fed.us/pubs/4285

Nowak, D.J., & Crane, D.E. (2000). The urban forest effects (UFORE) model: Quantifying urban forest structure and functions. In M. Hansen, & T. Burk (Eds.), *Proceedings: Integrated Tools for Natural Resources Inventories in the 21st Century* (pp. 714-720). St. Paul, MN: United States Forest Service.

Nowak, D.J., & Crane, D.E. (2002). Carbon storage and sequestration by urban trees in the USA. *Environmental Pollution, 116*(3), 381-389.

Nowak, D.J., Crane, D.E., & Stevens, J.C. (2006). Air pollution removal by urban trees and shrubs in the United States. *Urban Forestry & Urban Greening, 4*, 115-123.

Nowak, D.J., & Dwyer, J.F. (2007). Understanding the benefits and costs of urban forest ecosystems. In J.E. Kuser (Ed.), *Urban and community forestry in the northeast (2nd ed.)* (pp. 25-46). New York, NY: Springer Science.

Nowak, D.J., Stevens, J.C., Sisinni, S.M., & Luley, C.J. (2002). Effects of urban tree management and species selection on atmospheric carbon dioxide. *Journal of Arboriculture, 28*(3), 113-122.

Nowak, D.J., & Walton, J.T. (2005). Projected urban growth (2000-2050) and its estimated impact on the US forest resource. *Journal of Forestry, December*, 383-389.

Oke, T.R. 1995. The heat island of the urban boundary layer: Characteristics, causes and effects. In J.E. Cermak (Ed.), *Wind climate in cities* (pp. 81–107). Netherlands: Kluwer Academic Publishers.

Ordóñez, C., & Duinker, P.N. (2010). Interpreting sustainability for urban forests. *Sustainability, 2*, 1510-1522.

Pataki, D.E., Alig, R.J., Fung, A.S., Golubiewski, N.E., Kennedy, C.A., McPherson, E.G., … & Lankao, P.R. (2006). Urban ecosystems and the North American carbon cycle. *Global Change Biology, 12*(11), 2092–2102.

Pauleit, S., & Duhme, F. (2000). GIS assessment of Munich's urban forest structure for urban planning. *Journal of Arboriculture, 26*(3), 133-141.

Peckham, S. (2010). *Nature in the city: Ecological consciousness development associated with naturalized urban spaces and urban forest values in Calgary, AB and Halifax, NS* (Unpublished master's thesis). Dalhousie University, Canada.

Pickett, S.T.A., & Cadenasso, M.L. (2008). Linking ecological and built components of urban mosaics: An open cycle of ecological design. *Journal of Ecology, 96*, 8-12.

Pickett, S.T.A., Cadenasso, M.L., Grove, J.M., Boone, C.G., Groffman, P.M., Irwin, E., … & Warren, P. (2011). Urban ecological systems: Scientific foundations and a decade of progress. *Journal of Environmental Management, 92*, 331-362.

Raedeke, D.A.M., & Raedeke, K.J. (1995). Wildlife habitat design in urban forest landscapes. In G. Bradley (Ed.), *Urban forest landscapes: Integrating multidisciplinary perspectives* (pp. 139-149). Seattle, WA: University of Washington Press.

Randrup, T.B., Konijnendijk, C., Dobbertin, M.K., & Prüller, R. (2005). The concept of urban forestry in Europe. In C. Konijnendijk, K. Nilsson, T.B. Randrup, & J. Schipperijn (Eds.), *Urban forests and trees* (pp. 9-21). New York, NY: Springer Science.

Ristea, C., Maness, T. C. (2009). Opportunities, challenges and markets for forest carbon offset projects. *The Forestry Chronicle 85(5)*, 715-718.

Rowntree, R.A. (1984). Ecology of the urban forest: Introduction to part I. *Urban Ecology, 8*, 1-11.

Rowntree, R.A. (1986). Ecology of the urban forest: Introduction to part II. *Urban Ecology, 9*, 229-243

Rowntree, R.A., & Nowak, D.J. (1991). Quantifying the role of urban forests in removing atmospheric carbon dioxide. *Journal of Arboriculture, 17*(10), 269-275.

Sanders, R.A. (1984). Some determinants of urban forest structure. *Urban Ecology, 8*(1-2), 13-27.

Satterthwaite, D. (2010). Solutions the contribution of cities to global warming and their potential contributions to solutions. *Environment and Urbanization Asia, 1*(1), 1-12.

Schroeder, H.W., & Green, T.L. (1985). Public preference for tree density in municipal parks. *Journal of Arboriculture, 11*(9), 272-277.

Sieghardt, M., Mursch-Radlgruber, E., Paoletti, E., Couenberg, E., Dimitrakopoulus, A., Rego, F., … & Randrup, T.B. (2005). The abiotic urban environment - Impact of urban growing conditions on urban vegetation. In C.C. Konijnendijk, K. Nilsson, T.B. Randrup, & J. Schipperijn (Eds.), *Urban forests and trees* (pp. 281-323). New York, NY: Springer.

Sierra Club. (1998). *Sprawl: The dark side of the American dream*. Retrieved April 28, 2011 from http://www.sierraclub.org/sprawl/report98/

Simpson, J.R. (2002). Improved estimates of tree-shade effects on residential energy use. *Energy and Buildings, 34*, 1067-1076.

Sovacool, B.K. (2011). The policy challenges of tradable credits: A critical review of eight markets. *Energy Policy, 39*, 575-585.

Spurr, S.H., & Barnes, B.V. (1980). *Forest ecology.* New York, NY: Ronald Press Company

Squires, G.D. (Ed.). (2002). Urban sprawl and the uneven development of metropolitan America. In G.D. Squires (Ed.), *Urban sprawl: Causes, consequences and policy responses* (pp. 1-22). Washington, DC: The Urban Institute Press.

Starfield, A.M. (1997). A pragmatic approach to modeling for wildlife management. *The Journal of Wildlife Management, 61*(2), 261-270.

Statistics Canada. (2007). *Urban area (UA)*. Retrieved April 13, 2011 from http://www12.statcan.ca/census-recensement/2006/ref/dict/geo049-eng.cfm

Statistics Canada. (2009). *Population, urban and rural, by province and territory (Canada).* Retrieved April 14, 2011 from http://www40.statcan.ca/l01/cst01/demo62a-eng.htm

Sundquist, E.T., Ackerman, K.V., Parker, L., & Huntzinger, D.N. (2009). An introduction to global carbon cycle management. In B.J. McPherson & E.T. Sundquist (Eds.), *Carbon sequestration and its role in the global carbon cycle* (pp. 1-23). Washington, DC: American Geophysical Union.

Tello, M.-L., Tomalak, M., Siwecki, R., Gáper, J., Motta, E., & Mateo-Sagasta, E. (2005). Biotic urban growing conditions – Threats, pests and diseases. In C.C. Konijnendijk, K. Nilsson, T.B. Randrup, & J. Schipperijn (Eds) *Trees*, (pp. 325-365). New York, NY: Springer.

Tisdale, H. (1942). The process of urbanization. *Social Forces, 20*(3), 311-316.

Tyrväinen, L., & Miettinen, A. (2000). Property prices and urban forest amenities. *Journal of Environmental Economics and Management, 39*, 205-223.

Tsihrintzis, V.A., & Hamid, R. (1997). Modeling and management of urban stormwater runoff quality: A review. *Water Resources Management, 11*, 137–164.

Ulrich, R.S. (1984). View through a window may influence recovery from surgery. *Science, 224*, 420-421.

Ulrich, R.S. (1986). Human responses to vegetation and landscape. *Landscape and Urban Planning, 13*, 29-44.

United Nations Climate Change Conference (UNCCC). (2007). *Uniting on climate change*. Retrieved April 13, 2011 from http://unfccc.int/resource/docs/publications/unitingonclimate_eng.pdf

United Nations Framework Convention on Climate Change (UNFCCC). (n.d.). *Feeling the heat.* Retrieved April 14, 2011 from http://unfccc.int/essential_background/feeling_the_heat/items/2918.php

United Nations-Habitat (UN-Habitat). (2009). *Planning sustainable cities: Global report on human settlements 2009*. Sterling, VA: Earthscan.

VanMetre, P.C., Mahler, B.J., & Furlong, E.T. (2000). Urban sprawl leaves its PAH signature. *Environmental Science and Technology, 34*(4), 4064-4070.

Vitousek, P.M., Mooney, H.A., Lubchenco, J., & Melillo, J.M. (1997). Human domination of Earth's ecosystems. *Science, 277*, 494-499.

Watson, R.T., Noble, I.R., Bolin, B., Ravindranath, N.H., Verardo, D.J., & Dokken, D.J. (Eds.). (2000). *Land-use, land-use change and forestry: A special report of the Intergovernmental Panel on Climate Change.* Cambridge, UK: Cambridge University Press.

Wolf, K.L. (2003). Public response to the urban forest in inner-city business districts. *Journal of Arboriculture, 29*(3), 117-126.

Yang, J., McBride, J., Zhoub, J., & Sun, Z. (2005). The urban forest in Beijing and its role in air pollution reduction. *Urban Forestry & Urban Greening, 3*, 65–78

Yue, G. (2010). *Mapping traditional bird knowledge for urban bird conservation in Halifax, Nova Scotia, Canada* (Unpublished master’s thesis). Dalhousie University, Canada.

Zipperer, W.C., Sisinni, S.M., Pouyat, R.V., & Foresman, T.W. (1997). Urban tree cover: An ecological perspective. *Urban Ecosystems, 1*, 229-246.

CHAPTER 3: METHODS

3.1 The Study Site: Burnside Industrial Park

Burnside Industrial Park (BIP) is a light industrial and commercial zone located within the Halifax Regional Municipality (HRM), Nova Scotia, Canada (lat 44.7, long -63.6) (Figure 3-1). As one of the approximately 1,000 Canadian industrial parks (Dalhousie University, 2001), BIP consists of approximately 1270 ha and is home to an estimated 1,500 businesses employing 15,000 people (HRM, 2010). BIP, as one of the largest industrial parks in the country, and as such is of economic significance to HRM and Atlantic Canadian provinces alike. One of the park's greatest assets is its highly accessible location, as it is not only extensively serviced via road and rail, but it also encompasses the Atlantic Gateway Halifax Logistics Park, thereby making the transportation of goods by seaway accessible as well. Furthermore, Burnside is proximal to Halifax's central business district and Stanfield International Airport (Canmac Economics Limited, 2010). Although managed by HRM, properties within the park are owned by municipal (50.7%), provincial (4.3%), and federal (1.1%) governments, as well as private individuals and companies (43.9%) (See *Appendix 1* for a summary of BIP land ownership).

Development of the park began approximately forty years ago, and its growth continues to encroach into naturalized forest and undeveloped land today (Côté & Smolenaars, 1997). Because of these development pressures, the BIP landscape's C sequestration and storage capacities were diminished through deforestation, as well as disturbance and removal of forest litter and soil (both are important C stores) (Dalhousie University, 2001). Afforestation efforts within BIP are, from a per-unit area standpoint, the most effective mode to improve its C sequestration and storage potential (Dalhousie University, 2001). As an urban, light-industrial and commercial area under intensive anthropogenic development pressures, BIP was therefore selected as an ideal case for investigating the underexploited potential for C sequestration and storage thereof.

Figure 3-1: Aerial photographs used to classify BIP land cover

3.2 Classification of Land Cover within Burnside Industrial Park

A series of aerial photographs taken during the spring/summer months of 2008 were obtained from Bing Maps (©Microsoft). These photographs were digitized to create an all-encompassing land cover map of BIP using the scanning method, of which classifies land cover within the park into one of the following five categories: 1) Grey; 2) Construct; 3) Brown; 4) Disturbed Green; and 5) Undisturbed Green (Figure 3-2; Tables 3-1 and 3-2) (Nowak et al., 2006). Digitization occurred at 1:1000m scale, except for objects less than 4m in width and/or length, in which case a 1:500m scale was used. Features measuring less than 1m in width or length were not digitized. The smallest polygon digitized is a 0.0005ha Disturbed Green polygon, the largest a 510ha Grey polygon. All data used in the GIS were obtained from Halifax Regional Municipality via Dalhousie University's GIS Centre, and the GIS used for digitization and map creation was ESRI ArcGIS software (version 9.3).

As previously discussed in *Chapter 2*, urban ecosystems are highly heterogeneous by nature, and there exist an infinite number of ways to classify the heterogeneity of an ecosystem of interest, and are dictated by the research questions of interest (Zipperer et al., 1997; Cadenasso et al., 2007 Pickett and Cadenasso, 2008). As such, it was necessary to establish definitive criteria for each land cover class to facilitate achieving accuracy and precision while conducting photo interpretation (Pauleit and Duhme, 2000). This was achieved through consultation of other land cover classification criteria within peer-reviewed and government literature (primarily Anderson et al., 1976; McPherson, 1998; Homer et al., 2004; NRCan, 2008). Full descriptions of criteria consulted to identify each land cover category are found within *Appendix 1*.

Figure 3-2: Land cover classification map of BIP

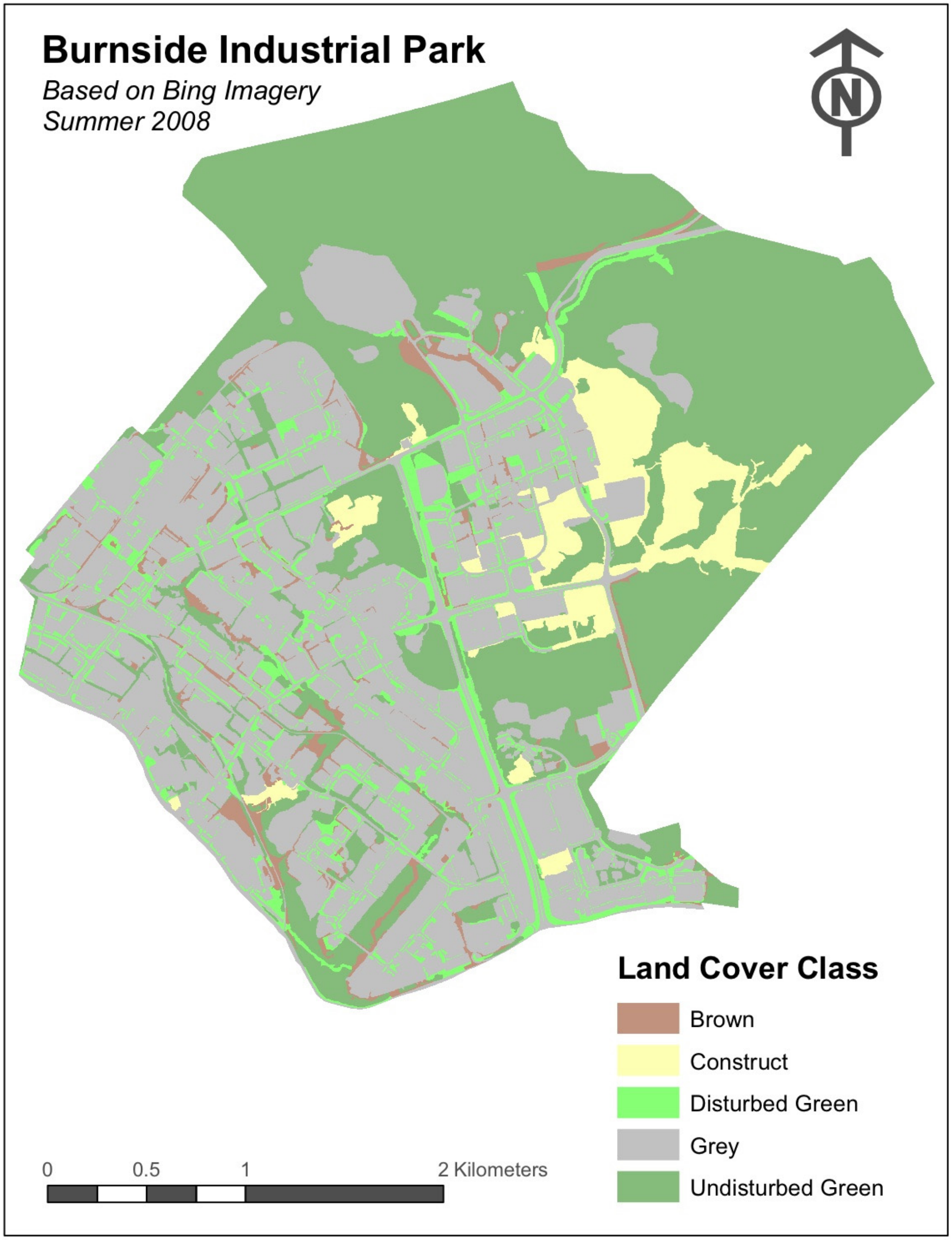


Table 3-2: Summary of land cover category descriptions. For full land cover category descriptions, see *Appendix 1*.

Land cover category	**Description**
Grey	- Land currently occupied or otherwise not intended to accommodate present or future urban tree growth - Features include ✓ permanent infrastructures (i.e. buildings, parking lots, transportation corridors (including roads and railroads), sidewalks, concrete boulevards), ✓ storage areas, ✓ recreational fields, and ✓ hydrological features not encompassed within Undisturbed Green land cover (e.g. lakes, rivers, ponds).
Brown	- Land with potential to accommodate tree growth upon site amendment and appearing to be otherwise idle - Features include ✓ large areas of exposed soil or gravel ✓ chlorotic/browning tendency of existing vegetation
Construct	- Land exhibiting evidence of recent construction or development activities, primary cover is typically soil or gravel - Features include ✓ poured foundations ✓ semi-constructed roads ✓ various evidence of permanent infrastructure development, such as the presence of large construction equipment (e.g. dump trucks, cranes) ✓ forest patches < 0.35ha, as it appears unlikely that these remnants will be preserved within this area
Disturbed Green	- Land currently accommodating or able to immediately accommodate future urban tree growth upon little to no site amendment, primary cover is herbaceous vegetation but includes woody vegetation as well - Features include ✓ lawns ✓ meadows ✓ grassed boulevards and road medians
Undisturbed Green	- Land currently accommodating tree growth within a naturalized or forested state, primary cover is woody vegetation - Features include ✓ contiguous forest patches ✓ areas of high-density trees where additional tree planting does not seem practical or feasible ✓ rivers, streams, footpaths, small roads, utility corridors that are engulfed entirely by otherwise Undisturbed Green classified land cover

Table 3-1: Summary of land cover classes digitized in BIP

Land cover class	Total polygons (#)	Smallest polygon (ha)	Largest polygon (ha)	Average (ha)	Sum (ha)	Percent total coverage (%)
Grey	24	0.002	510	22.0	526	41.5
Brown	181	0.001	1.8	0.18	32	2.5
Construct	16	0.2	43.5	4.6	73.0	5.8
Disturbed Green	1159	0.0005	4.2	0.076	87.6	6.9
Undisturbed Green	121	0.01	217	4.5	550	43.4

3.3 Modeling the Potential for Carbon Sequestration and Storage within the Burnside Industrial Park Urban Forest

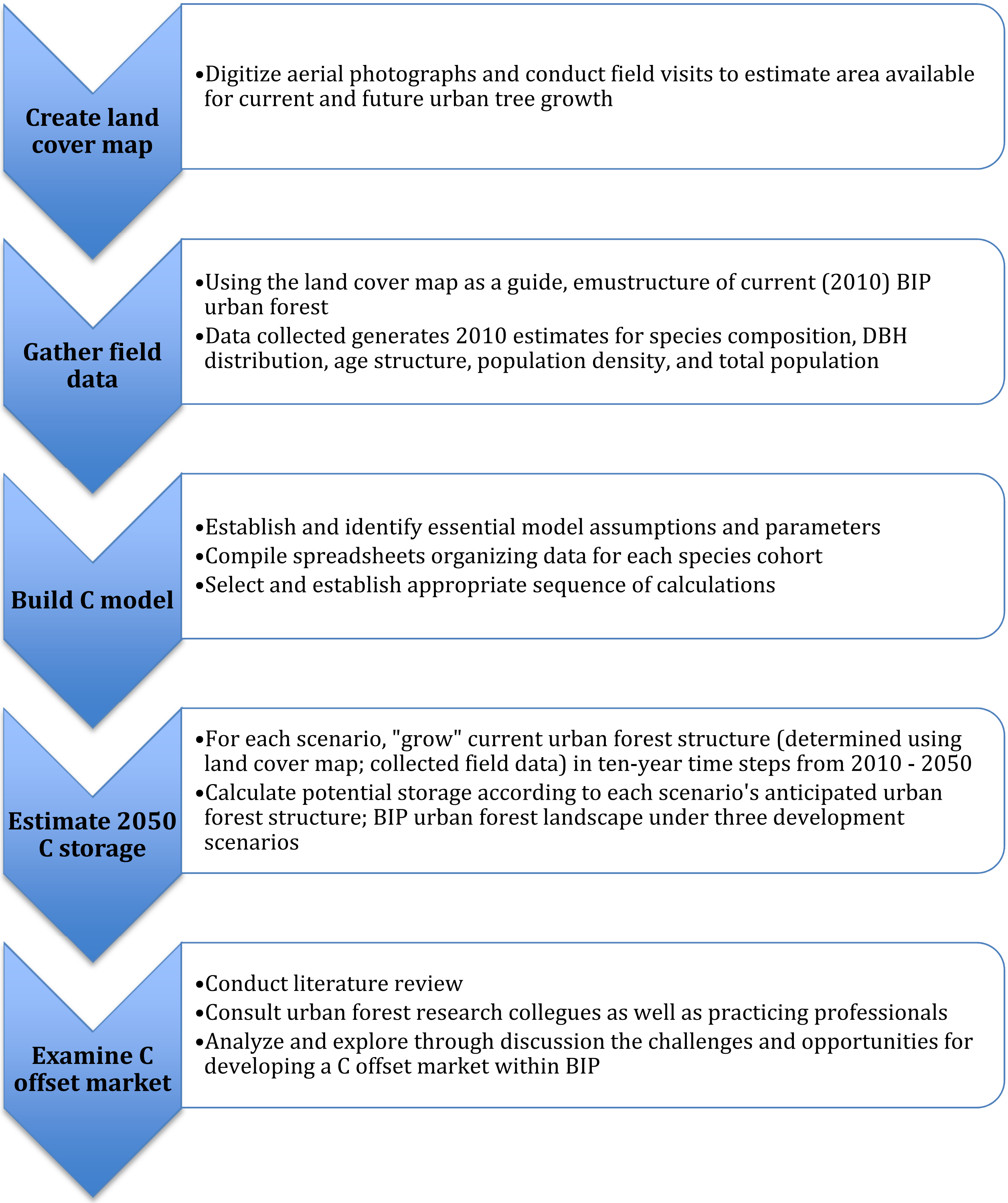
The C model's primary function and purpose is to generate an estimate of BIP urban forest structure in year 2050 under the three urban forest development scenarios through simulated growth. Once urban forest structure is determined, the C storage within the population of interest can be calculated. C storage within biomass is equal to approximately 0.5 the value of the estimated woody biomass of any given tree (Ovington, 1957; Reichle et al., 1973; Ajtay et al., 1977; Houghton et al., 1985; McPherson, 1998; Nowak and Crane, 2000) (Table 3-3). By simply summing the total biomass for each individual tree present within the 2050 urban forest population of interest, an estimate of C storage can therefore be made. C sequestration, as a rate, is another simple calculation. The difference between C stores of the 2010 and the 2050 urban forest of interest divided by 40 (number of years the C storage occurs) calculates the average rate at which the urban forest stores C as biomass. Although these calculations are simple to make, there are a multitude of considerations that were accounted for to generate estimates of three possible 2050 urban forest structures. These considerations are explored in-depth within the remainder of this section.

Table 3-3: Calculations used to estimate C sequestration and storage of current and future BIP urban forest structures

Purpose	Unit	Calculation
Carbon storage per species cohort	kg C/species cohort	$C_{\text{store/species cohort}} = 0.5ab$ *where:* a = # trees in species cohort; b = above-ground dry weight biomass (kg/tree); 0.5 = conversion factor (above-ground dry weight biomass to C)
Carbon stored by total population	kg C/total population	$C_{\text{store of total population}} = \text{Sum}(C_{\text{stored/species cohort}})$
Net carbon sequestration	kg carbon stored/year	$\frac{[(\text{total C stored by year } y \text{ forest}) - (\text{total C stored in year } x \text{ forest})]}{\#\text{ years}}$

Creation of a land cover map provided a platform from which other estimates regarding current and anticipated urban forest structure could be based upon, and ultimately an estimation of C sequestration and storage potential of the BIP urban forest could be made (Figure 3-3). There are many challenges associated with attempting to quantify and emulate ecosystems. The area of interest for this research is that of the BIP urban forest, specifically the C sequestration and storage potential thereof. As such, an arguably infinite list of components, processes, and interactions and could be identified as being influential on C sequestration and storage potentials of the BIP urban forest landscape. Unfortunately, it is inherently impossible to construct a C model that could possibly account for every factor influencing C sequestration and storage within the BIP urban forest ecosystem (Starfield, 1997; Jackson et al., 2000; Birdsey, 2006). The key factors driving the BIP urban forest C model were selected in an effort to provide a simplified representation of the C sequestration and storage potential of the BIP urban forest, and are as follows:

Figure 3-3: Conceptual diagram of methods employed to achieve thesis research objectives including a brief rationale for each one selected.



Create land cover map

- Digitize aerial photographs and conduct field visits to estimate area available for current and future urban tree growth

Gather field data

- Using the land cover map as a guide, emustructure of current (2010) BIP urban forest
- Data collected generates 2010 estimates for species composition, DBH distribution, age structure, population density, and total population

Build C model

- Establish and identify essential model assumptions and parameters
- Compile spreadsheets organizing data for each species cohort
- Select and establish appropriate sequence of calculations

Estimate 2050 C storage

- For each scenario, "grow" current urban forest structure (determined using land cover map; collected field data) in ten-year time steps from 2010 - 2050
- Calculate potential storage according to each scenario's anticipated urban forest structure; BIP urban forest landscape under three development scenarios

Examine C offset market

- Conduct literature review
- Consult urban forest research collegues as well as practicing professionals
- Analyze and explore through discussion the challenges and opportunities for developing a C offset market within BIP

- Area available for current and additional tree growth;
- Current tree density and total population;
- Species composition, dbh distribution, and age structure;
- Longevity;
- Growth rate;
- dbh look-up table;
- Species-specific biomass equations;
- Tree mortality; and
- Tree natality

A complete list of all assumptions and parameters selected for this C model can be found in *Appendix 1*. Although the selection of C model features may oversimplify the present BIP urban forest ecosystem, Carreiro and Zipperer (2008) argue that even the most basic urban forest data can be employed as a tool to effectively allocating available urban forest management resources. The remainder of this section explores the operational assumptions and parameters of the C model in two parts: 1) assumptions and parameters derived using the land cover map; and 2) assumptions and parameters derived from other sources (primarily from peer-reviewed literature).

3.3.1 Assumptions and parameters obtained using the land cover map and field data

All of the C model parameters discussed in this section are structural in nature, and as such, commonly emerge throughout the literature as being of significance when estimating urban forest C sequestration and storage potentials (e.g. Rowntree and Nowak, 1991; Nowak, 1994b; Jo and McPherson, 1995; McPherson, 1998; Nowak and Crane, 2000). They include area available for tree growth, tree density and population, and species composition, dbh distribution, as well as tree age. Additionally, estimates generated for each of these features derived using the BIP land cover map to some extent, and most served to initialize 2010 (aka current) BIP urban forest structure.

- Area available tree growth

Area available for current and future urban tree growth was achieved through classifying land cover of BIP, and is represented by the Disturbed Green land cover category. As introduced within *Section 3.2*, this land cover category represents available area within BIP that could readily accommodate tree growth. Although other land cover types include trees that sequester and store C as biomass (most notably the Undisturbed Green land cover class), for the purpose of this thesis, the C model only quantifies the C dynamics within Disturbed Green land cover.

- Tree density and total population

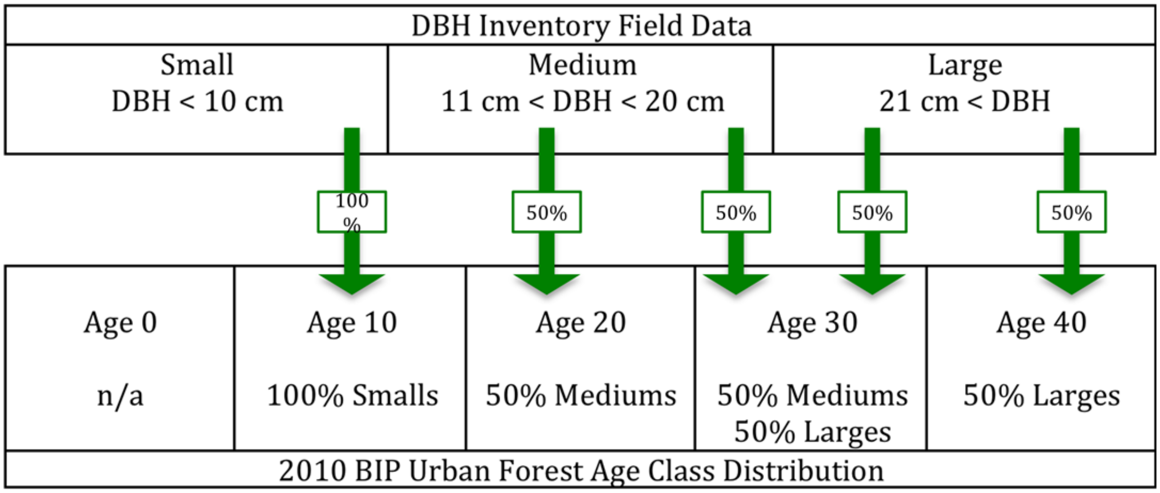
The current tree population within the Disturbed Green land-cover within BIP was estimated based on simply counting trees within a pre-determined area of Disturbed Green land. A total of 355 trees within randomly selected Disturbed Green polygons, totaling an area of approximately 6.5 ha were counted. Dividing the total number of trees by the estimated area yielded an urban forest density estimate 55 trees/ha. Assuming this density to be consistent throughout the Disturbed Green land-cover, the 2010 BIP urban forest estimate was generated by multiplying current tree density (55 trees/ha) by the total Disturbed Green land cover (87ha), yielding a total population estimate of 4,785.

- Species composition, dbh distribution, and age structure

According to Nowak (1993) two of the most important factors to consider while calculating C storage of a tree are related to species and diameter distributions. Storage rates of carbon also vary between species and size, as larger trees store more C than small trees. As such, a picture of the current BIP urban forest species composition and dbh distribution was constructed by conducting sample inventory. Trees inventoried were located within randomly selected Disturbed Green polygons, whose sum area was 124 ha (approximately 10% of the area of BIP). A total of 417 trees were identified and classified into one of three dbh categories: small (dbh < 10cm), medium (11cm < dbh < 20cm), or large (21cm < dbh) (See original species and dbh inventory data, *Appendix* 1). Thirty unique species were identified within the sample population.   A proportional estimate was applied to the inventoried species to obtain an estimate of current BIP urban forest species composition and associated diameter distribution (*Appendix 1*).

Estimating the age structure of the BIP urban forest is an important feature to include within the model, as the model accounts for tree growth via increasing dbh, which is related to age, species, and longevity. Because tree age and dbh are closely related in open-grown trees (Husch et al., 1982; Vanclay, 2003; Chen and Jim, 2008), dbh distribution inventory data was transformed to initialize the 2010 BIP urban forest age structure (Figure 3-4). The resultant age-class structure represents the age-class distribution of all species within the 2010 BIP urban forest. In an effort to make a conservative estimate of C sequestration and storage potential, the model assumes that no tree is older than forty years (as park development commenced forty years ago), as well as an absence of Age 0 trees within the 2010 BIP urban forest. *Appendix 1* provides a complete summary of operational details of model assumptions and parameters.

Figure 3-4: Converting dbh class to represent age structure of the 2010 BIP urban forest.



3.3.2 Assumptions and parameters obtained from other sources

The following C model assumptions and parameters were derived primarily through the consultation of peer-reviewed literature to provide initial and future estimates of C sequestration and storage potential within the BIP urban forest landscape:

- Longevity
- Growth rate
- dbh look-up table
- Species-specific biomass equations
- Tree mortality
- Tree natality

Although some of these assumptions and parameters serve to initialize the model, the majority function to simulate urban forest growth over time.

- Longevity

The longevity of individual trees is an important factor to consider within an urban forest C model, as tree lifespans are partially dictated by predetermined genetic factors. Within the model, species-specific longevities derived from the literature inform other operations within the model, namely growth and mortality rates (See *Appendix 1* for the complete list of anticipated longevities of each species).

- Growth rate

Growth rates of trees vary by species and life stage. To recognize differences in growth rates among species, all tree species within BIP were categorized into one of three growth-rate categories that included a predetermined per-decade dbh increase value (e.g. Nowak et al., 2002). Growth rates were adapted to compensate for varying growth rates experienced during each tree's life, as younger trees tend to experience higher growth rates than older trees (Birdsey, 1992; Pregitzer and Euskirchen, 2004). To be clear, if *tree y* had *growth rate x*, for the first 1/3 of *tree y*'s life, *growth rate x* was applied. During the second 1/3 of *tree y*'s life, a *growth rate of ½ x* was applied. In the final 1/3 of *tree y*'s life, a *growth rate of ¼ x* was applied.

This decision is supported by a study completed by McPherson (1998), who modeled tree growth rates to decrease as dbh class increased (See *Appendix 1* for the complete list of species growth rates).

- dbh look-up table

A dbh look-up table was included within the model to function directly with species-specific biomass equations. The dbh look-up table provides a species-specific estimate of a tree's dbh, based on age, within the model. Although other methods exist for estimating tree age, measuring dbh is a simple, non-invasive, and inexpensive method common for estimating tree age (Husch et al., 1977; Vanclay, 2003). dbh estimates were derived using the associated species longevity and growth rate (*Appendix 1* contains the dbh look-up table, which includes all tree dbh and corresponding age estimates).

- Species-specific biomass equations

Species-specific biomass equations derived from the literature (Duinker, 1981; Ter-Mikaelian and Korzukhin, 1997; Jenkins et al., 2003, 2004) were used in conjunction with the dbh look-up table to estimate the C sequestration and storage potential of the BIP urban forest. All biomass equations used within the model were calibrated to calculate AG dry weight biomass expressed in kg per tree, including foliage. The value calculated for AG dry weight biomass of a tree was then converted to total kg C stored per tree by multiplying the biomass estimate by a factor of 0.5. This biomass-to-carbon conversion factor is widely accepted and utilized (e.g. Ovington, 1957; Reichle et al., 1973; Ajtay et al., 1977; Houghton et al., 1985; Nowak, 1994b; McPherson, 1998; Nowak and Crane, 2000; Nowak and Crane, 2002; Nowak et al., 2002). The model assumes that all trees assigned Age 0 have negligible biomass, are assigned a value of zero, and therefore do not contribute towards the overall C sequestration and storage estimates.

When species-specific biomass equations were not available, the closest relative within the same genus from the list of current and desirable species biomass equation was used. If no other species within the same genus were present within the list, the best-suited biomass equation derived from Jenkins et al. (2003, 2004) was selected. *Salix nigra* was the only exception, as a family-specific (Salicaceae) biomass equation was used (derived from Ter-Mikaelian and Korzukhin, 1997). If more than one biomass equation was found for a species, the most geographically proximate equation was selected. In an effort to mitigate bias associated with correction factors associated with unique biomass equations, all correction factors were omitted from the model's calculations. This is because correction factors are generally developed specifically to account for tree growth associated with the geographic location of the study area (Jenkins et al., 2003) (See *Appendix 1* for a complete list of biomass equations and associated references).

McHale et al. (2009) raise a concern of increasing prominence within urban forest C estimation methods with respect to biomass equations. Because there is essentially a complete lack of species-specific biomass equations developed exclusively for urban trees, all biomass equations used within the BIP urban forest C model were originally developed and intended to be applied within naturalized forest settings. Other urban forest researchers have also identified this as a critical avenue for future research so as to advance the understanding of urban forest C sequestration and storage potentials (e.g. Nowak, 1993; Nowak and Crane, 2002). Because of this gap in knowledge within the urban forest sector, similar research has relied on forest-derived biomass equations to estimate C sequestration and storage, and is therefore an intrinsic limitation for any urban forest C model relying on the use of biomass equations (McHale et al., 2009). Additionally, because of this same limitation, several biomass equations within the model were utilized outside of the dbh ranges they for which they were originally calibrated, a practice that is not uncommon within construction of forest biomass C models (e.g. Rowntree and Nowak, 1991; Nowak, 1994a).

- Tree mortality

Mortality rates of trees within the urban forest are an important factor to consider while projecting future C sequestration and storage potentials of urban forest landscapes (Nowak et al., 2004). Biotic and abiotic conditions influence urban tree mortality, most notably tree size and age, species, and condition, as well as general environmental conditions imposed by urban settings (Nowak et al., 2004; Sieghardt et al., 2005; Tello et al., 2005). To recognize these aspects, each tree within the model experiences three mortality rates throughout the duration of its life. All mortality rates within this model are correlated with individual species longevity. Trees at each extreme of the age spectrum experience higher mortality rates, because younger, smaller trees, as well as older, larger trees generally experience higher mortality rates because of establishment and senescence, respectively (Richards, 1979; Nowak et al., 1990; Nowak et al., 2004).

Nowak et al. (2004) associated surrounding land use with urban tree mortality rates, finding trees located in commercial and industrial landscapes (paralleling that of BIP) to have elevated rates of mortality because of intensified environmental pressures posed by traffic (both vehicular and pedestrian), lack of maintenance programs, and construction activity (namely direct tree removal and soil compaction). These factors are reflected within the mortality calculations, as each tree in the model experiences a different mortality rate during each third of its life (See *Appendix 1*). All trees younger than twenty years of age experience higher mortality rates to account for vulnerability associated with establishment. Trees older than twenty years of age and not within the final third of their lifespan experience a more modest, stabilized mortality rate. A species-specific elevated mortality rate (based on longevity) is applied during the final third of every tree's life to account for mortalities related to senescence. However, tree condition is not directly accounted for within the mortality calculation, as all trees within the model are assumed to be in "good" condition.

The mortality rates used within this model are higher than others found within some of the literature (e.g. Richards, 1979; Nowak and Crane, 2002). This was a conscious decision made in part to preserve the conservative nature of the potential

C sequestration and storage estimates of the BIP urban forest, in addition to accounting for the generally higher mortality rates experienced by urban trees within commercial and industrial landscapes (Nowak et al., 2004).

- Tree natality

New trees are introduced into the BIP urban forest to fulfill one of two possible purposes: 1) to replace tree loss due to mortalities; or 2) as a part of a planting program as prescribed by one of three possible urban-forest development programs. Because all trees within the model that die are replaced with Age 0 trees, the total number of replacement trees introduced each decade is directly informed by the total number of mortalities within the BIP urban forest of the preceding decade.

A list of fifteen desirable species for BIP urban forest development was developed, from which all replacement and planting-program associated trees are selected (*Appendix 1*). These species were chosen to favour the eventual nativization of the BIP urban tree population. All natalities are evenly distributed amongst the desirable species list; no preference is given to any one species, genus, or family. Doing so enables undesirable species, such as the highly invasive and over-planted urban tree, *Acer platanoides*, to eventually become eliminated from the BIP urban forest, while simultaneously enabling the establishment of a more desirable species composition of the BIP urban forest.

3.4 Assessing Potential Urban Forest Development via Viability of Current Carbon Offset Markets

Increasing presence of availability and access to C offsets which are of high calibre (i.e., those that adhere to the latest, most rigorous criteria) could perhaps be creating a nîche market for those interested in soothing their conscience in an effort to mitigate CO_2 emissions. One prevalent example is that of air travel. For example, Air Canada developed a "Carbon Offset Program", in collaboration with a not-for-profit organization, Zerofootprint. Air Canada offers a voluntary option for its customers to estimate the amount of CO_2 produced as a result of air travel (Air Canada, 2011). Air Canada customers are directed to a C offset calculator, and are given one of two options for offsetting: by their specific air travel trip (whereby the customer identifies both departure and arrival airports), or by specifying any amount of C to offset. Customers are then able to choose the project(s) to which their funds are allocated, and range from $14 to $20/tonne C, depending on the project(s) chosen. All offset projects are based in Canada.

Although perhaps a crude estimate, it is hoped that a simple program following a similar structure to that offered by Air Canada could be implemented to derive funds for intention of enhancing the urban forest C sequestration and storage capacity within BIP. Such a program would be valuable because of its representative value as a "starting point", that is, from which BIP urban forest C sequestration and storage potentials would only improve. Under a project-based, voluntary C market scenario, implementation of a C market within BIP for the purpose of developing the urban forest would provide an option for business and land owners to achieve C offsets within the Burnside community. Under this assumption, the project-scenario must be quantified, and demonstrate a reduction in CO_2 emissions from the non-project scenario. Ideally, the subsequent C offset project would set a market price for tCO_2e offsets, and revenue generated from selling C credits would fund project implementation.

Because of the lack of a regulating body governing voluntary C markets, not all C offsets offered in voluntary markets are created equal. It is important to engage several stakeholders involved with the purchasing and selling of C offsets to conduct thorough, independent research to establish and become familiar with the criteria that separate reputable C offsets, credits and associated projects from low-quality options. Quantification methods (Birdsey, 2006; Environment Canada, 2008), verification and double-counting (DSF, 2008; Environment Canada, 2008), additionality (Ristea and Maness, 2009), leakage (Birdsey, 2006; Environment Canada, 2008; Ristea and Maness, 2009; Sovacool, 2011), and permanence and project timelines (Carins and Lasserre, 2004; Birdsey, 2006; Ristea and Maness, 2009) of C offsets are prominent criteria that emerge throughout C offset, credit, and market literature. These criteria, as well as other current and emerging issues within the realm of C quantification, are explored and discussed within *Chapter 5* of the thesis, which explores the entitled potential for urban forest development via carbon credits within BIP.

3.5 References

Air Canada. (2011). *Carbon offset program.* Retrieved December 6, 2011 from http://www.aircanada.com/en/travelinfo/traveller/zfp.html

Ajtay, G.L., Ketner, P., & Duvigneaud, P. (1977). Terrestrial primary production and phytomass. In B. Bolin, E.T. Degens, S. Kempe, & P. Ketner (Eds.), *The global carbon cycle* (pp. 129-236). New York, NY: John Wiley & Sons.

Anderson, J.R., Hardy, E.E., Roach, J.T., & Witmer, R.E. (1976). A land use and land cover classification system for use with remote sensor data (US Geological Survey Professional Paper 964). Retrieved from United States Geological Survey: http://landcover.usgs.gov/pdf/anderson.pdf

Birdsey, R.A. (1992). Carbon storage and accumulation in United Sates forest ecosystems (General Technical Report WO-59). Retrieved from United States Forest Service: http://www.treesearch.fs.fed.us/pubs/15215

Birdsey, R.A. (2006). Carbon accounting rules and guidelines for the United States forest sector. *Journal of Environmental Quality, 35*, 1518-1524.

Cadenasso, M.L., Pickett, S.T.A., & Schwarz, K. (2007). Spatial heterogeneity in urban ecosystems: Reconceptualizing land cover and a framework for classification. *Frontiers in Ecology and the Environment, 5*(2), 80-88.

Canmac Economics Limited. (2010). *Economic impact: Burnside business park.* Retrieved February 22, 2011 from http://www.halifax.ca/business_parks/documents/FinalReport_July30_2010.pdf

Carins, R.D., & Lasserre, P. (2004). Reinforcing economic incentives for carbon credits for forests. *Forest Policy and Economics, 6*, 321-328.

Carreiro, M.M. & Zipperer, W.C. (2008). Urban forestry and the eco-city: Today and tomorrow. In M.M. Carreiro, Y.-C. Song, & J. Wu (Eds.), *Ecology, planning, and management of urban forests* (pp. 435-456). New York, NY: Springer Science.

Chen, S.S., & Jim, C.Y. (2008). The urban forest management of Nanjing city: Key characteristics and management assessment. In M.M. Carreiro, Y.-C. Song, & J. Wu (Eds.), *Ecology, planning, and management of urban forests* (pp. 259-278). New York, NY: Springer Science.

Côté, R.P., & Smolenaars, T. (1997). Supporting pillars for industrial ecosystems. *Journal of Cleaner Production, 5*(1-2), 67-74.

David Suzuki Foundation. (2008). Credit check: A comparative evaluation of tree-planting and fossil-fuel emission reduction offsets (A David Suzuki Foundation Technical Paper). Retrieved from David Suzuki Foundation: http://www.davidsuzuki.org/publications/downloads/2008/Credit_Check_080701.pdf

Duinker, P.N. (1981). *Biomass prediction equations for ten tree species in central Nova Scotia.* (Unpublished master's thesis). Dalhousie University, Canada.

Environment Canada. (2008). *Turning the corner: Canada's offset system for greenhouse gasses*. Retrieved December 8, 2011 from http://www.ec.gc.ca/doc/virage-corner/2008-03/526_eng.htm

Halifax Regional Municipality (HRM). (2010). *Burnside business park*. Retrieved February 22, 2011 from http://www.halifax.ca/business_parks/parks/burnside.html

Homer, C., Huang, C., Yang, L., Wylie, B., & Coan, M. (2004). Development of a 2001 National land-cover database for the United States. *Photogrammetric Engineering & Remote Sensing*, *70*(7), 829–840.

Houghton, R.A., Schlesinger, W.H., Brown, S., & Richards, J.F. (1985). Carbon dioxide exchange between the atmosphere and terrestrial ecosystems. In J. R. Trabalka (Ed.), *Atmospheric carbon dioxide and the global carbon cycle*, (pp. 114-140). Washington, D.C.: United States Department of Energy.

Husch, B., Miller, C., & Beers, T.W. (1982). *Forest mensuration*. New York, NY: John Wiley & Sons.

Jackson, L.J., Trebitz, A.S., & Kottingham, K.L. (2000). An introduction to the practice of ecological modelling. *BioScience, 50*(8), 694-706.

Jenkins, J.C., Chojnacky, D.C., Heath, L.S., & Birdsey, R.A. (2003). National-scale biomass estimators for United States tree species. *Forest Science, 49*(1), 12–35.

Jenkins, J.C., Chojnacky, D.C., Heath, L.S., Birdsey, R.A., & Richard, A. (2004). Comprehensive database of diameter-based biomass regressions for North American tree species (General Technical Report NE-319). Retrieved from United States Forest Service: http://www.uvm.edu/~jcjenkin/jenkins%20et%20al.%202004.pdf

Jo, H.K., & McPherson, E.G. (1995). Carbon storage and flux in urban residential greenspace. *Journal of Environmental Management, 45*, 109-133.

McHale, M.R, Burke, I.C., Lefsky, M.A., Peper, P.J., & McPherson, E.G. (2009). Urban forest biomass estimates: Is it important to use allometric relationships developed specifically for urban trees? *Urban Ecosystems, 12*, 95-113.

McPherson, E.G. (1998). Atmospheric carbon dioxide reduction by Sacramento's urban forest. *Journal of Arboriculture, 24*(4), 215-223.

Natural Resources Canada (NRCan). (2009). *The atlas of Canada – Land cover.* Retrieved April 29, 2011 from http://atlas.nrcan.gc.ca/site/english/maps/environment/land/landcover/1

Nowak, D.J. (1993). Atmospheric carbon reduction by urban trees. *Journal of Environmental Management, 37*, 207-217.

Nowak, D.J. (1994a). Understanding the structure of urban forests. *Journal of Forestry, 92,* 42–46.

Nowak, D.J. (1994b). Atmospheric carbon dioxide reduction by Chicago's urban forest. In E.G. McPherson, D.J. Nowak, & R.A. Rowntree (Eds.), *Chicago's urban forest ecosystem: Results of the Chicago urban forest climate project* (pp. 83-94) (General Technical Report NE-186). Retrieved from United States Forest Service: http://www.treesearch.fs.fed.us/pubs/4285

Nowak, D.J., & Crane, D.E. (2000). The urban forest effects (UFORE) model: Quantifying urban forest structure and functions. In M. Hansen, & T. Burk (Eds.), *Proceedings: Integrated Tools for Natural Resources Inventories in the 21st Century* (pp. 714-720). St. Paul, MN: United States Forest Service.

Nowak, D.J., & Crane, D.E. (2002). Carbon storage and sequestration by urban trees in the USA. *Environmental Pollution, 116*(3), 381-389.

Nowak, D.J., Crane, D.E., & Stevens, J.C. (2006). Air pollution removal by urban trees and shrubs in the United States. *Urban Forestry & Urban Greening, 4*, 115-123.

Nowak, D.J., Kuroda, M., & Crane, D.E. (2004). Tree mortality rates and tree population projections in Baltimore, Maryland, USA. *Urban Forestry & Urban Greening, 2*, 139-147.

Nowak, D.J., McBride, J.R., & Beatty, R.A. (1990). Newly planted street tree growth and mortality. *Journal of Arboriculture, 16*(5), 124-129.

Nowak, D.J., Stevens, J.C., Sisinni, S.M., & Luley, C.J. (2002). Effects of urban tree management and species selection on atmospheric carbon dioxide. *Journal of Arboriculture, 28*(3), 113-122.

Ovington, J.D. (1957). The volatile matter, organic carbon and nitrogen contents of tree species grown in close stands. *The New Physiologist, 56*, 1-11.

Pauleit, S., & Duhme, F. (2000). GIS assessment of Munich's urban forest structure for urban planning. *Journal of Arboriculture, 26*(3), 133-141.

Pickett, S.T.A., Cadenasso, M.L., Grove, J.M., Boone, C.G., Groffman, P.M., Irwin, E., … & Warren, P. (2011). Urban ecological systems: Scientific foundations and a decade of progress. *Journal of Environmental Management, 92*, 331-362.

Pregitzer, K.S, & Euskirchen, E.S. (2004). Carbon cycling and storage in world forests: Biome patterns related to forest age. *Global Change Biology, 10*, 2052–2077.

Reichle, D.E., Dinger, B.E., Edwards, N.T., Harrits, W.F, & Sollins, P. (1973). Carbon flow and storage in a forest ecosystem. In G.M. Woodwell, & E.V. Pecans (Eds.), *Carbon and the Biosphere – Proceedings of the 24th Brookhaven Symposium in Biology* (pp. 345-365)1973 May 16-18. Upton, NY: US Atomic Energy Commission.

Richards, N.A. (1979). Modeling survival and consequent replacement needs in a street tree population. *Journal of Arboriculture, 5*(11), 251-255.

Ristea, C., Maness, T. C. (2009). Opportunities, challenges and markets for forest carbon offset projects. *The Forestry Chronicle 85(5)*, 715-718.

Rowntree, R.A., & Nowak, D.J. (1991). Quantifying the role of urban forests in removing atmospheric carbon dioxide. *Journal of Arboriculture, 17*(10), 269-275.

Sieghardt, M., Mursch-Radlgruber, E., Paoletti, E., Couenberg, E., Dimitrakopoulus, A., Rego, F., … & Randrup, T.B. (2005). The abiotic urban environment - Impact of urban growing conditions on urban vegetation. In C.C. Konijnendijk, K. Nilsson, T.B. Randrup, & J. Schipperijn (Eds.), *Urban forests and trees* (pp. 281-323). New York, NY: Springer.

Sovacool, B.K. (2011). The policy challenges of tradable credits: A critical review of eight markets. *Energy Policy, 39*, 575-585.

Starfield, A.M. (1997). A pragmatic approach to modeling for wildlife management. *The Journal of Wildlife Management, 61*(2), 261-270.

Tello, M.-L., Tomalak, M., Siwecki, R., Gáper, J., Motta, E., & Mateo-Sagasta, E. (2005). Biotic urban growing conditions – Threats, pests and diseases. In C.C. Konijnendijk, K. Nilsson, T.B. Randrup, & J. Schipperijn (Eds) *Trees*, (pp. 325-365). New York, NY: Springer.

Ter-Mikaelian, M.T., Korzukhin, M.D. 1997. Biomass equations for sixty-five North American tree species. *Forest Ecology and Management, 97*, 1-24.

Vanclay, J.K. (2003). Realizing opportunities in forest growth modeling. *Canadian Journal of Forest Research, 33,* 536–541

Zipperer, W.C., Sisinni, S.M., Pouyat, R.V., & Foresman, T.W. (1997). Urban tree cover: An ecological perspective. *Urban Ecosystems, 1*, 229-246.

CHAPTER 4: POTENTIAL FOR CARBION DIOXIDE SEQUESTRATION AND STORAGE WITHIN BURNSIDE INDUSTRIAL PARK, DARTMOUTH, NOVA SCOTIA

4.1 Introduction

As levels of atmospheric CO_2 continue to increase, so do concerns surrounding the potential impacts of global climate change. Examples of anticipated impacts of global climate change recognized by the Intergovernmental Panel on Climate Change (IPCC) include increased global mean temperatures, sea-level rise, decreased access to freshwater, extinction of climatically sensitive biota, and continued intensification of extreme weather events (IPCC, 2007). The need for atmospheric CO_2 mitigation has never been as pressing as it is today, as evidence continues to accumulate supporting a strong relationship between increasing atmospheric CO_2 levels with increasing surface air temperature of the Earth (Keeling 1973; IPCC, 2007).

Never before has society been as urbanized as today, with over 80% of the global population residing in urban areas (UN-Habitat, 2009). Urbanization, as defined by Tisdale (1942), "is a process of population concentration" (p. 311). The two main sources of anthropogenically produced atmospheric CO_2 are via 1) fossil-fuel combustion; and 2) deforestation through land use change (Frumkin, 2002; Pataki et al., 2006). Although both of these activities occur within rural and urban settings, they are also often the direct result of urbanization. Examples of environmental impacts associated with urbanization include decreased air and water quality, disruption of multiple ecological cycles, and reduced natural biodiversity, as well as the creation of urban heat islands (McKinney, 2002; Duh et al., 2008; Ewing, 2008; Grimm et al., 2008).

In 2005, the IPCC produced a special report specifying five ways in which atmospheric CO_2 levels could be reduced. One of the options presented in this report was enhancing biological C sequestration and storage (IPCC, 2005). Usually, sequestration efforts occur within rural and hinterland settings. However, there is an increasing body of research investigating the potential C sequestration and storage potentials associated with urban forest development (Rowntree and Nowak, 1991; Jo and McPherson, 1995; Myeong et al., 2006). Furthermore, urban forests provide a multitude of environmental, economic, and social benefits to urban communities that rural and hinterland forests simply cannot because of their location far from concentrations of people. Many urban forest benefits help to mitigating negative impacts innately associated with urbanization, such as alleviating pollutant levels in air and water, and diminishing urban heat islands (Dwyer et al., 1992; McPherson et al., 1994; Dwyer et al., 2000)

One aspect of urbanization of particular interest is that of economy of land; how land is allocated during development directly affects C dynamics of the respective landscape. Low-density urban sprawl is a pattern of urban development making significant contribution to atmospheric CO_2 levels in addition to the previously identified modes of CO_2 production associated with general urban development tendencies. For the purpose of this research, low-density urban sprawl is defined by three characteristics: 1) distinct segregation of land uses; 2) low-density development; and 3) dependence on automobiles as the primary mode of transportation within the community (Sierra Club, 1998; Johnson, 2000; Frumkin, 2002; Squires, 2002; Kahn, 2006, Pataki et al., 2006).

Burnside Industrial Park (BIP), located in Dartmouth, Nova Scotia, Canada, is a light-industrial/commercial embodying the characteristics of CO_2-intensive, low-density urban sprawl (Figure 4-1). As such, it exemplifies the two primary modes by which humans contribute to atmospheric levels of CO_2, and was therefore selected as the case study for this research. The initial BIP landscape was entirely forested before initial development began approximately forty years ago, and the introduction of industry and associated urban infrastructures have facilitated increased concentration of fossil-fuel-combusting activities within the area.

Figure 4-1: Aerial photograph of the study site, Burnside Industrial Park.

Development of the park is not yet complete; much of the land within BIP remains forested today, but is slated for future expansion. Developed areas of the park exhibit extremely low urban tree population densities, coinciding closely with estimates of tree densities within industrial and commercial settings made by other urban forest researchers (e.g. Rowntree and Nowak, 1991; Nowak, 1993; McPherson, 1998; Nowak et al., 2002). To what degree might urbanized areas such as low-density, industrial/commercial landscapes represent overlooked opportunities for enhancing C sequestration storage? This general question drives our primary research questions, as follows:

- How much C is being stored by the 2010 BIP urban forest today?
- What is the potential for future C sequestration and storage in the 2050 BIP urban forest, under the following three urban-forest development scenarios:
    1. Maintenance of the 2010 urban forest population of trees;
    2. Maintenance of the 2010 urban forest in addition to planting 50% of all 2010 vacancies (i.e. plantable spots); and
    3. Maintenance of the 2010 urban forest in addition to planting 100% of all 2010 vacancies.

Two research objectives were established. The first objective was to determine the existing forest structure within BIP. This involved the creation of a land-cover map using a GIS in conjunction with aerial photography, site visits, and tree inventories. The second objective was to develop an urban-forest C model to use in conjunction with data derived from the land-cover map. To achieve these objectives, a mixed-methods approach was used to quantify C sequestration and storage potentials for three BIP urban-forest development scenarios.

4.2 Methods

Many factors influence C sequestration and storage potentials of urban trees. Although our understanding of urban-forest C dynamics continues to improve, quantification of this resource is complicated, as is quantification of any aspect of real-world ecosystems (Starfield, 1997; Jackson et al., 2000; Birdsey, 2006). As technologies have advanced and improved, so too has our ability to establish fluidity when calling upon a mixed-methods approach to quantify various aspects urban forest ecosystems (Nowak et al., 2006; Dwyer and Miller, 1999; Myeong et al., 2006). Such amalgamation has enabled various urban forest stakeholders to gain new and valuable perspectives into urban forest resources (Nowak et al., 2002). Two common technologies were integrated in our work - GIS and C models. The technologies were both critical to our determination of the C sequestration and storage potentials of the BIP urban forest.

4.2.1 The study area

BIP is a light-industrial/commercial park that encompasses approximately 1270 ha and is located in Dartmouth, Nova Scotia, Canada (Figure 4-1). As the largest park of its kind in Atlantic Canada, BIP is home to an estimated 1,500 businesses and employs 15,000 people (HRM, 2010). As such, it is a vital economic component of the Atlantic region as a whole. Land within the park is owned both privately and by three levels of government (municipal, provincial, and federal).

4.2.2 Importance of establishing current urban forest structure

To construct a viable estimate of C sequestration and storage potential within the BIP urban forest, we begin by analyzing the urban forest structure as it influences most of the functions and services provided by urban forests (Sanders, 1984; Zipperer et al., 1997; Pickett and Cadenasso, 2007). Structure, as defined by Nowak (1994a), "…is the spatial arrangement of vegetation in relation to other objects, such as buildings, within urban areas" (p. 42). The structural features accounted for by the BIP urban forest C model include area available for current and future tree growth, tree population density, total population estimate, species composition, size (diameter at breast height, or dbh) distribution, and age structure.

4.2.3 Using GIS to construct a land cover map of Burnside Industrial Park

To determine the area available for tree planting, land cover within BIP was organized into one of five categories (Table 4-1). This was achieved by first establishing definitions for each of the land cover categories to help ensure consistency by providing guidance during the photo interpretation process (Pauleit and Duhme, 2000). Employing the scanning method (Nowak et al., 1996), land cover within the aerial photographs of BIP (obtained from Microsoft Bing; photographed during the spring and summer months of 2008), in addition to an overlay of official boundary data (obtained from Halifax Regional Municipality), were digitized at a 1:1000 scale using ESRI ArcGIS software (version 9.3). Features measuring less than 4m but greater than 1m in width and/or length were digitized at a 1:500 scale. Features less than 1m in width and/or length were not digitized. The map was used as a base from which urban forest structural features were estimated in conjunction with field data.

Table 4-1: Description of BIP land cover categories

Land cover category	Description
Grey	- Land currently occupied or otherwise not intended to accommodate present or future urban tree growth - Features include ✓ permanent infrastructures (i.e. buildings, parking lots, transportation corridors (including roads and railroads), sidewalks, concrete boulevards), ✓ storage areas, ✓ recreational fields, and ✓ hydrological features not encompassed within Undisturbed Green land cover (e.g. lakes, rivers, ponds).
Brown	- Land with potential to accommodate tree growth upon site amendment and appearing to be otherwise idle - Features include ✓ large areas of exposed soil or gravel ✓ chlorotic/browning tendency of existing vegetation
Construct	- Land exhibiting evidence of recent construction or development activities, primary cover is typically soil or gravel - Features include ✓ poured foundations ✓ semi-constructed roads ✓ various evidence of permanent infrastructure development, such as the presence of large construction equipment (e.g. dump trucks, cranes) ✓ forest patches < 0.35ha, as it appears unlikely that these remnants will be preserved within this area
Disturbed Green	- Land currently accommodating or able to immediately accommodate future urban tree growth upon little to no site amendment, primary cover is herbaceous vegetation but includes woody vegetation as well - Features include ✓ lawns ✓ meadows ✓ grassed boulevards and road medians
Undisturbed Green	- Land currently accommodating tree growth within a naturalized or forested state, primary cover is woody vegetation - Features include ✓ contiguous forest patches ✓ areas of high-density trees where additional tree planting does not seem practical or feasible ✓ rivers, streams, footpaths, small roads, utility corridors that are engulfed entirely by otherwise Undisturbed Green classified land cover

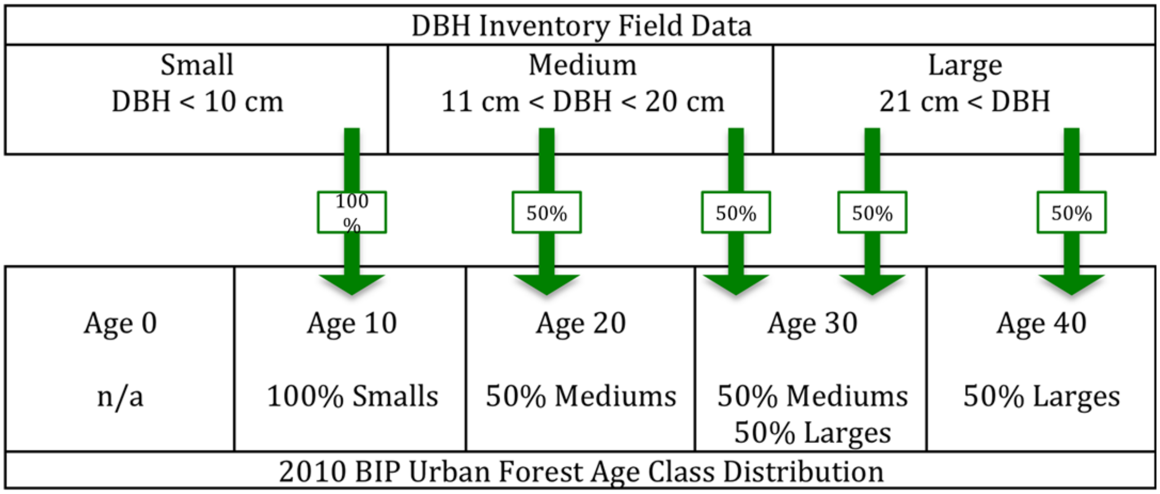
4.2.4 2010 Urban forest density and total population

We assumed a desirable tree density of 1000 trees/ha for the Disturbed Green land cover (i.e. plantable space). This is rather high by urban-forest standards, but low for timber-producing forests. We aimed for high density to show full carbon-sequestration potential. Given the extent of Disturbed Green land cover, it could potentially accommodate 87,000 additional trees. The current BIP urban forest density and subsequent total tree population was determined using the land cover map. Randomly selected Disturbed Green polygons were selected and visited; all trees within each site visited were counted.

4.2.5 2010 Urban forest species composition, diameter at breast height distribution, and age structure

Species composition, dbh distribution, and age structure of the BIP forest are all vital for the purpose of estimating C sequestration and storage, because different species and sizes of trees sequester and store C at different rates and quantities, respectively (Nowak, 1993). A polygon consisting of approximately 10% of total area of BIP was drawn over a previously developed portion of BIP. Development of the park began forty years ago, so infrastructure patterns within newer portions of the park vary from those established during earlier phases of implementation. The polygon, relying on our photointerpretive judgment, was drawn to contain an estimated ½ older development and ½ newer development in an effort to establish an acceptable representation of development patterns present within the park. Polygon boundaries were established using right-of-ways as a guide, to appease issues regarding accessibility of land. During a field visit, all trees within the Disturbed Green polygons falling within this boundary polygon were inventoried for species and dbh. Some thirty-tree species were recorded. A proportional estimate was applied to establish species composition of the current (2010) urban forest. Diameters of inventoried trees were estimated and classified into one of three dbh categories: small (<10cm), medium (>10cm, <20cm), and large (>20cm). We assumed that tree age is closely related to dbh (Husch et al., 1982; Vanclay, 2003), and converted the dbh data to tree ages to establish an initial age structure for modeling purposes (Figure 4-2).

Figure 4-2: Converting dbh class to represent age structure of the 2010 BIP urban forest.



4.2.6 Overview of operational assumptions

The model constructed for this research generates deterministic estimates of urban forest C storage and sequestration. The C model operates in ten-year time steps; all urban forest development scenarios commence in year 2010, using the 2010 urban forest structure as the base from which it is grown, to year 2050. There are several features of urban forest growth this model attempts to account for, including species-specific longevities, growth rates, mortality rates, and biomass equations. All trees are assumed to be in “good” condition, and as such, no specific adjustments were made to account for mortalities associated with environmental stress, pests, diseases, or other unforeseeable circumstances that may contribute to significantly altered mortality rates. Climate-change implications on tree development are not considered.

New trees (i.e. natalities) are introduced into the model as replacement trees or *Scenario* trees. Replacement trees are trees planted to replace decadal mortalities;

the number of mortalities informs the number of replacement trees in the previous decade of growth simulated by the C model. *Scenario* trees refer to those introduced into the model as a component of urban forest development *Scenario 2* and *Scenario 3*. All scenario trees are introduced in year 2020. Species selections for all natalities, regardless if they are replacement or scenario trees, are distributed evenly from a list of fifteen desirable species, native to the Acadian Forest region (*Appendix 1*, Table 12). Additionally, every new tree is added into the "Age 0" class in an effort to preserve a conservative biomass estimate, as all "Age 0" trees are assumed to have negligible biomass, and are automatically assigned a value of zero.

4.2.7 Longevity and growth rate

The longevity of a given species is partially determined by genetic factors, and should be considered when modeling C sequestration and storage within an urban forest landscape. As such, respective longevities were applied to determine growth and mortality rates.

Each species was assigned a growth rate of low, medium, or high in an effort to recognize various growth rates among species. Furthermore, a given tree will experience different growth rates depending on life stage, as younger, establishing trees tend to experience higher growth rates than that of their older, senescing counterparts (Birdsey, 1992; McPherson, 1998) (Table 4-2). Growth rates for each species were determined through consulting the database created by Rostami (2011). Where data were unavailable, consultation with urban forest professionals and research colleagues was undertaken to determine an estimate of the appropriate longevity and/or growth rate. See *Appendix 1.*

Table 4-2: Sample species representing the relationship between longevity and growth rate within the BIP urban forest C model

Botanical name	Longevity (years)	Growth rate category	Growth rate values (cm/decade)			
			Initial value	First 1/3 life	Second 1/3 life	Third 1/3 life
Acer rubrum	100	medium	10	10	5	2.5
Acer saccharinum	130	high	15	15	7.5	3.75
Acer saccharum	200	low	7.5	7.5	3.75	1.875

4.2.8 Mortalities and natalities

The mortality rates for each species incorporated into C-model calculations were informed by their respective longevities. All trees are assigned three mortality rates, depending on age, within the model. Trees at each end of the age spectrum experience higher mortality rates, because younger trees are susceptible to failure due to establishment issues, and older trees fail as they reach senescence (Nowak et al, 1990). Trees younger than twenty years experience a mortality rate of 0.9 each decade; between the ages of twenty until the final third of their life experience a 0.95 mortality rate per decade. Trees in their final third of anticipated longevity are assigned species-specific mortality rates per decade determined using the following calculation: [# remaining trees – (10[# remaining trees/1/3 lifespan])] (See *Appendix 1*, Table 14 for a summary of all mortality calculations).

All mortalities are replaced with natalities (i.e. new trees). The sums of all mortalities directly inform the number of natalities. New trees introduced into the model from development *Scenarios 1* and *Scenario 2* are included, in entirety, in year 2020. All natalities are introduced into the model as "Age 0" (therefore having zero biomass), and are distributed evenly among fifteen desirable species, all of which are native to the Acadian forest region (*Appendix 1*, Table 12).

4.2.9 Biomass equations, dbh look-up table, and biomass-to-carbon calculation

Once the growth of the 2010 (i.e. initial) urban forest has occurred for the first time step (i.e. year 2010 through 2020), total C storage is calculated for each species using allometric biomass equations. All biomass equations require tree dbh to calculate above-ground (AG) dry weight biomass of each individual tree. The dbh table (Table 4-4) provides species-specific dbh estimates based on tree age, and was informed by the previously discussed species longevities and growth rates. All biomass equations were derived from the literature and calculate AG biomass only (including foliage), primarily from Jenkins et al., (2003, 2004) and Ter-Mikaelian and Korzukhin(1997).

When species-specific biomass equations were not available, the closest relative within the same genus from the list of desirable species was used. If no species within the same genus was available, the most appropriate equation from Jenkins et al. (2003, 2004) was selected. When more than one option for biomass equation selection was presented, the equation whose data were derived from the nearest geographic proximity was chosen (See Table 4-3 for a complete list of all biomass equations used within the BIP urban forest C model). All correction factors were omitted from biomass equations as a bias mitigation effort (Jenkins et al., 2003). Simply summing the biomass estimates for each species within a given population yields the total biomass. This value was then converted to C using a factor of 0.5, a widely applied biomass-to-C conversion factor (Ajtay et al., 1977; Houghton et al., 1985; Nowak and Crane, 2002)

Table 4-3: Biomass equations used within the carbon model (1 of 3)

Botanical name	Original biomass equation	a	b	Study location	dbh range (cm)	Reference
Acer campestre	ln W = a + b ln D	-1.9702	2.3405	n/a	n/a	*Acer rubrum*
Acer platanoides	ln W = a + b ln D	-1.9702	2.3405	n/a	n/a	*Acer rubrum*
Acer rubrum	ln W = a + b ln D	-1.9702	2.3405	Nova Scotia	1.3 - 32.3	Duinker, 1981
Acer saccharinum	bm = Exp(a + b ln dbh)	-1.9123	2.3651	General: USA	>2.5 to 66	Jenkins et al., 2003; 2004 (soft maple/birch)
Acer saccharum	ln W = a + b ln D	-1.876	2.3924	Nova Scotia	1.2 - 33.5	Duinker, 1981
Aesculus hippocastanum	bm = Exp(a + b ln dbh)	-2.48	2.4835	General: USA	>2.5 to 56	Jenkins et al., 2003; 2004, (mixed hardwood)
Amelanchier canadensis	bm = Exp(a + b ln dbh)	-2.48	2.4835	General: USA	>2.5 to 56	Jenkins et al., 2003; 2004 (mixed hardwood)
Betula alleghaniensis	ln W = a + b ln D	-2.1306	2.451	Nova Scotia	2.6 - 29.0	Duinker, 1981
Betula papyrifera	ln W = a + b ln D	-2.0045	2.3634	Nova Scotia	1.1 - 31.4	Duinker, 1981
Betula pendula	ln W = a + b ln D	-2.0045	2.3634	n/a	n/a	*Betula papyrifera*
Fagus grandifolia	$M=aD^b$	0.1958	2.2538	New Brunswick	2 to 29	Ter-Mikaelian and Korzukhin, 1997
Fagus sylvatica	$M=aD^b$	0.1958	2.2538	n/a	n/a	*Fagus grandifolia*
Fraxinus nigra	$M=aD^b$	0.1634	2.348	Upper Great Lakes	4 to 32	Ter-Mikaelian and Korzukhin, 1997
Gleditsia triacanthos	bm = Exp(a + b ln dbh)	-2.48	2.4835	General: USA	>2.5 to 56	Jenkins et al., 2003; 2004 (mixed hardwood)
Juniperus scopulorum	bm = Exp(a + b ln dbh)	-0.7152	1.7029	General: USA	>2.5 to 78	Jenkins et al., 2003; 2004 (woodland)

Table 4-3, continued. Biomass equations used within the carbon model (2 of 3)

Botanical name	Original biomass equation	a	b	Study location	dbh range (cm)	Reference
Malus spp.	bm = Exp(a + b ln dbh)	-2.48	2.4835	General: USA	>2.5 to 56	Jenkins et al., 2003; 2004 (mixed hardwood)
Ostrya virginiana	bm = Exp(a + b ln dbh)	-2.48	2.4835	General: USA	>2.5 to 56	Jenkins et al., 2003; 2004 (mixed hardwood)
Picea abies	$M=aD^b$	0.2722	2.104	New York	12 to 44	Ter-Mikaelian and Korzukhin, 1997
Picea pungens	ln W = a + b ln D	-1.7957	2.2417	n/a	n/a	*Picea rubens*
Picea rubens	ln W = a + b ln D	-1.7957	2.2417	Nova Scotia	2.5 - 28.3	Duinker, 1981
Pinus banksiana	$M=aD^b$	0.1093	2.3291	Nova Scotia	3 - 33.4	Ter-Mikaelian and Korzukhin, 1997
Pinus strobus	$M=aD^b$	0.1617	2.142	New Brunswick	2 to 37	Ter-Mikaelian and Korzukhin, 1997
Pinus sylvestris	$M=aD^b$	0.1093	2.3291	n/a	n/a	*Pinus banksiana*
Populus grandidentata	ln W = a + b ln D	-2.32	2.3773	Nova Scotia	1.2 - 33.8	Duinker, 1981
Populus tremuloides	ln W = a + b ln D	-2.3778	2.4085	Nova Scotia	0.8 - 26.5	Duinker, 1981
Pyrus calleryana	bm = Exp(a + b ln dbh)	-2.48	2.4835	General: USA	>2.5 to 56	Jenkins et al., 2003; 2004 (mixed hardwood)
Quercus rubra	$M=aD^b$	0.1335	2.422	Upper Great Lakes	5 to 34	Ter-Mikaelian and Korzukhin, 1997
Salix nigra	$M=aD^b$	0.1619	2.0552	Maine	3 to 24	Ter-Mikaelian and Korzukhin, 1997
Sorbus aucuparia	bm = Exp(a + b ln dbh)	-2.48	2.4835	General: USA	>2.5 to 56	Jenkins et al., 2003; 2004 (mixed hardwood)

Table 4-3, continued. Biomass equations used within the carbon model (3 of 3)

Botanical name	Original biomass equation	a	b	Study location	DBH range (cm)	Reference
Syringa reticulata	bm = Exp(a + b ln dbh)	-2.48	2.4835	General: USA	>2.5 to 56	Jenkins et al., 2003; 2004 (mixed hardwood)
Thuja occidentalis	$M=aD^b$	0.1148	2.1439	New Brunswick	2 to 30	Ter-Mikaelian and Korzukhin, 1997
Tilia americana	$M=aD^b$	0.0872	2.3539	Upper Great Lakes	4 to 47	Ter-Mikaelian and Korzukhin, 1997
Tsuga canadensis	$M=aD^b$	0.1617	2.1536	New Brunswick	2 to 34	Ter-Mikaelian and Korzukhin, 1997
Ulmus americana	$M=aD^b$	0.0825	2.468	Upper Great Lakes	4 to 29	Ter-Mikaelian and Korzukhin, 1997
Zelkova serrata	bm = Exp(a + b ln dbh)	-2.48	2.4835	General: USA	>2.5 to 56	Jenkins et al., 2003; 2004 (mixed hardwood)

Table 4-4: Sample of dbh table utilized within the urban forest C model

Botanical Name	Longev-ity (years)	Growth rate (cm/decade)			Growth rate *x* applied after age…		Estimated dbh (cm) at age…								
		1	**2**	**3**	**1**	**2**	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**
Acer rubrum	100	10	5	2.5	30	70	0	10.00	20.00	30.00	35.00	40.00	45.00	47.50	50.00
Acer saccharinum	130	15	7.5	3.75	40	90	0	15.00	30.00	45.00	60.00	67.50	75.00	82.50	90.00
Acer saccharum	200	7.5	3.75	1.875	70	130	0	7.50	15.00	22.50	30.00	37.50	45.00	52.50	56.25

4.3 Results and Discussion

4.3.1 Land cover map of Burnside Industrial Park

Urban ecosystems are highly fragmented and heterogeneous by nature, and as such, there are arguably an infinite number of ways to classify, categorize, and otherwise comprehend the heterogeneity (Myeong et al., 2006; Cadenasso et al., 2007; LaPaix and Freedman, 2010). Employing a GIS in conjunction with high-resolution aerial photography and management-objective-oriented land-cover classification criteria is a relatively simple, inexpensive, and effective way for urban forest managers to explore various forest-management options. Area available for tree growth directly dictates forest structure and, therefore, C sequestration and storage potentials (Nowak, 1994a). Quantifying the area available for current tree growth through construction of a land-cover map provided a basis from which the three urban forest development scenarios could be compared and contrasted.

The largest land cover class within BIP's 1270 ha is Undisturbed Green, accounting for approximately 550 ha. The next largest land cover class was Grey (526 ha), followed subsequently by Disturbed Green (87.6 ha), Construct (73.0 ha), and Brown (32 ha) (Table 4-5; Figure 4-3). The land cover class of particular interest for the purpose of enhancing the C sequestration and storage potential of the park's urban forest is the Disturbed Green class, whose current tree density is 55 trees/ha. The total current population was calculated by multiplying the estimated current density by Disturbed Green area, yielding a current tree population estimate to be 4,785. Assuming a maximum desirable density of 1000 trees/ha within this land cover class, and accounting for the existing population, 82,215 vacancies were identified for future urban forest development. This value represents *Scenario 3*: 100% planting of all vacancies. *Scenario 2*, 50% planting of all identified vacancies, entails the planting of 41,108 vacancies.

According to Pickett and Cadenasso (2007), "Acknowledging the role of design in the urban mosaic allows plant ecologists to consider new urban vegetation as a tool to enhance the environmental goods and services it provides and supports throughout the metropolis, and not just in designated reserves" (p. 9). Aside from estimating the total available area for improving urban forest structure, the land cover map unveiled the total number of polygons within each land cover category. Although the Disturbed Green land cover class accounts for a meager 7% of total park area, it comprises substantially more polygons than any other land cover category. These data reflect a high degree of fragmentation that commonly exists within urban ecosystems (Cadenasso et al., 2007; Pickett and Cadenasso, 2007). This simple insight could aid urban forest managers by encouraging them to pursue objective-oriented urban-forest-management options to optimize services and benefits provided by urban vegetation (Cadenasso et al., 2007; Pickett and Cadenasso, 2007). For example, urban foresters who reduce fragmentation of vegetated areas within urban landscapes can help mitigate habitat losses associated with urban development, thereby resulting in increased biodiversity within urban areas (Rowntree, 1986; McKinney, 2002; Alvey, 2006; Yue, 2010)

Table 4-5: Summary of BIP land cover

Land cover class	**Total polygons (#)**	**Sum (ha)**	**Percent total coverage (%)**
Grey	24	526	41.5
Brown	181	32	2.5
Construct	16	73.0	5.8
Disturbed Green	1159	87.6	6.9
Undisturbed Green	121	550	43.4

Figure 4-3: Land cover classification map of Burnside Industrial Park

4.3.2 Carbon storage and sequestration potentials of the Burnside Industrial Park urban forest

As anticipated, the results generated by the C model reveal a direct relationship between tree density and overall population of the urban forest, and subsequently C storage and sequestration potentials; higher densities of trees yield higher C storage and sequestration potentials (Figure 4-4). For example, in year 2050, *Scenario 1* (population maintenance only) and *Scenario 3* (100% planting of all vacancies), experience vastly different C-stores. *Scenario 3* yields eighteen times more trees (Table 4-6), eight times more C storage (Figure 4-4), and ten times greater rate of C sequestration (Table 4-7) than the urban forest structure within *Scenario 1*. All values within tables 4-6 and 4-7, as well as within Figure 4-4, can simply be multiplied by eighty-seven (i.e. the total area available for urban tree growth) to obtain overall estimates within BIP.

Figure 4-4: Carbon storage potentials of the BIP urban forest under three development scenarios, in tonnes carbon per hectare (tC/ha)

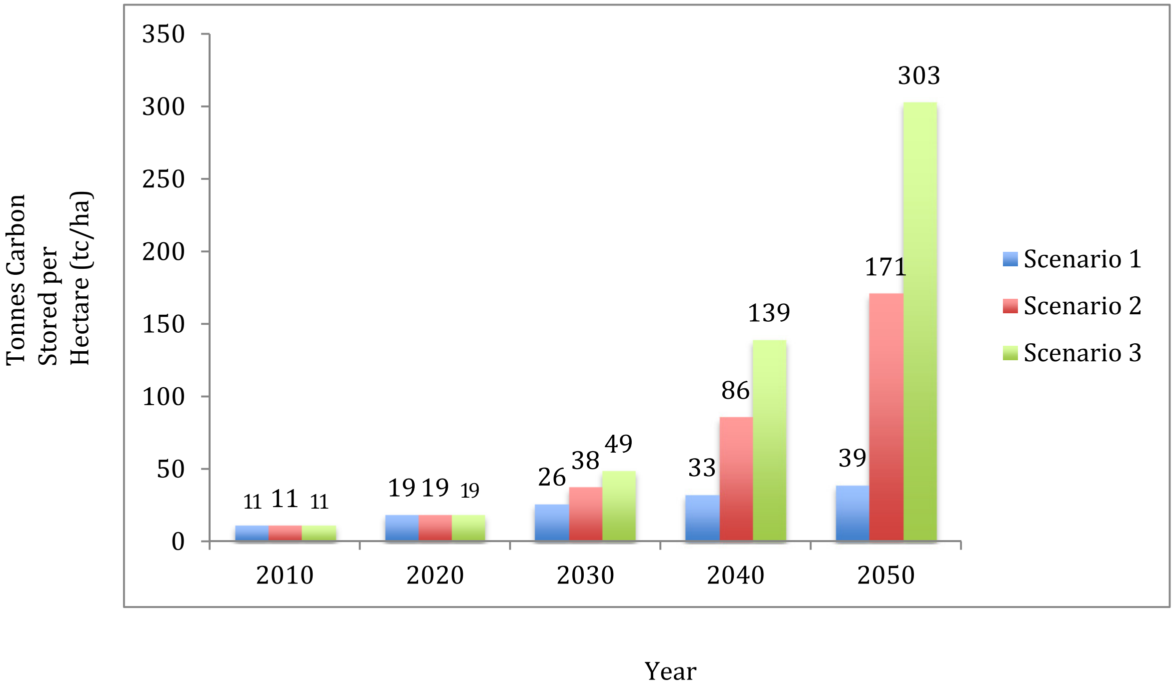


Table 4-6: Tree population per hectare (# trees/ha)

	2010	2020	2030	2040	2050
Scenario 1	55	55	55	55	55
Scenario 2	55	528	528	528	528
Scenario 3	55	1,000	1,000	1,000	1,000

Table 4-7: Carbon sequestration rate by scenario and time period (tC/yr/ha)

	2010-2020	2020-2030	2030-2040	2040-2050	Average
Scenario 1	0.7	0.7	0.6	0.7	0.7
Scenario 2	0.7	1.9	4.8	8.5	4.0
Scenario 3	0.7	3.0	9.0	16.4	7.3

Within the model, tree age is directly informed by estimated dbh, as prescribed by the dbh look-up table (*Appendix 1,* Table 10). Therefore, as a tree ages, its dbh increases. Because dbh is used by each species-specific allometric biomass equation, an individual tree will store more C as its dbh increases with age. *Scenarios 1, 2,* and *3* all demonstrate an increase in C storage between 2010 and 2050. It is then logical, when managing an urban forest from a C sequestration standpoint, to plant and maintain large trees within the urban forest. There is large body of evidence and argument supporting this very notion of establishing large-stature urban trees not only to maximize C sequestration and storage potentials of urban forests, but other urban forest services as well (e.g. Nowak, 1994b; McPherson et al., 1997; Nowak, 2002a; USDA Forest Service, 2004).

We caution, though, that tree density is also a strong determinant of C sequestration and storage potentials of urban forest landscapes. All planted trees start at the same small size, and it takes considerable time for a tree to become large. In the first few decades of growth, trees growing closer together will sequester more carbon per unit area because more of the area is dominated sooner by tree leaves capturing sunlight. If carbon sequestration is the goal, then the earlier the planted site becomes fully occupied with tree-based photosynthetic capacity (i.e., tree leaves), the better. This occurs much earlier with close spacings (e.g., 3 m) than wide spacings (e.g., the 6-10 m typical of street-side plantings).

It is often not practical for urban forest managers to plant large-stature trees in every available planting spot. Concerns associated with safety (e.g. visibility) and future maintenance requirements (e.g. pruning to accommodate various infrastructures) are considered within any successful urban forest management program. Structural management also depends on the objectives identified by forest managers themselves (Nowak, 1994a), or by property covenants within a given community or area slated for development such as BIP. Diversification of urban forest structure is another component of successful urban forest management, as it essentially serves as an "urban forest structure insurance policy" (Richards, 1993; Dwyer et al., 2000, Nowak and Miller, 2008).

C storage and sequestration potentials of an urban forest are not simply dependant on species or tree size. A wide range of environmental factors – both biotic and abiotic – influence biomass accumulation and therefore C sequestration and storage potential of an individual tree (McDonnell and Pickett, 1990; Dwyer et al., 2000; Sieghardt et al., 2005; Tello et al., 2005). Potential disturbances (e.g. pest outbreaks, storm damage), tree condition (e.g. "excellent" vs. "poor"), and impacts of future climate change (e.g. increased precipitation, increased temperatures) were not included within the models used here. As our goal was to provide a rough estimate of C potentials, we felt it reasonable to take a simple approach to a first approximation.

4.3.3 Challenges with relying on rural forest derived biomass equations for estimating urban tree biomass

Trees grow in response to their environment. As a result, trees that grow in open spaces and at low population densities, as is often the case in urban areas, will have a different physio-morphological structure than those grown within a silvicultural or rural forest setting. Open-grown trees grown at lower densities in urban settings tend to have more AG biomass per tree than trees grown within higher-density rural forest settings (Jo and McPherson, 1995). Urban and rural trees, being subject to highly contrasting growing conditions, therefore accumulate biomass differently. However, the lack of previous research in the field of urban tree biomass accumulation has resulted in a paucity of allometric biomass equations designed specifically for calculating urban tree biomass. Much of the existing research dedicated to quantifying biomass and C sequestration and storage potentials of urban forests therefore have relied on biomass equations derived from data obtained from rural forests (e.g. Rowntree and Nowak, 1991; Nowak, 1993; McPherson, 1998; McPherson and Simpson, 1999).

A common practice for estimating urban-forest biomass when using rural-forest biomass equations is to reduce the overall estimate by a factor of 0.8, a factor whose origin is questionable (Jo and McPherson, 1995; McPherson, 1998; Nowak and Crane, 2000; Nowak, 1994b; McHale et al., 2009). We believe applying a reduction factor while calculating AG biomass for urban trees is both unnecessary and unwarranted, and is a practice that should be omitted when relying on rural forest derived biomass equations, because "… urban trees tend to grow faster than rural trees, they sequester more CO_2 on a per tree basis" (McPherson, 1998, p. 219). As such, this model does not apply a biomass reduction factor to generated estimates (McHale et al., 2009).

4.3.4 Other urban forest benefits

Aside from the C sequestration and storage potentials themselves, urban trees can actually help mitigate atmospheric CO_2 levels indirectly through reducing levels of energy consumption of buildings (Heisler, 1986; McPherson, 1993: Akbari et al., 1997; McPherson and Simpson, 1999; Gill et al., 2007). This aspect of CO_2 mitigation can be enhanced through strategic tree selection and subsequent placement; such a strategy can also be incorporated as a component of urban forest management plans.

Other than CO_2-related benefits, establishment and success of urban trees (both as individuals and as a component of the larger urban forest) provide numerous benefits to urban areas (Nowak, 2006). Many research efforts have been dedicated to investigating, quantifying, and otherwise exposing these benefits in association with developing sound urban forest structure (e.g. Konijnendijk et al., 2005; Nowak and Dwyer, 2007; Carreiro et al., 2008). Examples of these benefits include reduced stress and anxiety (Ulrich, 1984), increased property values (Anderson and Cordell, 1998), and improved air and water quality within urban areas (Nowak, 2006).

4.4 Conclusion

The results of this research demonstrate a substantial increase C sequestration and storage capacities that could be realized by intensified tree planting efforts within a light-industrial and commercial landscape such as BIP. We believe our case study parallels the same kind of potential for C sequestration and storage within these landscape types within North America, and cumulatively, certainly represent ample yet overlooked opportunities for C sequestration and storage in urban areas. We advocate that intensified tree planting within urbanized areas is an opportunity – not only for enhancing C sequestration and storage potentials thereof – but also for optimizing other benefits provided by urban trees to these communities.

The condition of the current (i.e. 2010) BIP urban forest is sparse with a meager population density of 55 trees/ha storing 11 tC/ha. The gap in C sequestration and storage between *Scenario 1* (i.e. population maintenance) and *Scenario 2* (i.e. 50% planting of all vacancies) and *Scenario 3* (i.e. 100% planting of all vacancies) become increasingly apparent over time. If the current population is maintained, the C storage potential by 2050 is estimated to be 39 tC/ha, paling in comparison to the 171 tC/ha and 303 tC/ha estimated in *Scenario 2* and *Scenario 3*, respectively.

While much of the literature advocates the benefits provided by large stature trees to urban communities, all trees are small trees at the beginning of their life. It is not practical or from an urban forest management standpoint to plant large stature trees in every available planting spot. Immediately increasing the density of urban trees, even those of small stature, will quickly yield substantial increases in C sequestration and storage within any urban forest landscape, while also providing a myriad of other benefits to the community as they develop into mature trees. We therefore recommend increasing tree density via intensified tree planting efforts as an ideal strategy for optimizing C sequestration and storage potentials of urbanized landscapes.

With respect to future development of BIP land that is currently forested, we recommend the conservation of forest patches wherever possible. These areas represent areas of high tree density, and their conservation represents CO_2 mitigation opportunities via emission in two ways: 1) existing C stored as biomass is not released via deforestation; and 2) CO_2 emissions generated via fossil fuel consumption of machinery used to remove trees from a landscape are not created (i.e. emission avoidance). Additionally, as a value-added approach for managing atmospheric CO_2 via urban forest development, we recommend that tree selection and placement be considered and implemented to minimize energy consumption of buildings within BIP. Doing so will further contribute to atmospheric CO_2 mitigation efforts within the BIP landscape.

4.5 References

Ajtay, G.L., Ketner, P., & Duvigneaud, P. (1977). Terrestrial primary production and phytomass. In B. Bolin, E.T. Degens, S. Kempe, & P. Ketner (Eds.), *The global carbon cycle* (pp. 129-236). New York, NY: John Wiley & Sons.

Akbari, H., Kurn, D.M., Bretz, S.E., & Hanford, J.W. (1997). Peak power and cooling energy savings of shade trees. *Energy and Buildings, 25*, 139-148.

Alvey, A.A. (2006). Promoting and preserving biodiversity in the urban forest. *Urban Forestry & Urban Greening, 5*(4), 195-201.

Anderson, L.M., & Cordell, H.K. (1988). Influence of trees on residential property values in Athens, Georgia (USA): A survey based on actual sales prices. *Landscape and Urban Planning, 15,* 153-164.

Birdsey, R.A. (1992). Carbon storage and accumulation in United Sates forest ecosystems (General Technical Report WO-59). Retrieved from United States Forest Service: http://www.treesearch.fs.fed.us/pubs/15215

Birdsey, R.A. (2006). Carbon accounting rules and guidelines for the United States forest sector. *Journal of Environmental Quality, 35*, 1518-1524.

Cadenasso, M.L., Pickett, S.T.A., & Schwarz, K. (2007). Spatial heterogeneity in urban ecosystems: Reconceptualizing land cover and a framework for classification. *Frontiers in Ecology and the Environment, 5*(2), 80-88.

Carreiro, M.M., Song, Y.-C., & Wu, J. (Eds.). (2008). *Ecology, planning, and management of urban forests – International perspectives.* New York, NY: Springer Science.

Duh, J.-D., Shandas, V., Chang, H., & George, L.A. (2008). Rates of urbanization and the resiliency of air and water quality. *Science of the Total Environment, 400*, 238-256

Dwyer, J.F., McPherson, E.G., Schroeder, H.W., & Rowntree, R.A. (1992). Assessing the benefits and costs of the urban forest. *Journal of Arboriculture, 15*, 247-252.

Dwyer, M.C., & Miller, R.W. (1999). Using GIS to assess urban tree canopy benefits and surrounding greenspace distributions. *Journal of Arboriculture, 25*(2), 102-107.

Dwyer, J.F., Nowak, D.J., Noble, M.H., & Sisinni, S.M. (2000). Connecting people with ecosystems in the 21st century: An assessment of our nation's urban forests (General Technical Report PNW-GTR-490). Retrieved from United States Forest Service: http://www.treesearch.fs.fed.us/pubs/29448

Ewing, R.H. (2008). Characteristics, causes, and effects of sprawl: A literature review. In Marzluff, J.M., Shulenberger, E., Endlicher, W., Alberti, M., Bradley,G., Ryan, C., … & Simon, U., *Urban ecology: An international perspective on the interaction*

Frumkin, H. (2002). Urban sprawl and public health. *Public Health Reports, 117*(3), 201-217.

Gill, S.E., Handley, J.F., Ennos, A.R., & Pauleit, S. (2007). Adapting cities for climate change: The role of the green infrastructure. *Built Environment, 33*(1), 115-133.

Grimm, N.B., Faeth, S.H., Golubiewski, N.E., Redman, C.L., Wu, J., Bai, X., & Briggs, J.M. (2008). Global climate change and the ecology of cities. *Science, 319*, 756-560.

Halifax Regional Municipality (HRM). (2010). *Burnside business park*. Retrieved February 22, 2011 from http://www.halifax.ca/business_parks/parks/burnside.html

Heisler, G.M. (1986). Energy savings with trees. *Journal of Arboriculture, 12*(5), 113-125.

Houghton, R.A., Schlesinger, W.H., Brown, S., & Richards, J.F. (1985). Carbon dioxide exchange between the atmosphere and terrestrial ecosystems. In J. R. Trabalka (Ed.), *Atmospheric carbon dioxide and the global carbon cycle*, (pp. 114-140). Washington, D.C.: United States Department of Energy.

Husch, B., Miller, C., & Beers, T.W. (1982). *Forest mensuration*. New York, NY: John Wiley & Sons.

Intergovernmental Panel on Climate Change (IPCC). (2005). *IPCC special report on carbon dioxide capture and storage.* London, UK: Cambridge University Press.

Intergovernmental Panel on Climate Change (IPCC). (2007). Climate change 2007: Impacts, adaptation, and vulnerability. In M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, & C.E. Hanson (Eds.), *Fourth assessment report of the Intergovernmental Panel on Climate Change, 2007*. Cambridge, UK: Cambridge University Press.

Jackson, L.J., Trebitz, A.S., & Kottingham, K.L. (2000). An introduction to the practice of ecological modelling. *BioScience, 50*(8), 694-706.

Jenkins, J.C., Chojnacky, D.C., Heath, L.S., & Birdsey, R.A. (2003). National-scale biomass estimators for United States tree species. *Forest Science, 49*(1), 12–35.

Jenkins, J.C., Chojnacky, D.C., Heath, L.S., Birdsey, R.A., & Richard, A. (2004). Comprehensive database of diameter-based biomass regressions for North American tree species (General Technical Report NE-319). Retrieved from United States Forest Service: http://www.uvm.edu/~jcjenkin/jenkins%20et%20al.%202004.pdf

Jo, H.K., & McPherson, E.G. (1995). Carbon storage and flux in urban residential greenspace. *Journal of Environmental Management, 45*, 109-133.

Johnson, M.P. (2000). Environmental impacts of urban sprawl: A survey of the literature and proposed research agenda. *Environment and Planning, 33*, 717-735.

Kahn, M.E. (2006). *Green cities: Urban growth and the environment.* Washington, DC: Brookings Institution Press.

Keeling, C.D. (1973). Industrial production of carbon dioxide from fossil fuels and limestone. *Tellus, XXV*(2),174-198.

Konijnendijk, C.C., Nilsson, K., Randrup, T.B. & Schipperijn, J. (Eds). (2005). *Urban forests and trees*. New York, NY: Springer Science.

LaPaix, R., & Freedman, B. (2010). Vegetation structure and composition within urban parks of Halifax Regional Municipality, Nova Scotia, Canada. *Landscape and Urban Planning, 98,* 124-135.

McDonnell, M.J., & Pickett, S.T.A. (1990). The study of ecosystem structure and function along urban-rural gradients: An unexploited opportunity for ecology. *Ecology, 71,* 1231–1237.

McHale, M.R, Burke, I.C., Lefsky, M.A., Peper, P.J., & McPherson, E.G. (2009). Urban forest biomass estimates: Is it important to use allometric relationships developed specifically for urban trees? *Urban Ecosystems, 12*, 95-113.

McKinney, M.L. (2002). Urbanization, biodiversity, and conservation. *BioScience, 52*(10), 883-890.

McPherson, E.G. (1993). Evaluating the cost effectiveness of shade trees for demand-side management. *The Electricity Journal, 6*(9), 57-65.

McPherson, E.G. (1998). Atmospheric carbon dioxide reduction by Sacramento's urban forest. *Journal of Arboriculture, 24*(4), 215-223.

McPherson, E.G., Nowak, D.J., Heisler, G., Grimmond, S., Souch, C., Grant, R., & Rowntree, R.A. (1997). Quantifying urban forest structure, function, and value: The Chicago Urban Forest Climate Project. *Urban Ecosystems, 1*, 49–61.

McPherson, E.G., Nowak, D.J., & Rowntree, R.A. (Eds.). (1994). Chicago's urban forest ecosystem: Results of the Chicago urban forest climate project. (General Technical Report NE-186). Retrieved from United States Forest Service: http://www.treesearch.fs.fed.us/pubs/4285

McPherson, E.G., & Simpson, J.R. (1999). Carbon dioxide reduction through urban forestry: Guidelines for professional and volunteer tree planters. (General Technical Report PSW-GTR-171). Retrieved from United States Department of Agriculture, Forest Service: http://www.treesearch.fs.fed.us/pubs/6779

Myeong, S., Nowak, D.J., & Duggin, M.J. (2006). A temporal analysis of urban forest carbon storage using remote sensing. *Remote Sensing of Environment, 101*, 277-282.

Nowak, D.J. (1993). Atmospheric carbon reduction by urban trees. *Journal of Environmental Management, 37*, 207-217.

Nowak, D.J. (1994a). Understanding the structure of urban forests. *Journal of Forestry, 92,* 42–46.

Nowak, D.J. (1994b). Atmospheric carbon dioxide reduction by Chicago's urban forest. In E.G. McPherson, D.J. Nowak, & R.A. Rowntree (Eds.), *Chicago's urban forest ecosystem: Results of the Chicago urban forest climate project* (pp. 83-94) (General Technical Report NE-186). Retrieved from United States Forest Service: http://www.treesearch.fs.fed.us/pubs/4285

Nowak, D.J. (2006). Institutionalizing urban forestry as a "biotechnology" to improve environmental quality. *Urban Forestry & Urban Greening, 5*, 93-100.

Nowak, D.J., & Crane, D.E. (2000). The urban forest effects (UFORE) model: Quantifying urban forest structure and functions. In M. Hansen, & T. Burk (Eds.), *Proceedings: Integrated Tools for Natural Resources Inventories in the 21st Century* (pp. 714-720). St. Paul, MN: United States Forest Service.

Nowak, D.J., & Crane, D.E. (2002). Carbon storage and sequestration by urban trees in the USA. *Environmental Pollution, 116*(3), 381-389.

Nowak, D.J., Crane, D.E., Stevens, J.C., & Ibarra, M. (2002). Brooklyn's urban forest. (General Technical Report NE-290). Retrieved from United States Department of Agriculture, Forest Service: http://www.fs.fed.us/ne/newtown_square/publications/technical_reports/pdfs/2002/gtrne290.pdf

Nowak, D.J., & Dwyer, J.F. (2007). Understanding the benefits and costs of urban forest ecosystems. In J.E. Kuser (Ed.), *Urban and community forestry in the northeast (2nd ed.)* (pp. 25-46). New York, NY: Springer Science.

Nowak, D.J., & Miller, R.W. (2008). Assessing urban forest structure: Introduction. *Arboriculture & Urban Forestry, 34*(6), 333.

Nowak, D.J., Rowntree, R.A., McPherson, E.G., Sisinni, S.M., Kerkmann, E.R., & Stevens, J.C. (1996). Measuring and analyzing urban tree cover. *Landscape and Urban Planning, 36*, 49-57.

Pataki, D.E., Alig, R.J., Fung, A.S., Golubiewski, N.E., Kennedy, C.A., McPherson, E.G., … & Lankao, P.R. (2006). Urban ecosystems and the North American carbon cycle. *Global Change Biology, 12*(11), 2092–2102.

Pauleit, S., & Duhme, F. (2000). GIS assessment of Munich's urban forest structure for urban planning. *Journal of Arboriculture, 26*(3), 133-141.

Pickett, S.T.A., & Cadenasso, M.L. (2007). Linking ecological and built components of urban mosaics: An open cycle of ecological design. *Journal of Ecology, 96*, 8-12.

Richards, N. (1993). Reasonable guidelines for street tree diversity. *Journal of Arboriculture, 19*(6), 344-350.

Rostami, M. (2011). *Tree species selection for the Halifax urban forest under a changing climate*. (Unpublished master's thesis). Dalhousie University, Canada.

Rowntree, R.A. (1986). Ecology of the urban forest: Introduction to part II. *Urban Ecology, 9*, 229-243

Rowntree, R.A., & Nowak, D.J. (1991). Quantifying the role of urban forests in removing atmospheric carbon dioxide. *Journal of Arboriculture, 17*(10), 269-275.

Sanders, R.A. (1984). Some determinants of urban forest structure. *Urban Ecology, 8*(1-2), 13-27.

Sieghardt, M., Mursch-Radlgruber, E., Paoletti, E., Couenberg, E., Dimitrakopoulus, A., Rego, F., … & Randrup, T.B. (2005). The abiotic urban environment - Impact of urban growing conditions on urban vegetation. In C.C. Konijnendijk, K. Nilsson, T.B. Randrup, & J. Schipperijn (Eds.), *Urban forests and trees* (pp. 281-323). New York, NY: Springer.

Sierra Club. (1998). *Sprawl: The dark side of the American dream*. Retrieved April 28, 2011 from http://www.sierraclub.org/sprawl/report98/

Squires, G.D. (Ed.). (2002). Urban sprawl and the uneven development of metropolitan America. In G.D. Squires (Ed.), *Urban sprawl: Causes, consequences and policy responses* (pp. 1-22). Washington, DC: The Urban Institute Press.

Starfield, A.M. (1997). A pragmatic approach to modeling for wildlife management. *The Journal of Wildlife Management, 61*(2), 261-270.

Tello, M.-L., Tomalak, M., Siwecki, R., Gáper, J., Motta, E., & Mateo-Sagasta, E. (2005). Biotic urban growing conditions – Threats, pests and diseases. In C.C. Konijnendijk, K. Nilsson, T.B. Randrup, & J. Schipperijn (Eds) *Trees*, (pp. 325-365). New York, NY: Springer.

Ter-Mikaelian, M.T., Korzukhin, M.D. 1997. Biomass equations for sixty-five North American tree species. *Forest Ecology and Management, 97*, 1-24.

Tisdale, H. (1942). The process of urbanization. *Social Forces, 20*(3), 311-316.

United Nations-Habitat (UN-Habitat). (2009). *Planning sustainable cities: Global report on human settlements 2009*. Sterling, VA: Earthscan.

United States Department of Agriculture, Forest Service (USDA Forest Service). (2004). The large tree argument: The case for large-stature trees vs. small-stature trees. Retrieved from http://www.fs.fed.us/psw/programs/uesd/uep/products/cufr_511_large_tree_argument.pdf

Ulrich, R.S. (1984). View through a window may influence recovery from surgery. *Science, 224*, 420-421.

Vanclay, J.K. (2003). Realizing opportunities in forest growth modeling. *Canadian Journal of Forest Research, 33,* 536–541

Yue, G. (2010). *Mapping traditional bird knowledge for urban bird conservation in Halifax, Nova Scotia, Canada* (Unpublished master's thesis). Dalhousie University, Canada.

Zipperer, W.C., Sisinni, S.M., Pouyat, R.V., & Foresman, T.W. (1997). Urban tree cover: An ecological perspective. *Urban Ecosystems, 1*, 229-246.

CHAPTER 5: POTENTIAL FOR URBAN FOREST DEVELOPMENT VIA CARBON CREDITS WITHIN BURNSIDE INDUSTRIAL PARK, DARTMOUTH, NOVA SCOTIA

5.1 Global Climate Change and Atmospheric Carbon Dioxide

Awareness of the relationship between levels of atmospheric greenhouse gasses (GHGs) and how they may be driving global climate change has become increasingly prevalent. It is now a widely accepted notion that anthropogenic activities are influencing concentrations of atmospheric GHGs, which are, in turn, altering the earth's climate. Carbon dioxide (CO_2) is a GHG of high notoriety because of the extent to which anthropogenic activities have influenced its presence within the atmosphere (IPCC, 2005; IPCC, 2007a; Sundquist et al., 2009). Since its inception in 1988, the Intergovernmental Panel on Climate Change (IPCC) has produced a comprehensive compilation of scientific research that has been used to inform a better understanding of the potential implications of climate change (e.g. IPCC, n.d.). Anticipated impacts include increased mean global temperatures, sea-level rise, decreased access to freshwater resources, extinction of climactically sensitive biota, and continued intensification of extreme weather events (IPCC, 2007b).

There are many environmental impacts associated with anthropogenic activities, the two primary contributing towards increased atmospheric CO_2 levels include combustion of fossil fuels, and land-use change via deforestation (Dixon et al., 1994; Sundquist et al., 2009). While these activities occur in essentially every community inhabited by people, the process of societal urbanization inherently contributes to atmospheric CO_2 levels via both of these modes. Furthermore, urban areas impose a number of self-generated environmental impacts, such as increased volume and pollutant loading of stormwater runoff, creation of urban heat islands, and amplified concentrations of heavy metals, including (but not limited to) mercury, lead, and zinc (Oke, 1995; Tsihrintzis and Hamid, 1997; Sieghardt et al., 2005). This is an issue of increasing concern because, currently, the world's population is predominately urban; a trend that is anticipated to continue into the future (UN-Habitat, 2009).

5.2 Enhancing Biological Carbon Sequestration and Storage through Traditional and Urban Forestry

In an effort to better understand how society might mitigate potential impacts of climate change, the IPCC compiled a special report that identifies and explores several options for effective CO_2 mitigation. Of these options, enhancing biological absorption capacities within forests and soils (IPCC, 2005) is particularly pertinent to this research. Trees sequester and, over the duration of their lives, store atmospheric CO_2 as biomass carbon (C). Traditionally, efforts towards enhancing biological sequestration and storage capacities for CO_2 mitigation have been focused within rural and hinterland forest settings. However, trees in urban area also possess both the potential and ability to sequester and store C as biomass. In this respect, much research has been dedicated to exploring and quantifying the potential role of urban forest development as an additional and overlooked opportunity for enhancing biological C sequestration within urban landscapes (e.g. Rowntree and Nowak, 1991; Nowak, 1993; Nowak, 1994; Jo and McPherson, 1995; McPherson, 1998; Nowak and Crane, 2002; Brack, 2002; Myeong et al., 2006).

There are many additional and regionally significant benefits associated with maintaining and improving upon existing urban forest structure. Urban trees, as components of urban ecosystems, provide specific benefits to communities precisely because of their location. Aside from biological C sequestration and storage, urban trees can mitigate atmospheric CO_2 via emissions avoidance. When strategically placed around buildings, they help reduce energy consumption (and therefore CO_2 emissions) by providing shade and wind block (Heisler, 1986; McPherson, 1993; Akbari et al., 1997, 2001; Simpson 2002; Gill et al., 2007).

Examples of other benefits include improved air and water quality, increased biodiversity and habitat for a variety of flora and fauna, increased real estate values, as well as enhanced opportunities for recreation, leisure, and relaxation for urban residents (Dwyer et al., 1992; McPherson et al., 1994; Dwyer et al., 2000).

5.3 Potential for Urban Forest Carbon Offsets as a Tool for Atmospheric Carbon Dioxide Mitigation

5.3.1 Carbon offset markets

The concept of emissions offset trading arose from increased concern about atmospheric CO_2 levels. Offsets generated by enhancing biological CO_2 sequestration and storage of forest biomass are but one piece of the climate-change mitigation puzzle (IPCC, 2007a; McCarl and Sands, 2007; Ristea and Maness, 2009; Sovacool, 2011). McHale et al. (2007) suggested that C offset markets provide an economically viable platform to mitigate atmospheric CO_2. Although often used synonymously, the term C offset and C credit differ. *C offset* refers to the measurement of the reduction of GHGs that are declared by, but not necessarily achieved by, an offset project. Conversely, a *C credit* is a C offset referred to in an economic context, and is typically expressed in \$/tonne of CO_2 equivalents (tCO_2e) (Environment Canada, 2008; Ristea and Maness, 2009). A single C credit represents one tonne of stored C. Essentially, C credits are the marketable version of C offsets achieved by (for the purpose of this manuscript) C stored as tree biomass.

C offsets are traded within one of two markets: 1) mandatory (i.e. compliance, regulatory), and 2) voluntary (USGAO, 2008; Ristea and Maness, 2009). Mandatory markets operate using a cap-and-trade mechanism, the Kyoto Protocol being the most prevalent example (Kirschbaum and Cowie, 2004; McHale et al., 2007; Ristea and Maness, 2009). The Kyoto Protocol was also the world's first internationally recognized offset trading market which, for all participating Annex 1 Parties, establishes legally binding offset targets (Kirschbaum and Cowie, 2004). Similar to mandatory offset markets, voluntary markets quantify C offsets generated by offset projects. The primary difference between the two is the lack of an overarching, regulatory body for verifying the quality of offsets traded within voluntary markets (Ristea and Maness, 2009; Bayon et al., 2009). As a result, the overall quality of offsets that exist within voluntary markets is inherently volatile and highly variable (Bayon et al., 2009).

5.3.2 The case of Burnside Industrial Park: Exploring potential viability of urban-forest-generated-carbon offsets as marketable carbon credits

To further explore the challenges and opportunities associated with generating C offsets within an urban forest context, we conducted a case study within Burnside Industrial Park (BIP). We quantified C sequestration and storage potentials associated with three urban-forest development scenarios. BIP is located in Dartmouth, Nova Scotia. It is a light-industrial and commercial park that is both well developed and poised for expansion onto lands currently forested (Figure 5-1). Prior to development, the BIP was entirely forested. Deforestation has occurred to accommodate urban infrastructures, such as highways, buildings, and light-industrial activities. Developed portions of the BIP exhibit low population densities of urban trees (55 trees/ha), and thus represent an opportunity for increased tree planting densities and therefore C sequestration and storage. This paper will explore the potential to which increased C sequestration and storage via urban forest development within the BIP could be achieved with financial assistance from current C credit markets.

Figure 5-1: Aerial photograph of the study site, Burnside Industrial Park.

5.4 Considerations for Estimating Development Potential in Burnside Industrial Park Urban Forest via Carbon Offset Markets

5.4.1 Estimated C sequestration and storage potential within the Burnside Industrial Park urban forest

Three scenarios of urban forest development were constructed by applying a mixed-methods approach that employed a geographic information system (GIS) in conjunction with a customized forest-development and C model. First, existing urban forest structure (including an estimate of the total number of potential planting spots) was estimated. This approach entailed the construction of a land cover map using aerial photography and GIS, in addition to the collection of field data. These data then informed the subsequent creation of a customized model of future urban forest development and C sequestration and storage within BIP.

We assumed a desired tree density of 1000 trees/ha (an increase from a current density estimate of 55 trees/ha) within already developed portions of the park. Total plantable area amounted to 87 ha. C storage estimates were generated for each urban-forest development scenario (See Tables 5-1, 5-2, and 5-3). *Appendix I* contains a complete compilation of the data used to inform the creation of the land cover classification map and operational assumptions and parameters for the BIP urban forest C model.

Table 5-1: Summary of urban forest development scenarios (total # trees)

Scenario	**Description**	**Addition to 2010 population**
1	Maintenance of 2010 population (4, 785)	4,785 + 0
2	Maintenance of population + 50% of all vacancies	4,785 + 44,108
3	Maintenance of population + 100% of all vacancies	4,785 + 82,215

Table 5-2: Summary of tree densities per scenario (trees/ha)

Scenario	Year				
	2010	**2020**	**2030**	**2040**	**2050**
Scenario 1	55	55	55	55	55
Scenario 2	55	528	528	528	528
Scenario 3	55	1,000	1,000	1,000	1,000

Table 5-3: Summary of carbon storage per hectare per scenario (tC/ha)

Scenario	Year				
	2010	**2020**	**2030**	**2040**	**2050**
Scenario 1	11	19	26	33	39
Scenario 2	11	19	38	86	171
Scenario 3	11	19	49	139	303

Upon quantifying the potential for C sequestration and storage of the BIP urban forest, the following research question was then posed to guide preparation of the remainder of this paper:

- To what extent might development of the BIP urban forest be financed through local businesses purchasing C credits via C offset markets?

There are numerous challenges and opportunities associated with mobilizing such a proposition. The remainder of the paper explores and describes the factors we perceive as being associated with pursuing such an opportunity, beginning with an assessment of the suitability of C offsets generated by urban trees and concluding with recommendations derived from this review.

5.4.2 What constitutes a high-quality carbon offset?

Since the inception of the Kyoto Protocol, the prevalence of C offset markets has increased and grown in popularity as a component of atmospheric CO_2 mitigation efforts. Examples of high-calibre protocols include the European Union Emissions Trading System, Kyoto Protocol's Clean Development Mechanism, British Columbia's Pacific Carbon Trust, and the Western Climate Initiative (EUETS, 2010; UNFCCC, 2011; PCT, 2012; WCI, 2010). Although yielding a high-quality offset, achieving these high standards is demanding of human, technological, and monetary resources.

Regardless of the market under which offsets are traded, quality assessments of C offsets typically rely on the following characteristics (Birdsey, 2006; DSF, 2008; Environment Canada, 2008; USGAO, 2008; Ristea and Maness, 2009; EUETS, 2010; WCI, 2010; Poudyal et al., 2011b; Sovacool, 2011; UNFCCC, 2011; PCT, 2012):

- Additionality and project baseline
- Quantification, monitoring, and verification
- Ownership and double counting
- Leakage
- Permanence
- Regional co-benefits

Similar to the style of review conducted by Poudyal et al. (2011b), this list was assembled by consulting C offset literature in addition to government and private-sector offset protocols that function within both mandatory and voluntary markets.

5.4.2.1 Additionality and project baseline

High-quality C offset projects must demonstrate additionality; that is, the C offset project scenario must demonstrate enhanced C sequestration and storage as compared to the non-project scenario (i.e. project baseline, business-as-usual) (USGAO, 2008; UNFCCC, 2011). The additionality of offsets generated by a given project is determined once a project baseline has been established. Establishing a clear definition of the project's baseline is important because, without doing so, it is impossible to assess the significance of contribution (i.e. additionality) of the proposed offset project (LeBlanc, 1999). According to the United States Government Accountability Office (USGAO) (2008), many C offset project stakeholders believe that "Additionality is fundamental to the credibility of offsets because only offsets that are additional to business-as-usual activities result in new environmental benefits" (p. 25).

The proposed scenarios of urban forest development within BIP establish a project baseline and demonstrate additionality. The project baseline is demonstrated on two fronts (summarized by Table 5-4): 1) by establishing 2010 as the project's base year, and 2) by quantifying both land cover composition and C storage of the 2010 urban forest. *Scenario 1* represents the baseline scenario, while *Scenario 2* and *Scenario 3* represent two alternatives for urban forest development. The C model generates estimated C sequestration and storage potentials for each scenario over the span of forty years (beginning in 2010, ending in 2050), and thereby provide estimates for the baseline scenario (*Scenario 1*) and additionality associated with the two urban forest development scenarios (*Scenario 2 and Scenario 3*).

Table 5-4: Proposed urban forest development project baseline

Baseline criteria	Unit	Value
Base year	year	2010
Area available for current and future tree growth	hectares	87
Urban forest population	# of trees	4,785
Carbon storage within current population	tonnes C	986

5.4.2.2 Quantification, monitoring, and verification

Methods selected to quantify and monitor C offsets produced by a given project are key factors contributing to C offset reputability, particularly when it comes to verification of the proposed offsets. Quantifying biomass generated by tree growth is not a novel or new practice, and, although there is room for improvement, urban foresters are able to generate urban forest C estimates. Quality C offsets are verified by a third-party organization which is hired to scrutinize, examine, and otherwise validate the offsets claimed by the proposed project (PCT, 2012). Appropriate selection of quantification and monitoring methods is important, as they must adequately reflect in sufficient detail the factors influencing C sequestration and storage. Although there are many challenges associated with quantifying real-world ecosystem dynamics (Starfield, 1997; Jackson et al., 2000; Birdsey, 2006), anyone wanting to develop quality C offsets must provide detailed and transparent records of quantification and monitoring processes so that the proposed offsets can be objectively reviewed and subsequently verified (WCI, 2010).

As alluded to by Poudyal et al. (2011b), quantification and monitoring procedures in the urban forest setting should be developed closely and in accordance with the selected C offset protocol standards. Verification of these methods is then contracted to a third-party verifier. Quantification, monitoring, and verification of C offsets can be particularly intensive on human, technological, and monetary resources and can therefore become a barrier for achieving desirable, high-quality C offsets (Poudyal et al., 2011b; Sedjo and Macauley, 2011). Transaction costs are of special concern, especially for small offset projects. This trepidation was reiterated by Sovacool (2011), who enumerated barriers associated with adhering to the Kyoto Protocol's Clean Development Mechanism offset criteria. Such barriers include the time it takes to complete a review and perform an audit, and the costs associated with lengthy evaluation processes.

Because of the small-scaled nature of the BIP urban forest, monitoring and subsequent verification of C offsets could be a relatively simple undertaking, especially when compared to large-scale projects occurring within rural and hinterland settings (Hoover, 2011). Consider the following example: The C model that generated estimates of C sequestration and storage created for fulfilling the objectives of this research does so on a species-specific and per-tree basis. Upon planting, trees could be monitored individually, and could be assessed on features such as overall condition (e.g. "good", "fair", or "poor") and dbh. The specifications of the offset protocol being followed will dictate what urban forest features are measurable, as well as other details, such as frequency of measurements and site condition. Third-party offset verifiers could then analyze data generated from the C model and effectively compare the anticipated C offset results with results generated from data obtained through monitoring. They could also conduct their own site visits to verify the offsets associated with project implementation as being legitimate. Data requirements of offset verifiers depend on what is specified by the protocol being followed.

Within voluntary C offset markets, there is absence of an overarching protocol for proponents to follow while establishing the credibility of C offsets generated by their proposed projects (Ristea and Maness, 2009). As such, there are both advantages and disadvantages associated with the nature of today's voluntary C offset market. The USGAO (2008) outlined several potential issues identified by various stakeholders participating within C offset markets: "Increased federal oversight of the U.S. voluntary market could enhance the market's transparency and improve consumer protection, but may also reduce flexibility, increase administrative costs, and stifle innovation, according to certain stakeholders. However, some stakeholders said that concerns about the credibility of offsets could compromise the environmental integrity of a compliance system" (p. ii).

5.4.2.3 Ownership and double counting

It is important to clearly identify ownership of offsets generated by the project of interest. However, offset ownership is yet another challenge associated with the climate of today's offset markets. There are multiple C registries across North America, and because of the nature of voluntary offset markets, not all offsets are required to become registered (USGAO, 2008; AOR, 2011). Without a clear definition and database of offset ownership, it is possible for double counting to occur. If an offset is sold more than once, it is said to be double counted, and is therefore essentially void of worth (DSF, 2008). Within of BIP, offset ownership can become extraordinarily convoluted particularly associated with land that is privately owned. For example, these complications may arise because an individual lot may be owned by one party, developed by a second party, managed by a third party, and leased by a fourth. Because of the multiple parties often connected to a single property, important to clearly distinguish the difference between tree biomass and land ownership from that of offset ownership.

Double counting can occur in other ways as well, such as within internal workings of quantification mechanisms (e.g. establishment of project baseline; assumptions, parameters, and other factors included within a C model) and offsetting policies (e.g. should offsets generated by voluntary markets be counted towards provincial and/or national offset targets) (DSF, 2008).

A potential solution for matters pertaining to offset ownership and double counting could be the creation of a single offset registry that operates on a national, continental, or even international scale. However, this option would inevitably come with great needs for investment of time, expertise, and expense on the part of multiple parties involving both in mandatory and voluntary markets. As there are mixed property owners, developers, managers, tenants, and businesses owners within the area identified for urban forest development within BIP, defining unconfounded offset ownership will be a critical component of establishing reputable offsets (Tree Canada, 2009).

5.4.2.4 Leakage

Offset leakage occurs when offset projects contribute, either within or outside of the project's boundaries, to increased GHG emissions (UNFCCC, 2011). Traditional forests within rural and hinterland settings present arguably greater opportunities for offset leakage than urban forests internally (within project ownership) and externally (outside of project ownership), on local, national, and international platforms (Poudyal et al., 2011b; Sedjo and Macauley, 2011). Such opportunities for rural forest-based offset leakage typically occur through the harvesting of trees for various forest products, or deforestation via land-use change to accommodate, for example, urbanization and agriculture (Poudyal et al., 2011b; Sedjo and Macauley, 2011).

There are other opportunities for leakage to occur within an urban forest context. For example, Nowak et al. (2002b) highlighted the contribution of maintenance practices on the carbon dynamics of an urban forest. Although a variety of tree health-care practices (e.g. pruning, watering, debris removal, nutrient inputs) are vital for ensuring the overall health and success of a given tree, they suggested that unless conscious efforts are made to select C-free or low-C methods of maintenance (e.g. selecting a hand saw instead of a chain saw; rake instead of leaf blowers), there will be a net loss of C over the lifespan of a given tree (Nowak et al., 2002b). Conversely, Poudyal et al. (2011b) indicate a number of ways that urban forests may actually be less susceptible to leakage than rural offset projects, most notably because of reduced deforestation pressures (Poudyal et al., 2011b). They argue that trees within urban areas are less likely to be removed (i.e. harvested) as they are typically not grown for production purposes. This point is also reiterated by Tree Canada (2009), which suggested that urban trees are less subject to C losses associated with deforestation to accommodate urban development because the majority of tree removal associated with land-use change occurred during initial phases of development.

5.4.2.5 Permanence

Trees are organisms and thus have a finite lifespan. As is the case for any biomass-derived C offset, the issue of offset permanence is a major concern. Many C offset protocols indicate a timeframe within which C stores must be maintained in order to be identified as a "permanent" C store (e.g. 100-year minimum as specified by the United Nations Framework Convention on Climate Change), although timeframes for what qualifies offsets as permanent vary among protocols (Tree Canada, 2009; WCI, 2010).

Addressing the issue of offset permanence is complicated and highly contested (Herzog et al., 2003). A wide spectrum of factors influence the longevity (and therefore permanence) of tree-based offset projects, ranging from tree growth rates (influenced by environmental conditions, such as soil type, local climate), forest structure (such as species and age composition), and land ownership on which offset projects are established (which are subject to different types of natural and anthropogenic disturbances) (Yemshanov et al., 2007; DSF, 2008; Tree Canada, 2009; Yemshanov et al., 2012). Tree Canada's offset protocol identifies two primary aspects pertaining to offset permanence: a) ensuring land accommodating trees will not be deforested; and b) emission reversal prevention, the latter also being associated with leakage (Tree Canada, 2009). Essentially, the longer that biomass accumulation and storage can be maintained, the longer CO_2 is removed from atmospheric pools, which, in the case of providing marketable C offsets, is a desirable attribute.

Similar to circumstances associated with leakage, permanence of urban forest C-stores may arguably surpass those found within rural and hinterland settings. Within the context of BIP, the land of interest for the purpose of urban forest development has already experienced deforestation to accommodate urban infrastructures. In addition, urban trees are typically not harvested for their timber or other forest products (Tree Canada, 2009; Poudyal et al., 2011b). Therefore, the likelihood for tree removal within developed portions of the park is low. Poudyal et al. (2011b) suggested that urban forests may provide an advantage in respect of permanence of C offsets generated by tree growth. Because of co-benefits provided by urban trees, they are highly desirable to maintain and keep growing for long periods. Approximately 44% of the proposed 87ha area available for urban forest development within BIP is property currently owned and therefore maintained by the Halifax Regional Municipality (HRM). These trees are included in maintenance schemes which are working toward achieving HRM urban forest structural objectives as identified in the city's Urban Forest Master Plan (UFMP). C sequestration and storage objectives aside, there are many other reasons for preserving, maintaining, and encouraging growth and longevity of urban trees, and are discussed below.

5.4.2.6 Regional co-benefits

CO_2 is a gas that readily diffuses into the atmosphere, so the location of the trees grown to offset CO_2 emissions is of little significance to the global carbon budget. However, urban forests provide a myriad of other benefits that are only provided specifically because of tree location. As such, urban trees provide benefits to communities that rural or hinterland forest simply cannot.

Environmental benefits associated with urban forests include provision of habitat for fauna and other flora (McKinney, 2002; Yue, 2010), improved biogeochemical cycles that positively affect air and water quality (Dwyer et al., 1992; Nowak, 1994; Brack, 2002; Yang et al., 2005), and mitigation of urban heat islands (Dwyer et al., 2000). Examples of social benefits provided by urban forests include increased opportunities for recreation, leisure, and relaxation for urban residents (Dwyer et al., 1992; Peckham, 2010), and improved emotional and psychological health and well-being because, according to Ulrich (1984; 1986), the presence of urban vegetation reduces levels of stress and anxiety. Finally, there are many economic benefits associated with urban forests. Incorporating trees within urban landscapes reduces heating and cooling demands of the buildings they surround (Heisler, 1986; Akbari et al., 1997). This thereby reduces costs and CO_2 produced via reduced energy consumption. Other economic benefits include increased value of real estate (Anderson and Cordell, 1988), prolonged lifespan of urban infrastructure (such as asphalt) (McPherson and Muchnick, 2005) and stormwater drains (Maco and McPherson, 1993), and improved consumer-merchant relationships in commercial districts (Wolf, 2003). The aforementioned, among many other benefits, provide additional incentive for those participating in an urban forest C offset project to maintain and improve urban forest structure (which thereby have positive influences on other offset characteristics, such as permanence and leakage).

One unique, regional co-benefit associated with enhancing urban forest structure within BIP is the opportunity it presents to put concepts relating to industrial ecology into practice. In its essence, industrial ecology strives to parallel industrial, commercial, and/or human-made landscapes, systems, and communities with components, processes, and cycles within otherwise natural ecosystems (Côté and Smolenaars, 1997; Ehrenfeld and Gertler, 1997; Erkman, 1997; Wright et al., 2009). As such, improvement of urban forest structure within industrial park settings would help emulate natural energy flows that industrial ecosystems attempt to facilitate. Trees, as components of industrial ecosystems, will aid in further refinement and closure of material- and energy-use loops by sequestering and storing CO_2, a waste product generated within BIP. CO_2 is generated by numerous light-industrial and commercial activities within the boundaries of BIP. Such activities include tree removal (i.e. deforestation) to accommodate new urban development, energy consumption of buildings, and the transportation of people and goods. Implementation of an intensified urban forest development program will mitigate, at least in part, CO_2 generated by these local processes. In addition, urban forest development within any industrial park setting will help extend industrial ecological interactions by promoting natural functions and services within the park such as the improved storm water management, and localized climate regulation previously discussed.

5.5. An Additional Consideration: Estimated Cost Associated with Various Tree Planting Options within Burnside Industrial Park

Upon assessing multiple criteria of reputable C offsets, we propose that trees grown within an urban setting could indeed become a source of high-calibre C offsets, a sentiment echoed by Poudyal et al. (2011b). Unfortunately, a positive assessment of these potential offsets based on high-quality offset criteria is not enough to mobilize intensified urban forest development within BIP. One obvious and substantial cost associated with pursuing a C offset program as a means for urban forest development is associated with options available for potential tree planting and maintenance.

There are several options along the price spectrum of tree stock selection for forest managers. Options available at each end of the cost spectrum include seedlings, with an estimated installation price of $0.50 per tree, and caliper trees (root-collar diameter of 60mm), with an estimated installation price of $500/tree (J. Simmons, HRM Urban Forester, personal communication, March 2012). Based on these per-tree price estimates, we constructed the following cost scenarios associated with tree planting, based on urban forest development *Scenario 3* (100% planting of all vacancies within developed portions of BIP). *Scenario 3* was selected for this cost estimate because it simulates the highest density of urban tree growth (totaling 1000 trees/ha), and therefore yields the greatest number of potential C offsets.

Of 87 ha of area available for urban tree growth within developed portions of BIP, and assuming a desired density of 1000 trees/ha, there are an estimated 82,215 vacant sites to accommodate future tree growth (this estimate excludes the estimated current population of 4,785 trees). Assuming all newly planted trees were saplings, the estimated cost would be approximately $41,000; conversely, if all newly planted trees were of caliper size, the cost would be $41,000,000. Aside from cost, there are other implications associated with the type and size of tree that is planted as a component of a C offset program; one issue of particular interest is directly related to offset permanence.

Once trees are planted, they need to survive in order to sequester and store C as biomass. However, environmental conditions (such as site context, soil condition, water and nutrient availability, and potential stressors, such as pollutants and other anthropogenically imposed disturbances) will influence the success of any tree. There are advantages and disadvantages associated with planting seedlings or larger trees. For example, while planting smaller trees is more cost-effective on the implementation side, they are inherently more susceptible to succumb to failure under certain growing conditions. Conversely, larger trees, although substantially more expensive to implement, are inherently hardier than their seedling-sized counterparts.

There are widely varying site conditions in the proposed area for urban forest development in BIP, as urbanized landscapes possess notoriously high levels of heterogeneity (Zipperer et al., 1997; Cadenasso et al., 2007). To maximize tree success, and therefore C sequestration and storage potentials within the proposed BIP urban forest, environmental conditions for each individual site should be considered and assessed. This type of assessment would help inform appropriate tree selection to ensure highest rates of success for trees planted within the BIP urban-forest C offset program.

5.6 How Can We "Make it Work"? Practical Recommendations for Implementing Proposed Urban Forest Development within the Burnside Industrial Park

Given the modest size of the proposed C offset project within BIP, we believe that it is likely infeasible (at this time) to sell BIP urban forest C offsets as highest-calibre C credits in a formal C market. The major perceived hurdles of selling BIP urban forest generated C offsets within high-calibre markets to fund urban forest development are resource-related. For example, transaction costs associated with hiring a licensed, third-party verifier would be substantial. Preparing adequate documentation for adherence to high-calibre offset protocols is demanding on expertise resources, as it is of upmost importance to keep detailed records of all data and methods called upon to establish the project's baseline and future estimates of C sequestration and storage.

Another limitation is related to offset permanence. Extra costs are inevitable to ensure that the C offsets sold are indeed realized over a minimum of 100 years. Tree Canada (2009) recommend three methods by which offset providers could provide insurance for offsets sold to investors: 1) establishment of a plantation from which offsets are not sold; 2) only accounting for above-ground C-stores (as is the case within the C model created for the BIP urban forest); or 3) establishment of a contractual agreement indicating that the offset provider must provide for replacement offsets if faced with the loss of (e.g. related to unanticipated disturbances, such as fire or deforestation via land-use change) or lower-than-estimated biomass (and therefore) C accumulation. While selling offsets for above-ground biomass only, this option would certainly not insure offsets given the loss of all above-ground biomass due to an unforeseen disturbance event (e.g. fire, extreme weather event, catastrophic pest outbreak). This is an issue because trees generally store approximately 80% of their biomass in above-ground tissue.

However, as previously discussed in section 5.4.2.6 (Regional co-benefits), there are many additional benefits associated with improving urban forest structure that extend far beyond that of C sequestration and storage potentials. It is a widely accepted notion that larger trees provide more benefits than smaller trees (McPherson et al., 1997; Nowak, 2002a; USDA Forest Service, 2004). Because all trees begin life as small trees, the sooner trees are planted, the sooner they will grow into large trees. This makes it essential to plant more trees as soon as possible to maximize these benefits. While recognizing limitations associated with high-quality C offsets (discussed in the following section), we echo the sentiments of Hoover (2011, p. 476): "If we wait for every wrinkle to be sorted out we risk missing the window of opportunity to reap the greatest benefit from offset projects… We may not have all of the answers, but it's time to make it work".

5.6.1 Alternative strategies and considerations to support proposed urban forest development within Burnside Industrial Park

Two notable, positive features associated with the potential offsets that could be generated within the BIP urban forest include additionality and regional co-benefits. Based on results of our calculations to estimate current and future C sequestration and storage, *Scenario 2* and *Scenario 3* both provide additionality when compared to *Scenario 1*, the project's baseline scenario. Over the simulated course of forty years, *Scenario 2* (50% planting of all vacancies) and *Scenario 3* (100% planting of all vacancies) demonstrate net additional C stores of 11,480 t C and 22,956 t C , respectively, compared to the baseline. The prospect of the co-benefits associated with intensified tree planting also make these offsets especially enticing to local business owners. Not only would they receive recognition in the form of C offsets, but would experience, first hand, the additional co-benefits associated with a dramatically larger tree population. Therefore, the next questions are: How might this information regarding C sequestration and storage potentials within BIP be relayed in a practical, applicable sense to local business owners? And how might this information be utilized to entice prospective investors to fund urban-forest development efforts within BIP?

5.6.1.1 Aligning with existing urban forest management plans

Ownership of the land proposed for future urban forest development efforts within BIP is distributed amongst government (municipal (44%), provincial (5%), and federal (1%)) and private (50%) landowners. Land ownership, from a practical standpoint, imposes implications associated with the responsibility of planting and maintaining trees. Currently, HRM is on the cusp of completion of its first UFMP. The UFMP contains urban forest management objectives for the municipality, and includes land within BIP. HRM is responsible for planting and maintain trees on municipal property. We therefore suggest the creation of a land cover map to rank HRM-owned planting sites according to environmental conditions influencing tree growth. For example, sites could be rated on factors such as pollutant level, proximity to traffic (both pedestrian and vehicular), and soil type and/or condition. A general site-specific stress indicator could be assigned to each vacant planting spot, therefore providing a more realistic cost profile associated with tree planting. Sites rated as "low stress" (such as those far from roads and sidewalks, perhaps sheltered, and low identified pollution sources (such as salt spray or stormwater runoff)) could be planted with smaller, less expensive tree stock options (such as the $0.50/seedling), while sites rated as "high stress" could be planted with larger trees (such as the more expensive, $500/tree option). Each of the tree stock pricing options, albeit yielding drastically different cost estimates associated with establishing 100% of each, will yield the same net C storage by urban tree biomass by the year 2050: 23,000 tC.

Different issues are associated with planting 100% of either tree stock option. Planting 100% seedlings in vacant planting spots, while perhaps a more appealing option with respect to cost effectiveness (each tC estimated at a cost of $2), is not necessarily the best option to pursue for urban forest development. One concern with pursuing this option is that associated with seedling survival rate. Not all sites within BIP would be conducive for seedling growth, as they can present very harsh conditions for a small seedling to succeed. Conversely, planting 100% 60mm caliper trees may yield higher success rates in the face of adverse growing conditions, is cost prohibitive. This option drastically increases the cost of each tC stored by the BIP urban forest within *Scenario 3* to $2,000/tC. See Table 5-5 for a summary of all assumptions used to generate potential costs associated with tree planting estimates.

Table 5-5: Summary of estimated parameters used for estimating tree stock options

# Trees	82,215 945/ha
Estimated C store	23,000 tC 260 tC/ha
Plant 100% seedlings ($0.50/tree)	$41,000 (total) $470/ha $2 per tC
Plant 100% caliper trees ($500/tree)	$41,000,000 $470,000/ha $2,000 per tC
Total area for planting	87 ha

With these considerations in mind, we decided it would be reasonable to potentially sell BIP urban forest generated C offsets at a price of $20/tC. If each tC estimated to be sequestered and stored by the BIP urban forest were sold as C credits, $460,000 in gross revenues could be generated. If 100% of these revenues were directed towards tree planting, 920,000 seedlings or 920 caliper trees could be planted. As previously discussed, planting 100% seedlings or 100% caliper trees is, from a practical urban forest management perspective, undesirable for several reasons. We therefore suggest a mélange of the two tree stock types would provide a more successful and realistic estimate for BIP urban forest development. It is during this step that urban forest managers would consult a site-specific stress indicator map as a tool for ensuring, from both economic and rate-of-new-tree-success terms; maximum C storage per dollar invested in tree planting is achieved.

Consider the following BIP-specific example. If, upon completing a site-specific stress indicator map, the BIP urban forester rates 25% (i.e. approximately 20,554 spots) of all vacant planting spots as "high stress" (i.e. would accommodate $500-each caliper trees), and 75% (i.e. approximately 61,661 spots) of all vacant planting spots as "low stress" (i.e. would accommodate $0.50-each seedlings), that would leave approximately 22 ha to be planted with caliper trees, and 65 ha be planted with seedlings. Assuming all potential offsets are sold to generate revenue of $460,000, and the revenue is used, in entirety, to fund tree planting, the urban forester could plant 61,661 seedlings and 858 caliper trees.

Alternatively, the urban forester could plant every planting spot, regardless of the site rating, with seedlings (a total of 82,215 spots). This option would only cost $41,100, which is only approximately 9% of the proposed tree-planting budget. While perhaps not every seedling planted within a "high stress" site would survive, given the low cost of planting a seedling, the rewards associated with the survival of each seedling are therefore high. If this option were chosen, the remainder of the budget could be allocated towards replacing seedling mortalities with caliper trees (838 trees).

Although there are a variety of tree stock combination options, we advocate the importance of increasing overall tree density by filling every identified vacancy. To plant as many trees as possible, it is necessary to yield funding priority to seedlings; remaining funds are then allocated to plant as many caliper trees as the proposed $460,000 budget can afford.

5.6.1.2 Initialization of community-based urban-forest development program: Lessons from the City of Fredericton

Another possibility as a source of potential funding and other support for urban forest development within BIP is to engage local businesses in a community-based, urban-forest development program. Although not specifically designed for enhancing urban forest structure, the success of the community program *Green Matters*, run by the City of Fredericton, New Brunswick, serves as an example as to how a similar program may function within the context of BIP.

The primary objective of the *Green Matters* program is to encourage citizens, community groups, and businesses within the City of Fredericton to reduce their overall ecological and GHG footprints (Green Matters, n.d). There are many ways in which community members can participate in the program, including *Green Shops*, a branch of *Green Matters* specifically tailored to encourage the involvement of local businesses. To participate within the program, local business owners can request a *Green Shops* certification audit to be conducted. A *Green Shops* Coordinator then visits the business, and, using a set of pre-determined criteria (i.e. actionable items, including categories such as waste management and energy efficiency), evaluates the business and designates a subsequent member status. A business can achieve one of four possible statuses based on its audit performance. To become a *Green Shops* Member, a business must satisfy a minimum of 35% of criteria; Bronze Members satisfy 36-55%; Silver 56-75%; and Gold *Green Shops* Members satisfy 75% or more of the criteria (Green Shops, 2010). Post-audit, businesses are given recommendations for strategies to improve their status rating. Recognition for their efforts and participation is provided by items such as window decals for their shops, a *Green Shops* logo for their own websites (in addition to being listed and promoted on the *Green Shops* website) and access to a variety of other networking and support tools (Green Shops, 2010).

Green Matters and the associated program *Green Shops* encourage community members to reduce their GHG emissions. This program, offered from an environmental-integrity and sustainability standpoint, also provides an opportunity for individuals, community groups, and businesses to become a "peer leader and community steward in Fredericton" (GreenNexxus, n.d, para. 2). We believe that establishing a similar program would have the potential to function as a means to encourage urban forest development within BIP. Poudyal et al., (2011a) conducted a survey of perspectives of offset buyers, and found that urban forest offsets were strongly appealing because of their features such as co-benefits and an enhanced public image. For example, a proposed *Green Matters* program within HRM could include at least one criterion associated with various aspect of urban forest stewardship. Rewards could be given to businesses that take responsibility for the health and well-being of existing municipal and/or privately owned trees, or for the planting and maintenance of additional trees implemented on the previously identified vacant planting spots.

Establishing BIP business-based citizen forester groups is one potential component that could be included within a BIP-specific program similar to *Green Matters.* Citizen forester groups would take an active participatory role in the maintenance and improvement of urban forest structure within BIP. Such a program could be readily adopted into the already-existing citizen forestry program in place within the HRM UFMP. When community groups are interested in helping maintain and/or improve urban forest structure within HRM, the group can meet with HRM's urban forester to learn about urban forest management basics, such as species selection, and a variety of simple maintenance and tree health care techniques (J. Simmons

(HRM Urban Forester), personal communication, March 2012).

Another unique opportunity for improving urban forest structure within BIP may also lay in the development of a BIP-specific urban forest offset trading system. As such, we propose that a unique C offset protocol, registry, and subsequent trading system could be developed to function as a component of a program similar to Fredericton's *Green Matters*. The "*BIP urban forest C offset trading system*", while not designed to generate the highest-calibre offsets to be traded within pre-existing mandatory and voluntary markets, would take several measures to ensure potential offset investors that the offsets are, indeed, reputable and investment-worthy. Consider the following example: In the form of a work contract, an individual or small group of qualified and/or C offset market experienced individuals could be hired to develop and manage the *BIP urban forest C offset trading system*.

BIP-specific C offset protocol would define all of the previously discussed quality-offset characteristics and specify the type of detailed documentation required for each offset to be deemed tradable within the *BIP urban forest C offset trading system*. This documentation is necessary in order to ensure prospective offset investors the legitimacy generated offsets. It is even possible for some degree of third-party verification of the offsets to be included within the program, as offset verification duties could be contracted to a researcher and/or group of professional experts belonging to academic or professional institutions within HRM.

The *BIP urban forest C offset trading system* would also include an offset registry. This offset registry would clarify offset ownership, and thereby aid in avoiding the double counting offsets. A fixed price for C could be established within this trading system (e.g. $20/tC), and additional opportunities for investment could also be presented through an "offset embellishment" program. Similar to *Green Shops,* investors could be recognized for additional donations or other contributions directed towards enhancing the BIP urban forest. Examples of such contributions are monetary (e.g. paying a premium per tC purchased to be directed directly towards a BIP urban forest maintenance fund) or community-volunteer related (e.g. additional recognition for offset purchasers who also participate in citizen forestry programs).

5.7 Conclusions

The results generated by this research provide positive affirmation for the potentials of generating C offsets within an urban forest development context. Not only is there potential from a biophysical standpoint, but a marketable potential as well. The assessment of urban forest offset quality suggests these offsets indeed possess characteristics to be of high quality. However, at this time we concluded that the practical prospects of marketing high-calibre C offsets generated by BIP urban forest development are limited. While C offsets generated by urban forest development are capable of satisfying all the criteria that constitute high-quality C offsets, there are several burdens, many being cost-related, that currently prohibit the realistic pursuit of this opportunity at this time. Nevertheless, we do believe there are several lessons and positive aspects that can be derived from our consideration of urban forest C offsets as there are many benefits associated with improving upon urban forest structure within our communities. As an alternative to pursuing BIP-generated offsets as the highest-calibre C offsets, we advocate the development of an alternative program that could potentially serve as a means for obtaining funds and support from the BIP community for urban forest development. Essentially, any improvement to urban forest structure within BIP, even though the tree population density may never reach that of *Scenario 3* as yielding the most C offsets sequestered and stored by urban forest biomass, will yield at least modest C offset benefits to the BIP community, and will also provide a myriad of other benefits as the new trees grow into large, mature organisms.

5.8 References

Akbari, H., Kurn, D.M., Bretz, S.E., & Hanford, J.W. (1997). Peak power and cooling energy savings of shade trees. *Energy and Buildings, 25*, 139-148.

Akbari, H., Pomerantz, M., & Taha, H. (2001). Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. *Solar Energy, 70*(3), 295-310.

Alberta Offset Registry (AOR). (2011). Alberta emissions offset registry. Retrieved March 3, 2012 from http://carbonoffsetsolutions.climatechangecentral.com/offset-registry

Anderson, L.M., & Cordell, H.K. (1988). Influence of trees on residential property values in Athens, Georgia (USA): A survey based on actual sales prices. *Landscape and Urban Planning, 15,* 153-164.

Bayon, R., Hawn, A., Hamilton, K. (2009). *Voluntary carbon markets: An International business guide to what they are and how they work* (2nd ed.). London, UK: Earthscan.

Birdsey, R.A. (2006). Carbon accounting rules and guidelines for the United States forest sector. *Journal of Environmental Quality, 35*, 1518-1524.

Brack, C. (2002). Pollution mitigation and carbon sequestration by an urban forest. *Environmental Pollution, 116*, S195-S200.

Cadenasso, M.L., Pickett, S.T.A., & Schwarz, K. (2007). Spatial heterogeneity in urban ecosystems: Reconceptualizing land cover and a framework for classification. *Frontiers in Ecology and the Environment, 5*(2), 80-88.

Côté, R.P., & Smolenaars, T. (1997). Supporting pillars for industrial ecosystems. *Journal of Cleaner Production, 5*(1-2), 67-74.

David Suzuki Foundation. (2008). Credit check: A comparative evaluation of tree-planting and fossil-fuel emission reduction offsets (A David Suzuki Foundation Technical Paper). Retrieved from David Suzuki Foundation: http://www.davidsuzuki.org/publications/downloads/2008/Credit_Check_080701.pdf

Dixon, R.K., Brown, S., Houghton, R.A., Solomon, A.M., Trexler, M.C., & Wisniewski, J. (1994). Carbon pools and flux of global forest ecosystems. *Science, 263*, 185-191.

Dwyer, J.F., McPherson, E.G., Schroeder, H.W., & Rowntree, R.A. (1992). Assessing the benefits and costs of the urban forest. *Journal of Arboriculture, 15*, 247-252.

Dwyer, J.F., Nowak, D.J., Noble, M.H., & Sisinni, S.M. (2000). Connecting people with ecosystems in the 21st century: An assessment of our nation's urban forests (General Technical Report PNW-GTR-490). Retrieved from United States Forest Service: http://www.treesearch.fs.fed.us/pubs/29448

Ehrenfeld, J., & Gertler, N. (1997). Industrial ecology in practice: The evolution of interdependence at Kalundborg. *Journal of Industrial Ecology, 1*(1), 67-79.

Environment Canada. (2008). *Turning the corner: Canada's offset system for greenhouse gasses*. Retrieved from Environment Canada: http://www.ec.gc.ca/doc/virage-corner/2008-03/526_eng.htm

Erkman, S. (1997). Industrial ecology: An historical view. *Journal of Cleaner Production, 5*(1-2), 1-10.

European Union Emissions Trading System (EUETS). (2010). Emissions Trading S ystem. Retrieved March 16, 2012 from http://ec.europa.eu/clima/policies/ets/index_en.htm

Frumkin, H. (2002). Urban sprawl and public health. *Public Health Reports, 117*(3), 201-217.

Gill, S.E., Handley, J.F., Ennos, A.R., & Pauleit, S. (2007). Adapting cities for climate change: The role of the green infrastructure. *Built Environment, 33*(1), 115-133.

Green Matters. (n.d.). Retrieved March 18, 2012 from http://www.greenmattersfredericton.com/en/index.asp

GreenNexxus. (n.d.). The benefits of being a Green Matters Certified organization. Retrieved March 15, 2012 from http://espme.greennexxus.com/gmc/

Green Shops. (2010). How to join. Retrieved March 18, 2012 from http://www.greenshopsfredericton.ca/how-to-join

Grimm, N.B., Faeth, S.H., Golubiewski, N.E., Redman, C.L., Wu, J., Bai, X., & Briggs, J.M. (2008). Global climate change and the ecology of cities. *Science, 319*, 756-560.

Heisler, G.M. (1986). Energy savings with trees. *Journal of Arboriculture, 12*(5), 113-125.

Herzog, H., Calderia, K., & Reilly, J. (2003). An issue of permanence: Assessing the effectiveness of temporary carbon storage. *Climatic Change, 59,* 293–310.

Hoover, C.M. (2011). Response: Measurement, monitoring, and verification: make it work! *Journal of Forestry, 109,* 475-476.

Intergovernmental Panel on Climate Change (IPCC). (n.d.). Publications and data. Retrieved March 18, 2012 from http://www.ipcc.ch/publications_and_data/publications_and_data_reports.shtml#.T2aVdBx7FNs

Intergovernmental Panel on Climate Change (IPCC). (2005). *IPCC special report on carbon dioxide capture and storage.* London, UK: Cambridge University Press.

Intergovernmental Panel on Climate Change (IPCC). (2007a). Climate change 2007: Synthesis report. In R.K. Pachauri & A. Reisinger (Eds.), *Contribution of working groups I, II and III to the fourth assessment report of the Intergovernmental Panel on Climate Change*. Geneva, Switzerland: IPCC.

Intergovernmental Panel on Climate Change (IPCC). (2007b). Climate change 2007: Impacts, adaptation, and vulnerability. In M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, & C.E. Hanson (Eds.), *Fourth assessment report of the Intergovernmental Panel on Climate Change, 2007*. Cambridge, UK: Cambridge University Press.

Jenkins, J.C., Chojnacky, D.C., Heath, L.S., Birdsey, R.A., & Richard, A. (2004). Comprehensive database of diameter-based biomass regressions for North American tree species (General Technical Report NE-319). Retrieved from United States Forest Service: http://www.uvm.edu/~jcjenkin/jenkins%20et%20al.%202004.pdf

Jo, H.K., & McPherson, E.G. (1995). Carbon storage and flux in urban residential greenspace. *Journal of Environmental Management, 45*, 109-133.

Kirschbaum, M.U.F., & Cowie, A.L. (2004). A practical method to distinguish between human and natural factors in carbon accounting. *Climatic Change*, *67,* 417–436.

LeBlanc, A. (1999). Issues related to including forestry-based offsets in a GHG emissions trading system. *Environmental Science & Policy, 2,* 199-206.

Maco, S.E., & McPherson, E.G. (2003). A practical approach to assessing structure, function, and value of street tree populations in small communities. *Journal of Arboriculture, 29*(2), 84-97.

McCarl, B.A., & Sands, R.D. (2007). Competitiveness of terrestrial greenhouse gas offsets: are they a bridge to the future? *Climatic Change, 80,* 109–126.

McHale, M.R., McPherson, E.G., & Burke, I.C. (2007). The potential of urban tree plantings to be cost effective in carbon credit markets. *Urban Forestry & Urban Greening, 6,* 49-60.

McKinney, M.L. (2002). Urbanization, biodiversity, and conservation. *BioScience, 52*(10), 883-890.

McPherson, E.G. (1993). Evaluating the cost effectiveness of shade trees for demand-side management. *The Electricity Journal, 6*(9), 57-65.

McPherson, E.G. (1998). Atmospheric carbon dioxide reduction by Sacramento's urban forest. *Journal of Arboriculture, 24*(4), 215-223.

McPherson, E.G., & Muchnick, J. (2005). Effects of street tree shade on asphalt concrete pavement performance. *Journal of Arboriculture, 31*(6), 303-310.

McPherson, E.G., Nowak, D.J., Heisler, G., Grimmond, S., Souch, C., Grant, R., & Rowntree, R.A. (1997). Quantifying urban forest structure, function, and value: The Chicago Urban Forest Climate Project. *Urban Ecosystems, 1*, 49–61.

McPherson, E.G., Nowak, D.J., & Rowntree, R.A. (Eds.). (1994). Chicago's urban forest ecosystem: Results of the Chicago urban forest climate project. (General Technical Report NE-186). Retrieved from United States Forest Service: http://www.treesearch.fs.fed.us/pubs/4285

Myeong, S., Nowak, D.J., & Duggin, M.J. (2006). A temporal analysis of urban forest carbon storage using remote sensing. *Remote Sensing of Environment, 101*, 277-282.

Nowak, D.J. (1993). Atmospheric carbon reduction by urban trees. *Journal of Environmental Management, 37*, 207-217.

Nowak, D.J. (1994). Atmospheric carbon dioxide reduction by Chicago's urban forest. In E.G. McPherson, D.J. Nowak, & R.A. Rowntree (Eds.), *Chicago's urban forest ecosystem: Results of the Chicago urban forest climate project* (pp. 83-94) (General Technical Report NE-186). Retrieved from United States Forest Service: http://www.treesearch.fs.fed.us/pubs/4285

Nowak, D.J., & Crane, D.E. (2002). Carbon storage and sequestration by urban trees in the USA. *Environmental Pollution, 116*(3), 381-389.

Nowak, D.J., Crane, D.E., Stevens, J.C., & Ibarra, M. (2002a). Brooklyn's urban forest. (General Technical Report NE-290). Retrieved from United States Department of Agriculture, Forest Service: http://www.fs.fed.us/ne/newtown_square/publications/technical_reports/pdfs/2002/gtrne290.pdf

Nowak, D.J., Stevens, J.C., Sisinni, S.M., & Luley, C.J. (2002b). Effects of urban tree management and species selection on atmospheric carbon dioxide. *Journal of Arboriculture, 28*(3), 113-122.

Oke, T.R. 1995. The heat island of the urban boundary layer: Characteristics, causes and effects. In J.E. Cermak (Ed.), *Wind climate in cities* (pp. 81–107). Netherlands: Kluwer Academic Publishers.

Pacific Carbon Trust (PCT). (2012). Protocol for the creation of forest carbon offsets in British Columbia. Retrieved February 18, 2012 from http://www.env.gov.bc.ca/cas/mitigation/pdfs/Forest_Carbon_Offset_Protocol_v1_0_Web.pdf

Pataki, D.E., Alig, R.J., Fung, A.S., Golubiewski, N.E., Kennedy, C.A., McPherson, E.G., … & Lankao, P.R. (2006). Urban ecosystems and the North American carbon cycle. *Global Change Biology, 12*(11), 2092–2102.

Peckham, S. (2010). *Nature in the city: Ecological consciousness development associated with naturalized urban spaces and urban forest values in Calgary, AB and Halifax, NS* (Unpublished master's thesis). Dalhousie University, Canada.

Poudyal, N.C., Siry, J., & Bowker, J.M. (2010). Urban forests' potential to supply marketable carbon emission offsets: A survey of municipal governments in the United States. *Forest Policy and Economics, 12,* 432–438

Poudyal, N.C., Siry, J., & Bowker, J.M. (2011a). Urban forests and carbon markets: Buyers' perspectives. *Journal of Forestry, 109*(7), 378-385.

Poudyal, N.C., Siry, J., & Bowker, J.M. (2011b). Quality of urban forest carbon credits. *Urban Forestry & Urban Greening, 10*, 223-230.

Ristea, C., & Maness, T.C. (2009). Opportunities, challenges and markets for forest carbon offset projects. *The Forestry Chronicle 85(5)*, 715-718.

Rowntree, R.A., & Nowak, D.J. (1991). Quantifying the role of urban forests in removing atmospheric carbon dioxide. *Journal of Arboriculture, 17*(10), 269-275.

Sedjo, R. & Macauley, M. (2011). Forest carbon offsets: Possibilities and limitations. *Journal of Forestry, 109,* 470-473.

Sieghardt, M., Mursch-Radlgruber, E., Paoletti, E., Couenberg, E., Dimitrakopoulus, A., Rego, F., … & Randrup, T.B. (2005). The abiotic urban environment - Impact of urban growing conditions on urban vegetation. In C.C. Konijnendijk, K. Nilsson, T.B. Randrup, & J. Schipperijn (Eds.), *Urban forests and trees* (pp. 281-323). New York, NY: Springer.

Simpson, J.R. (2002). Improved estimates of tree-shade effects on residential energy use. *Energy and Buildings, 34*, 1067-1076.

Sovacool, B.K. (2011). The policy challenges of tradable credits: A critical review of eight markets. *Energy Policy, 39*, 575-585.

Starfield, A.M. (1997). A pragmatic approach to modeling for wildlife management. *The Journal of Wildlife Management, 61*(2), 261-270.

Sundquist, E.T., Ackerman, K.V., Parker, L., & Huntzinger, D.N. (2009). An introduction to global carbon cycle management. In B.J. McPherson & E.T. Sundquist (Eds.), *Carbon sequestration and its role in the global carbon cycle* (pp. 1-23). Washington, DC: American Geophysical Union.

Tree Canada. (2009). Tree Canada forest and urban tree carbon project protocol. A standard for the eligibility and measurement of Tree Canada carbon offset projects. Retrieved from Tree Canada: http://www.treecanada.ca/site/resources/pages/files/Carbon%20Protocol%20English.pdf

Tsihrintzis, V.A., & Hamid, R. (1997). Modeling and management of urban stormwater runoff quality: A review. *Water Resources Management, 11*, 137–164.

Ulrich, R.S. (1984). View through a window may influence recovery from surgery. *Science, 224*, 420-421.

Ulrich, R.S. (1986). Human responses to vegetation and landscape. *Landscape and Urban Planning, 13*, 29-44.

United Nations Framework Convention on Climate Change (UNFCCC). (2011). Clean Development Mechanism methodology booklet. Retrieved February 18, 2012 from http://cdm.unfccc.int/methodologies/documentation/meth_booklet.pdf#AR-AMS0006

United Nations-Habitat (UN-Habitat). (2009). *Planning sustainable cities: Global report on human settlements 2009*. Sterling, VA: Earthscan.

United States Department of Agriculture, Forest Service (USDA Forest Service). (2004). The large tree argument: The case for large-stature trees vs. small-stature trees. Retrieved from http://www.fs.fed.us/psw/programs/uesd/uep/products/cufr_511_large_tree_argument.pdf

United States Government Accountability Office (USGAO). (2008). Carbon offsets: The U.S. voluntary market is growing, but quality assurance poses challenges for market participants. (Report to Congressional Requestors GAO-08-1048). Retrieved from U.S. Government Accountability Office: http://www.gao.gov/products/GAO-08-1048.

Western Climate Initiative (WCI). (2010). Offset system essential elements final recommendations paper. Retrieved from Western Climate Initiative: http://www.westernclimateinitiative.org/component/remository/Offsets-Committee-Documents/Offset-Criteria-Draft-Recommendations/

Wolf, K.L. (2003). Public response to the urban forest in inner-city business districts. *Journal of Arboriculture, 29*(3), 117-126.

Wright, R.A., Côté , R.P., Duffy, J., & Brazner, J. (2009). Diversity and connectance in an industrial context: The case of Burnside Industrial Park. *Journal of Industrial Ecology, 13*(4), 551-564.

Yang, J., McBride, J., Zhoub, J., & Sun, Z. (2005). The urban forest in Beijing and its role in air pollution reduction. *Urban Forestry & Urban Greening, 3*, 65–78

Yemshanov, D., McKenney, D., Fraligh, S., & D'Eon, S. (2007). An integrated spatial assessment of the investment potential of three species in southern Ontario, Canada inclusive of carbon benefits. *Forest Policy and Economics 10,* 48-59.

Yemshanov, D., Biggs, J., McKenney, D.W., & Lempriere, T. (2012). Effects of permanence requirements on afforestation choices for carbon sequestration for Ontario, Canada*. Forest Policy and Economics, 14*, 6–18.

Yue, G. (2010). *Mapping traditional bird knowledge for urban bird conservation in Halifax, Nova Scotia, Canada* (Unpublished master's thesis). Dalhousie University, Canada.

Zipperer, W.C., Sisinni, S.M., Pouyat, R.V., & Foresman, T.W. (1997). Urban tree cover: An ecological perspective. *Urban Ecosystems, 1*, 229-246.

CHAPTER 6: CONCLUSIONS

6.1 Project Summary and Conclusions

In this study, we assessed the biophysical capacity of C sequestration and storage by the BIP urban forest, in addition to urban forest development financing opportunities via C offset markets. Three research questions were identified to provide guidance for the study, and are as follows:

- How much C is being stored by the BIP urban forest today (2010)?
- What is the potential for future C sequestration and storage in the 2050 BIP urban forest, under the following three urban-forest development scenarios:
    4. Maintenance of the 2010 urban forest population of trees;
    5. Maintenance of the 2010 urban forest in addition to planting 50% of all 2010 vacancies (i.e., plantable spots); and
    6. Maintenance of the 2010 urban forest in addition to planting 100% of all 2010 vacancies.
- To what extent might development of the BIP urban forest be financed through local businesses purchasing C credits through current C-offset markets?

The first two questions were answered concurrently, given the amount of methodological overlap needed to answer them. The last question was answered upon completion of the first two, its answer being partially informed by results generated from the first two questions. Conclusions derived from conducting the study are discussed below, and are divided into the following two sections: 1) Understanding urban forest carbon dynamics within the Burnside Industrial Park landscape; and 2) Potential for BIP urban forest development via C offset markets. The chapter concludes with suggestions for directions of future research efforts, in addition to final thoughts upon completion of this project.

6.1.1 Understanding urban forest carbon dynamics within the Burnside Industrial Park landscape

To answer the research questions, it was first necessary to establish an estimate of existing urban forest structure within BIP, including the area available to accommodate additional tree growth. Doing so provided several insights pertaining to the performance of current urban forest structure, in addition to the potential benefits (in our case, specifically related to C sequestration and storage) associated with proposed intensified tree planting efforts. Constructing an original C model enabled us to incorporate many important factors influencing urban tree growth within the BIP urban forest, such as tree age, species-specific growth and mortality rates, and biomass equations.

Results generated by the C model allude to the following conclusions regarding the potential for C sequestration and storage potentials within future development scenarios of the BIP urban forest landscape:

- The number of trees within an urban forest population influences C sequestration and storage potentials thereof; the more trees there are (and therefore the higher the population density), the more total C is sequestered and stored as urban tree biomass; and
- Larger trees sequester and store more C than smaller trees.

While not downplaying the positive benefits associated with promoting the establishment and growth of large-stature trees within an urban forest ecosystem (USDA Forest Service, 2004), we advocate the significance of urban tree density as a substantial factor influencing C sequestration and storage potentials. Time is a major determinant influencing tree growth, as all trees begin life as seedlings, and it takes time for small trees to become large. Because the focal point of our investigation is from a C sequestration standpoint, it is advantageous to plant many trees so their foliage maximizes the capture of sunlight per unit area. This results in enhanced C sequestration and storage potentials of a given area. Additionally, it is not always practical to accommodate large stature trees in every available planting spot for a variety of reasons (e.g. implications associated with visibility, and interference with urban infrastructure such as electricity lines).

6.1.1.1 Limitations associated with the Burnside Industrial Park urban forest carbon model

Numerous factors influence C sequestration and storage potentials of urban trees. Unfortunately, accurately accounting for every possible factor in a simple urban forest C model is impossible. This is an issue that permeates any attempt to quantify or otherwise emulate real-world ecosystems (Starfield, 1997; Jackson et al., 2000). While factors included within the BIP urban forest C model are similar to those found within other urban forest C models, factors such as potential disturbances (e.g. pest outbreaks, storm damage), tree health (e.g. "excellent" vs. "poor"), and potential impacts associated with climate change (e.g. increased temperatures) remain accounted for. We acknowledge there are inherent limitations within our urban forest C model, especially those associated with the selection and omission of biotic and abiotic factors that influence C sequestration and storage potentials of urban trees.

Another limitation associated with estimating C sequestration and storage potentials of urban trees lies with the veracity of results generated by selected biomass equations. McHale et al. (2009) highlighted the issue surrounding the use of rural-forest-based biomass equations (i.e., for trees growing in dense stands) for estimating biomass of urban trees. It has become standard practice within the realm of urban-forest C estimation to reduce a biomass value derived from a rural-forest-based biomass equation by multiplying the estimate by 0.8 (McHale et al., 2009). While acknowledging that trees grown in urban environments accumulate biomass differently than trees grown in rural environments, we question the rationale of applying this biomass reduction factor to urban trees. However, the proposition of conducting research to establish urban-tree-specific allometric biomass equations is not necessarily the solution (McHale et al., 2009). This is because of the high level of heterogeneity in urban areas. For example, within BIP, trees are grown in areas that are innately subject to high levels of environmental stress. Consider areas close to sidewalks and roads; they are exposed to higher levels of salt contamination simply because of salt application and subsequent spray as a result of winter safety precautions. Because of their location, these sites may actually have smaller available space to accommodate root growth (e.g. tree pits). These areas, therefore, could be in extremely high contrast of growing conditions when compared to sites located far from the roads and sidewalks (therefore having reduced exposure to salt), and with greater space for root growth. An example of this type of area could be only metres away from a high-stress site, and could be a large lawn or green space.

6.1.2 Potential for Burnside Industrial Park urban forest development via carbon offset markets

Upon conducting a review similar to that of Poudyal et al. (2011b) to assess the potential viability of BIP urban forest C offsets within mandatory and/or voluntary markets, we concluded that urban-forest-generated offsets can indeed adhere to high-standard offset quality protocols. However, we also concluded that at this time, forcing BIP urban-forest-generated offsets into existing protocols and markets to obtain funds for urban forest development is not feasible. The main barriers associated with pursuing this option are resource related, primarily monetary. As such, we have chosen to adopt the viewpoint of Hoover (2011, p. 476): "If we wait for every wrinkle to be sorted out we risk missing the window of opportunity to reap the greatest benefit from offset projects… We may not have all of the answers, but it's time to make it work".

In an attempt to make recommendations based on this research practical, realistic, and applicable within an urban forest development context, a basic framework from which a community-based C offset exchange program was proposed. Participating within the "*BIP urban forest C offset trading system"* could give local businesses an opportunity to help fund urban forest development via purchasing C offsets generated by urban forest development within BIP. Additional recognition could also be given to businesses choosing to engage within the program on other platforms as well. Examples of other urban forest enhancement opportunities include organization and formation of citizen forest-stewardship groups, or additional donations made to support general maintenance of trees within BIP.

6.2 Future Research Opportunities

Three research opportunities could be pursued to enhance the findings of this research. The first is associated with incorporating climate-change impacts and adaptation strategies into an urban forest C model. Given the limitations associated with this project (e.g. objectives, scope, timeline), we chose to omit factors associated with anticipated climate change in the Halifax region within our C model. For example, one way to incorporate climate-change adaptation strategies into the model is to redirect species selection for urban tree natalities that are better adapted to anticipated environmental conditions imposed by climate change. For example, Rostami (2011) completed a study examining fifty-seven tree species using ninety-five criteria to evaluate each species' performance under a changing climate. Furthermore, model parameters pertaining to impacts of climate change could be incorporated into the existing C model. The new parameters could potentially influence growth and mortality rates and overall tree health, and account for a variety of urban forest disturbances associated with a changing climate (e.g. increased frequency of extreme weather events, new pest and disease outbreaks).

The second opportunity for research lies in addressing our research questions in the context of other light-industrial and commercial landscape similar to BIP. While other studies have estimated similar low tree densities within industrial and commercial landscapes (e.g. Rowntree and Nowak, 1991; Nowak, 1993; McPherson, 1998), we are left unsure of the potential area available for intensified tree planting efforts (and therefore enhanced C sequestration and storage) within these landscapes. If the methods we used guided the quantification of potential urban forest C sequestration and storage in other light-industrial and commercial settings, we will greatly enhance our quantitative understanding of the true potential for C sequestration and storage in these bleak landscapes.

The third research opportunity we propose entails determining the thoughts and perceptions of BIP stakeholders with respect to developing an urban forest development program in the area. The proposed program could apply the same type of principles and incentives as Fredericton's *Green Matters*, and provide an additional opportunity associated with implementation of a *BIP urban forest C offset trading system*. Results of the survey could be used to develop a practical and applicable framework from which a realistic and attainable urban-forest development strategy could be developed in BIP. Poudyal et al. (2011a) conducted a similar survey, in which they presented various perspectives of potential C-offset investors. Perhaps their study could serve as a base from which this proposed study could be conducted in the BIP context.

6.3 Final Thoughts

Aside from the C sequestration and storage benefits, urban trees provide many other benefits to their communities. This research was dedicated to exploring the potential of BIP, a light-industrial and commercial landscape, to accommodate future tree growth to enhance C sequestration and storage potentials associated with its development. Both our urban-forest development scenarios yielded an increase in C sequestration and storage. While the C offsets generated by the BIP urban forest may be difficult to put into a high-calibre C offset market context, we do not discount the credibility of potential offsets that could be generated via urban forest development within BIP. The largest perceived hurdles associated with pursuing this as a viable option are, from our perspective, resource-related rather than offset-quality related.

What makes urban forest development for the purpose of creating C offsets unique is the plethora of regional co-benefits provided by urban trees. Urban forests, precisely because of their location, are able to provide benefits to communities that rural forests simply cannot. Feeling the cool air in the shade of a large oak on a hot summer's day, while stranded in an otherwise desolate, hot urban landscape, is an undeniably pleasurable human experience. This is but one example of the myriad ways people can interact with and appreciate trees in urban settings on a daily basis. Many of these benefits are unknown to the passerby (i.e. how does one appreciate C sequestration and storage of an individual tree?). While the value of sequestering and storing C has great value in and of itself, urban-forest management for C sequestration and storage has immense potential to contribute vast improvements to the overall condition of urban communities. When we treat the urban forest with the respect and attention it deserves, our urban successors will be richly blessed.

6.4 References

Hoover, C.M. (2011). Response: Measurement, monitoring, and verification: make it work! *Journal of Forestry, 109,* 475-476.

Jackson, L.J., Trebitz, A.S., & Kottingham, K.L. (2000). An introduction to the practice of ecological modelling. *BioScience, 50*(8), 694-706.

McHale, M.R, Burke, I.C., Lefsky, M.A., Peper, P.J., & McPherson, E.G. (2009). Urban forest biomass estimates: Is it important to use allometric relationships developed specifically for urban trees? *Urban Ecosystems, 12*, 95-113.

McPherson, E.G. (1998). Atmospheric carbon dioxide reduction by Sacramento's urban forest. *Journal of Arboriculture, 24*(4), 215-223.

Nowak, D.J. (1993). Atmospheric carbon reduction by urban trees. *Journal of Environmental Management, 37*, 207-217.

Poudyal, N.C., Siry, J., & Bowker, J.M. (2011a). Urban forests and carbon markets: Buyers' perspectives. *Journal of Forestry, 109*(7), 378-385.

Poudyal, N.C., Siry, J., & Bowker, J.M. (2011b). Quality of urban forest carbon credits. *Urban Forestry & Urban Greening, 10*, 223-230.

Rostami, M. (2011). *Tree species selection for the Halifax urban forest under a changing climate*. (Unpublished master's thesis). Dalhousie University, Canada.

Rowntree, R.A., & Nowak, D.J. (1991). Quantifying the role of urban forests in removing atmospheric carbon dioxide. *Journal of Arboriculture, 17*(10), 269-275.

Starfield, A.M. (1997). A pragmatic approach to modeling for wildlife management. *The Journal of Wildlife Management, 61*(2), 261-270.

United States Department of Agriculture, Forest Service (USDA Forest Service). (2004). The large tree argument: The case for large-stature trees vs. small-stature trees. Retrieved from http://www.fs.fed.us/psw/programs/uesd/uep/products/cufr_511_large_tree_argument.pdf

REFERENCES

Air Canada. (2011). *Carbon offset program.* Retrieved December 6, 2011 from http://www.aircanada.com/en/travelinfo/traveller/zfp.html

Ajtay, G.L., Ketner, P., & Duvigneaud, P. (1977). Terrestrial primary production and phytomass. In B. Bolin, E.T. Degens, S. Kempe, & P. Ketner (Eds.), *The global carbon cycle* (pp. 129-236). New York, NY: John Wiley & Sons.

Akbari, H. (2002). Shade trees reduce building energy use and CO_2 emissions from power plants. *Environmental Pollution, 116,* S119-S126.

Akbari, H., Kurn, D.M., Bretz, S.E., & Hanford, J.W. (1997). Peak power and cooling energy savings of shade trees. *Energy and Buildings, 25*, 139-148.

Akbari, H., Pomerantz, M., & Taha, H. (2001). Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. *Solar Energy, 70*(3), 295-310.

Alberta Offset Registry (AOR). (2011). Alberta emissions offset registry. Retrieved March 3, 2012 from http://carbonoffsetsolutions.climatechangecentral.com/offset-registry

Alig, R.J., & Butler, B.J. (2004). Projecting large-scale area changes in land use and land cover for terrestrial carbon analyses. *Environmental Management, 33*, 443–456.

Alig, R.J., Adams, D., & McCarl, B. (2002). Projecting impacts of global climate change the US forest and agricultural sectors and carbon budgets. *Forest Ecology and Management, 169*(1-2), 3–14.

Alvey, A.A. (2006). Promoting and preserving biodiversity in the urban forest. *Urban Forestry & Urban Greening, 5*(4), 195-201.

American Forests. (n.d.). *CITYgreen.* Retrieved May 9, 2011 from http://www.americanforests.org/productsandpubs/citygreen/

Anderson, J.R., Hardy, E.E., Roach, J.T., & Witmer, R.E. (1976). A land use and land cover classification system for use with remote sensor data (US Geological Survey Professional Paper 964). Retrieved from United States Geological Survey: http://landcover.usgs.gov/pdf/anderson.pdf

Anderson, L.M., & Cordell, H.K. (1988). Influence of trees on residential property values in Athens, Georgia (USA): A survey based on actual sales prices. *Landscape and Urban Planning, 15,* 153-164.

Bayon, R., Hawn, A., Hamilton, K. (2009). *Voluntary carbon markets: An International business guide to what they are and how they work* (2nd ed.). London, UK: Earthscan.

Birdsey, R.A. (1992). Carbon storage and accumulation in United Sates forest ecosystems (General Technical Report WO-59). Retrieved from United States Forest Service: http://www.treesearch.fs.fed.us/pubs/15215

Birdsey, R.A. (2006). Carbon accounting rules and guidelines for the United States forest sector. *Journal of Environmental Quality, 35*, 1518-1524.

Botkin, D.B., & Beveridge, C.E. (1997). Cities as environments. *Urban Ecology, 1*, 3-19.

Brack, C. (2002). Pollution mitigation and carbon sequestration by an urban forest. *Environmental Pollution, 116*, S195-S200.

Bradley, G. (1995a). Urban forest landscapes: Integrating multidisciplinary perspectives. In G. Bradley (Ed.), *Urban forest landscapes: Integrating multidisciplinary perspectives* (pp. 3-11). Seattle, WA: University of Washington Press.

Bradley, G. (Ed.). (1995b). Urban forest landscapes: *Integrating multidisciplinary perspectives*. Seattle, WA: University of Washington Press.

Cadenasso, M.L., Pickett, S.T.A., & Schwarz, K. (2007). Spatial heterogeneity in urban ecosystems: Reconceptualizing land cover and a framework for classification. *Frontiers in Ecology and the Environment, 5*(2), 80-88.

Canmac Economics Limited. (2010). *Economic impact: Burnside business park.* Retrieved February 22, 2011 from http://www.halifax.ca/business_parks/documents/FinalReport_July30_2010.pdf

Carins, R.D., & Lasserre, P. (2004). Reinforcing economic incentives for carbon credits for forests. *Forest Policy and Economics, 6*, 321-328.

Carreiro, M.M. (2008). Introduction: The growth of cities and urban forestry. In M.M. Carreiro, Y.-C. Song, & J. Wu (Eds.), *Ecology, planning, and management of urban forests* (pp. 3-9). New York, NY: Springer Science.

Carreiro, M.M. & Zipperer, W.C. (2008). Urban forestry and the eco-city: Today and tomorrow. In M.M. Carreiro, Y.-C. Song, & J. Wu (Eds.), *Ecology, planning, and management of urban forests* (pp. 435-456). New York, NY: Springer Science.

Carreiro, M.M., Song, Y.-C., & Wu, J. (Eds.). (2008). *Ecology, planning, and management of urban forests – International perspectives.* New York, NY: Springer Science.

Chen, S.S., & Jim, C.Y. (2008). The urban forest management of Nanjing city: Key characteristics and management assessment. In M.M. Carreiro, Y.-C. Song, & J. Wu (Eds.), *Ecology, planning, and management of urban forests* (pp. 259-278). New York, NY: Springer Science.

Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., … & van den Belt, M. (1987). The value of the world's ecosystem services and natural capital. *Nature, 387*(15), 253-260.

Côté, R.P., & Smolenaars, T. (1997). Supporting pillars for industrial ecosystems. *Journal of Cleaner Production, 5*(1-2), 67-74.

Dalhousie University. (2001). *Industrial parks and climate change with a case study of Debert, Nova Scotia.* Retrieved April 15, 2012 from http://sres.management.dal.ca/Files/eco-debert/climatechangefinal.pdf

David Suzuki Foundation. (2008). Credit check: A comparative evaluation of tree-planting and fossil-fuel emission reduction offsets (A David Suzuki Foundation Technical Paper). Retrieved from David Suzuki Foundation: http://www.davidsuzuki.org/publications/downloads/2008/Credit_Check_080701.pdf

Dixon, R.K., Brown, S., Houghton, R.A., Solomon, A.M., Trexler, M.C., & Wisniewski, J. (1994). Carbon pools and flux of global forest ecosystems. *Science, 263*, 185-191.

Duh, J.-D., Shandas, V., Chang, H., & George, L.A. (2008). Rates of urbanization and the resiliency of air and water quality. *Science of the Total Environment, 400*, 238-256

Duinker, P.N. (1981). *Biomass prediction equations for ten tree species in central Nova Scotia.* (Unpublished master's thesis). Dalhousie University, Canada.

Dwyer, J.F., McPherson, E.G., Schroeder, H.W., & Rowntree, R.A. (1992). Assessing the benefits and costs of the urban forest. *Journal of Arboriculture, 15*, 247-252.

Dwyer, J.F., Nowak, D.J., Noble, M.H., & Sisinni, S.M. (2000). Connecting people with ecosystems in the 21st century: An assessment of our nation's urban forests (General Technical Report PNW-GTR-490). Retrieved from United States Forest Service: http://www.treesearch.fs.fed.us/pubs/29448

Dwyer, M.C., & Miller, R.W. (1999). Using GIS to assess urban tree canopy benefits and surrounding greenspace distributions. *Journal of Arboriculture, 25*(2), 102-107.

Ehrenfeld, J., & Gertler, N. (1997). Industrial ecology in practice: The evolution of interdependence at Kalundborg. *Journal of Industrial Ecology, 1*(1), 67-79.

Environment Canada. (2008). *Turning the corner: Canada's offset system for greenhouse gasses*. Retrieved December 8, 2011 from http://www.ec.gc.ca/doc/virage-corner/2008-03/526_eng.htm

Erkman, S. (1997). Industrial ecology: An historical view. *Journal of Cleaner Production, 5*(1-2), 1-10.

European Union Emissions Trading System (EUETS). (2010). Emissions Trading System. Retrieved March 16, 2012 from http://ec.europa.eu/clima/policies/ets/index_en.htm

Ewing, R.H. (2008). Characteristics, causes, and effects of sprawl: A literature review. In Marzluff, J.M., Shulenberger, E., Endlicher, W., Alberti, M., Bradley,G., Ryan, C., … & Simon, U., *Urban ecology: An international perspective on the interaction between humans and nature* (pp. 519-535). New York, NY: Springer Science.

Freedman, B., & Keith, T. (1995). *Planting trees for carbon credits: A discussion of the issues, feasibility, and environmental benefits.* Ottawa, ON: Tree Canada Foundation.

Frumkin, H. (2002). Urban sprawl and public health. *Public Health Reports, 117*(3), 201-217.

Gill, S.E., Handley, J.F., Ennos, A.R., & Pauleit, S. (2007). Adapting cities for climate change: The role of the green infrastructure. *Built Environment, 33*(1), 115-133.

Gouldie, A., & Viles, H.A. (1997). *The earth transformed: An introduction to human impacts on the environment*. Oxford, UK: Blackwell.

Green Matters. (n.d.). Retrieved March 18, 2012 from http://www.greenmattersfredericton.com/en/index.asp

Green Shops. (2010). How to join. Retrieved March 18, 2012 from http://www.greenshopsfredericton.ca/how-to-join

GreenNexxus. (n.d.). The benefits of being a Green Matters Certified organization. Retrieved March 15, 2012 from http://espme.greennexxus.com/gmc/

Grimm, N.B., Faeth, S.H., Golubiewski, N.E., Redman, C.L., Wu, J., Bai, X., & Briggs, J.M. (2008). Global climate change and the ecology of cities. *Science, 319*, 756-560.

Halifax Regional Municipality (HRM). (2010). *Burnside business park*. Retrieved February 22, 2011 from http://www.halifax.ca/business_parks/parks/burnside.html

Heisler, G.M. (1986). Energy savings with trees. *Journal of Arboriculture, 12*(5), 113-125.

Herzog, H., Calderia, K., & Reilly, J. (2003). An issue of permanence: Assessing the effectiveness of temporary carbon storage. *Climatic Change, 59,* 293–310.

Homer, C., Huang, C., Yang, L., Wylie, B., & Coan, M. (2004). Development of a 2001 National land-cover database for the United States. *Photogrammetric Engineering & Remote Sensing*, *70*(7), 829–840.

Hoover, C.M. (2011). Response: Measurement, monitoring, and verification: make it work! *Journal of Forestry, 109,* 475-476.

Houghton, R.A., Schlesinger, W.H., Brown, S., & Richards, J.F. (1985). Carbon dioxide exchange between the atmosphere and terrestrial ecosystems. In J. R. Trabalka (Ed.), *Atmospheric carbon dioxide and the global carbon cycle*, (pp. 114-140). Washington, D.C.: United States Department of Energy.

Husch, B., Miller, C., & Beers, T.W. (1982). *Forest mensuration*. New York, NY: John Wiley & Sons.

Intergovernmental Panel on Climate Change (IPCC). (2005). *IPCC special report on carbon dioxide capture and storage.* London, UK: Cambridge University Press.

Intergovernmental Panel on Climate Change (IPCC). (2007). Climate change 2007: Impacts, adaptation, and vulnerability. In M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, & C.E. Hanson (Eds.), *Fourth assessment report of the Intergovernmental Panel on Climate Change, 2007*. Cambridge, UK: Cambridge University Press.

Intergovernmental Panel on Climate Change (IPCC). (2007a). Climate change 2007: Synthesis report. In R.K. Pachauri & A. Reisinger (Eds.), *Contribution of working groups I, II and III to the fourth assessment report of the Intergovernmental Panel on Climate Change*. Geneva, Switzerland: IPCC.

Intergovernmental Panel on Climate Change (IPCC). (2007b). Climate change 2007: Impacts, adaptation, and vulnerability. In M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, & C.E. Hanson (Eds.), *Fourth assessment report of the Intergovernmental Panel on Climate Change, 2007*. Cambridge, UK: Cambridge University Press.

Intergovernmental Panel on Climate Change (IPCC). (n.d.). Publications and data. Retrieved March 18, 2012 from http://www.ipcc.ch/publications_and_data/publications_and_data_reports.shtml#.T2aVdBx7FNs

Jackson, L.J., Trebitz, A.S., & Kottingham, K.L. (2000). An introduction to the practice of ecological modelling. *BioScience, 50*(8), 694-706.

Jenkins, J.C., Chojnacky, D.C., Heath, L.S., & Birdsey, R.A. (2003). National-scale biomass estimators for United States tree species. *Forest Science, 49*(1), 12–35.

Jenkins, J.C., Chojnacky, D.C., Heath, L.S., Birdsey, R.A., & Richard, A. (2004). Comprehensive database of diameter-based biomass regressions for North tree species (General Technical Report NE-319). Retrieved from United States Forest Service: http://www.uvm.edu/~jcjenkin/jenkins%20et%20al.%202004.pdf

Jo, H.-K. (2002). Impacts of urban greenspace on offsetting carbon emissions for middle Korea. *Journal of Environmental Management, 64,* 115-126.

Jo, H.K., & McPherson, E.G. (1995). Carbon storage and flux in urban residential greenspace. *Journal of Environmental Management, 45*, 109-133.

Johnson, M.P. (2000). Environmental impacts of urban sprawl: A survey of the literature and proposed research agenda. *Environment and Planning, 33*, 717-735.

Kahn, M.E. (2006). *Green cities: Urban growth and the environment.* Washington, DC: Brookings Institution Press.

Keeling, C.D. (1973). Industrial production of carbon dioxide from fossil fuels and limestone. *Tellus, XXV*(2),174-198.

Kirschbaum, M.U.F., & Cowie, A.L. (2004). A practical method to distinguish between human and natural factors in carbon accounting. *Climatic Change*, *67,* 417–436.

Konijnendijk, C.C., Nilsson, K., Randrup, T.B. & Schipperijn, J. (Eds). (2005). *Urban forests and trees*. New York, NY: Springer Science.

Kuo, F. E., & Sullivan, W. C. (2001). Environment and crime in the inner city: Does vegetation reduce crime? *Environment and Behavior, 33*(3), 343-365.

Kurz, W.A., Apps, M., Banfield, E., & Stinson, G. (2002). Forest carbon accounting at the operational scale. *The Forestry Chronicle, 78*(5), 672-679.

Landsberg, J. (2003). Physiology in forest models: History and the future. *Forest Biometry, Modelling and Information Sciences, 1,* 49-63.

LaPaix, R., & Freedman, B. (2010). Vegetation structure and composition within urban parks of Halifax Regional Municipality, Nova Scotia, Canada. *Landscape and Urban Planning, 98,* 124-135.

LeBlanc, A. (1999). Issues related to including forestry-based offsets in a GHG emissions trading system. *Environmental Science & Policy, 2,* 199-206.

Luyssaert, S., Schulze, E.-D., Börner, A., Knohl, A., Hessenmöller, D., Law, B.E., … & Grace, J. (2008). Old-growth forests as global carbon sinks. *Nature, 455*, 213-215.

Maco, S.E., & McPherson, E.G. (2003). A practical approach to assessing structure, function, and value of street tree populations in small communities. *Journal of Arboriculture, 29*(2), 84-97.

McCarl, B.A., & Sands, R.D. (2007). Competitiveness of terrestrial greenhouse gas offsets: are they a bridge to the future? *Climatic Change, 80,* 109–126.

McDonnell, M.J., & Pickett, S.T.A. (1990). The study of ecosystem structure and function along urban-rural gradients: An unexploited opportunity for ecology. *Ecology, 71,* 1231–1237.

McDonnell, M.J., Pickett, S.T.A., Groffman, P., Pouyat, R.V., Zipperer, W.C., Parmelee, R.W. … & Medley, K. (2008). Ecosystem processes along an urban-to-rural gradient. In J.M. Marzluff, E. Shulenberger, W. Endlicher, M. Alberti, G. Bradley… & U. Simon (Eds.), *Urban ecology - An international perspective on the interaction between humans and nature* (pp. 299-313). New York, NY: Springer Science.

McHale, M.R, Burke, I.C., Lefsky, M.A., Peper, P.J., & McPherson, E.G. (2009). Urban forest biomass estimates: Is it important to use allometric relationships developed specifically for urban trees? *Urban Ecosystems, 12*, 95-113.

McHale, M.R., McPherson, E.G., & Burke, I.C. (2007). The potential of urban tree plantings to be cost effective in carbon credit markets. *Urban Forestry & Urban Greening, 6,* 49-60.

McKinney, M.L. (2002). Urbanization, biodiversity, and conservation. *BioScience, 52*(10), 883-890.

McPherson, E.G. (1993). Evaluating the cost effectiveness of shade trees for demand-side management. *The Electricity Journal, 6*(9), 57-65.

McPherson, E.G. (1998). Atmospheric carbon dioxide reduction by Sacramento's urban forest. *Journal of Arboriculture, 24*(4), 215-223.

McPherson, E.G., & Muchnick, J. (2005). Effects of street tree shade on asphalt concrete pavement performance. *Journal of Arboriculture, 31*(6), 303-310.

McPherson, E.G., & Simpson, J.R. (1999). Carbon dioxide reduction through urban forestry: Guidelines for professional and volunteer tree planters. (General Technical Report PSW-GTR-171). Retrieved from United States Department of Agriculture, Forest Service: http://www.treesearch.fs.fed.us/pubs/6779

McPherson, E.G., & Simpson, J.R. (1999). Carbon dioxide reduction through urban forestry: Guidelines for professional and volunteer tree planters. (General Technical Report PSW-GTR-171). Retrieved from United States Forest Service:http://www.treesearch.fs.fed.us/pubs/6779

McPherson, E.G., Nowak, D.J., & Rowntree, R.A. (Eds.). (1994). Chicago's urban forest ecosystem: Results of the Chicago urban forest climate project. (General Technical Report NE-186). Retrieved from United States Forest Service: http://www.treesearch.fs.fed.us/pubs/4285

McPherson, E.G., Nowak, D.J., Heisler, G., Grimmond, S., Souch, C., Grant, R., & Rowntree, R.A. (1997). Quantifying urban forest structure, function, and value: The Chicago Urban Forest Climate Project. *Urban Ecosystems, 1*, 49–61.

McPherson, E.G., Rowntree, R.A., & Wagar, J.A. (1995). Energy-efficient landscapes. In G. Bradley (Ed.), *Urban forest landscapes: Integrating multidisciplinary perspectives* (pp. 150-160). Seattle, WA: University of Washington Press.

McPherson, E.G., Simpson, J., Marconett, D., Peper, P., & Aguaron, E. (2010). *Urban forests and climate change.* Retrieved May 9, 2011 from http://www.fs.fed.us/ccrc/topics/urban-forests/

McPherson, E.G., Simpson, J.R., Peper, P.J., Gardner, S.L., Vargas, K.E., & Xiao, Q. (2007). Northeast community tree guide: Benefits, costs, and strategic planting (General Technical Report PSW-GTR-202). Retrieved from United States Forest Service: http://www.treesearch.fs.fed.us/pubs/28759

National Aeronautics and Space Administration (NASA). (2011). *NASA's Terra satellite refines map of global land cover.* Retrieved April 29, 2011 from http://earthobservatory.nasa.gov/Newsroom/view.php?id=22585

Natural Resources Canada (NRCan). (2009). *The atlas of Canada – Land cover.* Retrieved April 29, 2011 from http://atlas.nrcan.gc.ca/site/english/maps/environment/land/landcover/1

Nieder, R., & Benbi, D.K. (2008). Carbon and nitrogen pools in terrestrial ecosystems. In R., Nieder, & D.K. Benbi (Eds.), *Carbon and nitrogen in the terrestrial environment* (pp. 5-43). New York, NY: Springer.

Nowak, D.J. (1993). Atmospheric carbon reduction by urban trees. *Journal of Environmental Management, 37*, 207-217.

Nowak, D.J. (1994). Atmospheric carbon dioxide reduction by Chicago's urban forest. In E.G. McPherson, D.J. Nowak, & R.A. Rowntree (Eds.), *Chicago's urban forest ecosystem: Results of the Chicago urban forest climate project* (pp. 83-94) (General Technical Report NE-186). Retrieved from United States Forest Service: http://www.treesearch.fs.fed.us/pubs/4285

Nowak, D.J. (1994a). Understanding the structure of urban forests. *Journal of Forestry, 92,* 42–46.

Nowak, D.J. (1994b). Atmospheric carbon dioxide reduction by Chicago's urban forest. In E.G. McPherson, D.J. Nowak, & R.A. Rowntree (Eds.), *Chicago's urban forest ecosystem: Results of the Chicago urban forest climate project* (pp. 83-94) (General Technical Report NE-186). Retrieved from United States Forest Service: http://www.treesearch.fs.fed.us/pubs/4285

Nowak, D.J. (1994c). Air pollution removal by Chicago's urban forest. In E.G. McPherson, D.J. Nowak, & R.A. Rowntree (Eds.), C*hicago's urban forest ecosystem: Results of the Chicago urban forest climate project* (pp. 63-81) (General Technical Report NE-186). Retrieved from United States Forest Service: http://www.treesearch.fs.fed.us/pubs/4285

Nowak, D.J. (2006). Institutionalizing urban forestry as a "biotechnology" to improve environmental quality. *Urban Forestry & Urban Greening, 5*, 93-100.

Nowak, D.J., & Crane, D.E. (2000). The urban forest effects (UFORE) model: Quantifying urban forest structure and functions. In M. Hansen, & T. Burk (Eds.), *Proceedings: Integrated Tools for Natural Resources Inventories in the 21st Century* (pp. 714-720). St. Paul, MN: United States Forest Service.

Nowak, D.J., & Crane, D.E. (2002). Carbon storage and sequestration by urban trees in the USA. *Environmental Pollution, 116*(3), 381-389.

Nowak, D.J., & Dwyer, J.F. (2007). Understanding the benefits and costs of urban forest ecosystems. In J.E. Kuser (Ed.), *Urban and community forestry in the northeast (2nd ed.)* (pp. 25-46). New York, NY: Springer Science.

Nowak, D.J., & Miller, R.W. (2008). Assessing urban forest structure: Introduction. *Arboriculture & Urban Forestry, 34*(6), 333.

Nowak, D.J., & Walton, J.T. (2005). Projected urban growth (2000-2050) and its estimated impact on the US forest resource. *Journal of Forestry, December*, 383-389.

Nowak, D.J., Crane, D.E., & Stevens, J.C. (2006). Air pollution removal by urban trees and shrubs in the United States. *Urban Forestry & Urban Greening, 4*, 115-123.

Nowak, D.J., Crane, D.E., Stevens, J.C., & Ibarra, M. (2002). Brooklyn's urban forest. (General Technical Report NE-290). Retrieved from United States Department of Agriculture, Forest Service: http://www.fs.fed.us/ne/newtown_square/publications/technical_reports/pdfs/2002/gtrne290.pdf

Nowak, D.J., Crane, D.E., Stevens, J.C., Hoehen, R.E., Walton, J.T., & Bond, J. (2008). A ground-based method of assessing urban forest structure and ecosystem services. *Arboriculture and Urban Forestry, 34*(6), 347-358.

Nowak, D.J., Kuroda, M., & Crane, D.E. (2004). Tree mortality rates and tree population projections in Baltimore, Maryland, USA. *Urban Forestry & Urban Greening, 2*, 139-147.

Nowak, D.J., McBride, J.R., & Beatty, R.A. (1990). Newly planted street tree growth and mortality. *Journal of Arboriculture, 16*(5), 124-129.

Nowak, D.J., Rowntree, R.A., McPherson, E.G., Sisinni, S.M., Kerkmann, E.R., & Stevens, J.C. (1996). Measuring and analyzing urban tree cover. *Landscape and Urban Planning, 36*, 49-57.

Nowak, D.J., Stevens, J.C., Sisinni, S.M., & Luley, C.J. (2002). Effects of urban tree management and species selection on atmospheric carbon dioxide. *Journal of Arboriculture, 28*(3), 113-122.

Oke, T.R. 1995. The heat island of the urban boundary layer: Characteristics, causes and effects. In J.E. Cermak (Ed.), *Wind climate in cities* (pp. 81–107). Netherlands: Kluwer Academic Publishers.

Ordóñez, C., & Duinker, P.N. (2010). Interpreting sustainability for urban forests. *Sustainability, 2*, 1510-1522.

Ovington, J.D. (1957). The volatile matter, organic carbon and nitrogen contents of tree species grown in close stands. *The New Physiologist, 56*, 1-11.

Pacific Carbon Trust (PCT). (2012). Protocol for the creation of forest carbon offsets in British Columbia. Retrieved February 18, 2012 from http://www.env.gov.bc.ca/cas/mitigation/pdfs/Forest_Carbon_Offset_Protocol_v1_0_Web.pdf

Pataki, D.E., Alig, R.J., Fung, A.S., Golubiewski, N.E., Kennedy, C.A., McPherson, E.G., … & Lankao, P.R. (2006). Urban ecosystems and the North American carbon cycle. *Global Change Biology, 12*(11), 2092–2102.

Pauleit, S., & Duhme, F. (2000). GIS assessment of Munich's urban forest structure for urban planning. *Journal of Arboriculture, 26*(3), 133-141.

Peckham, S. (2010). *Nature in the city: Ecological consciousness development associated with naturalized urban spaces and urban forest values in Calgary, AB and Halifax, NS* (Unpublished master's thesis). Dalhousie University, Canada.

Pickett, S.T.A., & Cadenasso, M.L. (2008). Linking ecological and built components of urban mosaics: An open cycle of ecological design. *Journal of Ecology, 96*, 8-12.

Pickett, S.T.A., Cadenasso, M.L., Grove, J.M., Boone, C.G., Groffman, P.M., Irwin, E., … & Warren, P. (2011). Urban ecological systems: Scientific foundations and a decade of progress. *Journal of Environmental Management, 92*, 331-362.

Poudyal, N.C., Siry, J., & Bowker, J.M. (2010). Urban forests' potential to supply marketable carbon emission offsets: A survey of municipal governments in the United States. *Forest Policy and Economics, 12,* 432–438 .

Poudyal, N.C., Siry, J., & Bowker, J.M. (2011a). Urban forests and carbon markets: Buyers' perspectives. *Journal of Forestry, 109*(7), 378-385.

Poudyal, N.C., Siry, J., & Bowker, J.M. (2011b). Quality of urban forest carbon credits. *Urban Forestry & Urban Greening, 10*, 223-230.

Pregitzer, K.S, & Euskirchen, E.S. (2004). Carbon cycling and storage in world forests: Biome patterns related to forest age. *Global Change Biology, 10*, 2052–2077.

Raedeke, D.A.M., & Raedeke, K.J. (1995). Wildlife habitat design in urban forest landscapes. In G. Bradley (Ed.), *Urban forest landscapes: Integrating multidisciplinary perspectives* (pp. 139-149). Seattle, WA: University of Washington Press.

Randrup, T.B., Konijnendijk, C., Dobbertin, M.K., & Prüller, R. (2005). The concept of urban forestry in Europe. In C. Konijnendijk, K. Nilsson, T.B. Randrup, & J. Schipperijn (Eds.), *Urban forests and trees* (pp. 9-21). New York, NY: Springer Science.

Reichle, D.E., Dinger, B.E., Edwards, N.T., Harrits, W.F, & Sollins, P. (1973). Carbon f low and storage in a forest ecosystem. In G.M. Woodwell, & E.V. Pecans (Eds.), *Carbon and the Biosphere – Proceedings of the 24th Brookhaven Symposium in Biology* (pp. 345-365)1973 May 16-18. Upton, NY: US Atomic Energy Commission.

Richards, N. (1993). Reasonable guidelines for street tree diversity. *Journal of Arboriculture, 19*(6), 344-350.

Richards, N.A. (1979). Modeling survival and consequent replacement needs in a street tree population. *Journal of Arboriculture, 5*(11), 251-255.

Ristea, C., & Maness, T.C. (2009). Opportunities, challenges and markets for forest carbon offset projects. *The Forestry Chronicle 85(5)*, 715-718.

Ristea, C., Maness, T. C. (2009). Opportunities, challenges and markets for forest carbon offset projects. *The Forestry Chronicle 85(5)*, 715-718.

Rostami, M. (2011). *Tree species selection for the Halifax urban forest under a changing climate*. (Unpublished master's thesis). Dalhousie University, Canada.

Rowntree, R.A. (1984). Ecology of the urban forest: Introduction to part I. *Urban Ecology, 8*, 1-11.

Rowntree, R.A. (1986). Ecology of the urban forest: Introduction to part II. *Urban Ecology, 9*, 229-243.

Rowntree, R.A., & Nowak, D.J. (1991). Quantifying the role of urban forests in removing atmospheric carbon dioxide. *Journal of Arboriculture, 17*(10), 269-275.

Sanders, R.A. (1984). Some determinants of urban forest structure. *Urban Ecology, 8*(1-2), 13-27.

Satterthwaite, D. (2010). Solutions the contribution of cities to global warming and their potential contributions to solutions. *Environment and Urbanization Asia, 1*(1), 1-12.

Schroeder, H.W., & Green, T.L. (1985). Public preference for tree density in municipal parks. *Journal of Arboriculture, 11*(9), 272-277.

Sedjo,R. & Macauley, M. (2011). Forest carbon offsets: Possibilities and limitations. *Journal of Forestry, 109,* 470-473.

Sieghardt, M., Mursch-Radlgruber, E., Paoletti, E., Couenberg, E., Dimitrakopoulus, A., Rego, F., … & Randrup, T.B. (2005). The abiotic urban environment - Impact of urban growing conditions on urban vegetation. In C.C. Konijnendijk, K. Nilsson, T.B. Randrup, & J. Schipperijn (Eds.), *Urban forests and trees* (pp. 281-323). New York, NY: Springer.

Sierra Club. (1998). *Sprawl: The dark side of the American dream*. Retrieved April 28, 2011 from http://www.sierraclub.org/sprawl/report98/

Simpson, J.R. (2002). Improved estimates of tree-shade effects on residential energy use. *Energy and Buildings, 34*, 1067-1076.

Sovacool, B.K. (2011). The policy challenges of tradable credits: A critical review of eight markets. *Energy Policy, 39*, 575-585.

Spurr, S.H., & Barnes, B.V. (1980). *Forest ecology.* New York, NY: Ronald Press Company.

Squires, G.D. (Ed.). (2002). Urban sprawl and the uneven development of metropolitan America. In G.D. Squires (Ed.), *Urban sprawl: Causes, consequences and policy responses* (pp. 1-22). Washington, DC: The Urban Institute Press.

Starfield, A.M. (1997). A pragmatic approach to modeling for wildlife management. *The Journal of Wildlife Management, 61*(2), 261-270.

Statistics Canada. (2007). *Urban area (UA)*. Retrieved April 13, 2011 from http://www12.statcan.ca/census-recensement/2006/ref/dict/geo049-eng.cfm

Statistics Canada. (2009). *Population, urban and rural, by province and territory (Canada).* Retrieved April 14, 2011 from http://www40.statcan.ca/l01/cst01/demo62a-eng.htm

Sundquist, E.T., Ackerman, K.V., Parker, L., & Huntzinger, D.N. (2009). An introduction to global carbon cycle management. In B.J. McPherson & E.T. Sundquist (Eds.), *Carbon sequestration and its role in the global carbon cycle* (pp. 1-23). Washington, DC: American Geophysical Union.

Tello, M.-L., Tomalak, M., Siwecki, R., Gáper, J., Motta, E., & Mateo-Sagasta, E. (2005). Biotic urban growing conditions – Threats, pests and diseases. In C.C. Konijnendijk, K. Nilsson, T.B. Randrup, & J. Schipperijn (Eds) *Trees*, (pp. 325-365). New York, NY: Springer.

Ter-Mikaelian, M.T., Korzukhin, M.D. 1997. Biomass equations for sixty-five North American tree species. *Forest Ecology and Management, 97*, 1-24.

Tisdale, H. (1942). The process of urbanization. *Social Forces, 20*(3), 311-316.

Tree Canada. (2009). Tree Canada forest and urban tree carbon project protocol. A standard for the eligibility and measurement of Tree Canada carbon offset projects. Retrieved from Tree Canada: http://www.treecanada.ca/site/resources/pages/files/Carbon%20Protocol%20English.pdf

Tsihrintzis, V.A., & Hamid, R. (1997). Modeling and management of urban stormwater runoff quality: A review. *Water Resources Management, 11*, 137–164.

Tyrväinen, L., & Miettinen, A. (2000). Property prices and urban forest amenities. *Journal of Environmental Economics and Management, 39***,** 205-223.

Ulrich, R.S. (1984). View through a window may influence recovery from surgery. *Science, 224*, 420-421.

United Nations Climate Change Conference (UNCCC). (2007). *Uniting on climate change*. Retrieved April 13, 2011 from http://unfccc.int/resource/docs/publications/unitingonclimate_eng.pdf

United Nations Framework Convention on Climate Change (UNFCCC). (n.d.). *Feeling the heat.* Retrieved April 14, 2011 from http://unfccc.int/essential_background/feeling_the_heat/items/2918.php

United Nations Framework Convention on Climate Change (UNFCCC). (2011). Clean Development Mechanism methodology booklet. Retrieved February 18, 2012 from http://cdm.unfccc.int/methodologies/documentation/meth_booklet.pdf#AR-AMS0006

United Nations-Habitat (UN-Habitat). (2009). *Planning sustainable cities: Global report on human settlements 2009*. Sterling, VA: Earthscan.

United States Department of Agriculture, Forest Service (USDA Forest Service). (2004). The large tree argument: The case for large-stature trees vs. small-stature trees. Retrieved from http://www.fs.fed.us/psw/programs/uesd/uep/products/cufr_511_large_tree_argument.pdf

United States Government Accountability Office (USGAO). (2008). Carbon offsets: The U.S. voluntary market is growing, but quality assurance poses challenges for market participants. (Report to Congressional Requestors GAO-08-1048). Retrieved from U.S. Government Accountability Office: http://www.gao.gov/products/GAO-08-1048

Vanclay, J.K. (2003). Realizing opportunities in forest growth modeling. *Canadian Journal of Forest Research, 33,* 536–541.

VanMetre, P.C., Mahler, B.J., & Furlong, E.T. (2000). Urban sprawl leaves its PAH signature. *Environmental Science and Technology, 34*(4), 4064-4070.

Vitousek, P.M., Mooney, H.A., Lubchenco, J., & Melillo, J.M. (1997). Human domination of Earth's ecosystems. *Science, 277*, 494-499.

Watson, R.T., Noble, I.R., Bolin, B., Ravindranath, N.H., Verardo, D.J., & Dokken, D.J. (Eds.). (2000). *Land-use, land-use change and forestry: A special report of the Intergovernmental Panel on Climate Change.* Cambridge, UK: Cambridge University Press.

Western Climate Initiative (WCI). (2010). Offset system essential elements final recommendations paper. Retrieved from Western Climate Initiative: http://www.westernclimateinitiative.org/component/remository/Offsets-Committee-Documents/Offset-Criteria-Draft-Recommendations/

White, T., Luckai, N., Larocque, G.R., Kurz, W.A., & Smyth, C. (2008). A practical approach for assessing the sensitivity of the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3). *Ecological Modelling, 219*, 373-382.

Wolf, K.L. (2003). Public response to the urban forest in inner-city business districts. *Journal of Arboriculture, 29*(3), 117-126.

Wright, R.A., Côté , R.P., Duffy, J., & Brazner, J. (2009). Diversity and connectance in an industrial context: The case of Burnside Industrial Park. *Journal of Industrial Ecology, 13*(4), 551-564.

Yang, J., McBride, J., Zhoub, J., & Sun, Z. (2005). The urban forest in Beijing and its role in air pollution reduction. *Urban Forestry & Urban Greening, 3*, 65–78.

Yemshanov, D., Biggs, J., McKenney, D.W., & Lempriere, T. (2012). Effects of permanence requirements on afforestation choices for carbon sequestration for Ontario, Canada*. Forest Policy and Economics, 14*, 6–18.

Yemshanov, D., McKenney, D., Fraligh, S., & D'Eon, S. (2007). An integrated spatial assessment of the investment potential of three species in southern Ontario, Canada inclusive of carbon benefits. *Forest Policy and Economics 10,* 48-59.

Yue, G. (2010). *Mapping traditional bird knowledge for urban bird conservation in Halifax, Nova Scotia, Canada* (Unpublished master's thesis). Dalhousie University, Canada.

Zipperer, W.C., Sisinni, S.M., Pouyat, R.V., & Foresman, T.W. (1997). Urban tree cover: An ecological perspective. *Urban Ecosystems, 1*, 229-246.

APPENDIX 1: COMPILATION OF OPERATIONAL DATA WITHIN THE BURNSIDE INDUSTRIAL PARK URBAN FOREST CARBON MODEL

Figure 1: Aerial photograph of the study site, Burnside Industrial Park (latitude 44.7, longitude -63.6) (Image copyright Microsoft Bing ®)

Table 1 (1 of 2): Land cover classification criteria used during photointerpretation

Land cover class	Description
Grey	The grey land-cover class represents land currently occupied or otherwise not intended to accommodate present or future urban tree growth. Grey land-cover contains below approximately 25% vegetative cover, frequently consisting of 0% vegetative cover. Examples of grey land-cover features include permanent infrastructures, such as buildings, parking lots, transportation corridors (including roads and railroads), sidewalks, concrete boulevards, as well as storage areas, recreational fields, and hydrological features (e.g. lakes, rivers, ponds). Special additions to this class include grassed medians located within road intersections, as well as the entire property belonging to the Nova Scotia East Coast Forensic Hospital and Correctional Facility. It is not reasonable to expect trees to be accommodated by these sites as trees have been removed purposefully to mitigate safety concerns.
Brown	The brown land-cover class represents land with potential to accommodate tree growth upon site amendment. Brown land-cover contains below approximately 75% vegetative cover, and typically consists of herbaceous annuals and perennials, and small woody shrubs. Trees are rarely present, if at all. Brown land-cover appears to be idle or not utilized for a specific purpose. Features indicating brown land-cover include large areas of exposed bare soil or gravel, and chlorotic/browning tendency of existing vegetation. As there is much ambiguity associated with the definition of Brown land-cover, this land-cover class is highly subjective and dependant on the photo-interpreter's perception of Brown land-cover.
Construct	The construction land-cover class represents all land exhibiting evidence of recent construction or development activities. Construction land-cover contains below approximately 25% vegetative cover. Often, this land-cover class consists entirely of bare soil or gravel. Much of the construction land-cover found with BIP is located adjacent to currently forested areas, because new development within BIP encroaches on this type of land. Examples of evidence suggesting construction activity include presence of poured foundations, semi-constructed roads (or other types of permanent infrastructure), and the presence of large construction equipment (e.g. dump trucks, cranes). Forest fragments existing as islands within construction land-cover classes below approximately 0.35 ha are included within this land class, as it is not expected they will remain intact upon completed development. Similar to the Brown land-cover class, there too is much ambiguity associated with the definition of Construction land-cover, therefore rendering this land-cover class highly reliant on the photo-interpreter's perception of Construction land-cover.

Table 1 (2 of 2): Land cover classification criteria used during photointerpretation

Land cover class	Description
Disturbed Green	The disturbed green land-cover class represents land currently accommodating or able to immediately accommodate future urban tree growth upon little to no site amendment. Disturbed green land-cover contains above approximately 75% vegetative cover, and includes herbaceous and woody plant materials. Examples of Disturbed Green land-cover include lawns, meadows, grassed boulevards and medians (with the exception of those located within road intersections – see section (1) Grey). Areas adjacent to transportation corridors and recreational fields with potential to easily accommodate urban tree growth are also found within this land-cover class. Deciphering among vegetative cover types (e.g. woody vs. herbaceous cover, height of vegetation) presents a major challenge for any photo interpreter. It is for this reason that disturbed green land-cover can be difficult to classify, and as such, is subject to the photo interpreter's perception of what land is decidedly Disturbed Green.
Undisturbed Green	The Undisturbed Green land-cover class represents land currently accommodating tree growth primarily within a naturalized or forested state. Undisturbed Green land-cover contains above approximately 75% vegetative cover, primarily that of dense, woody plant growth. Examples of Undisturbed Green land-cover include contiguous forest patches, and areas of high-density trees where additional tree planting does not seem practical. Features such as rivers, streams, footpaths, small roads, utility corridors are also included in this land-class. Deciphering among vegetative cover types (e.g. woody vs. herbaceous cover, height of vegetation) presents a major challenge for determining what land belongs to this land-cover class. It is for this reason that Undisturbed Green land-cover can be difficult to classify, and is subject to the photo interpreter's personal judgment.

Figure 2: Land cover classification map of Burnside Industrial Park

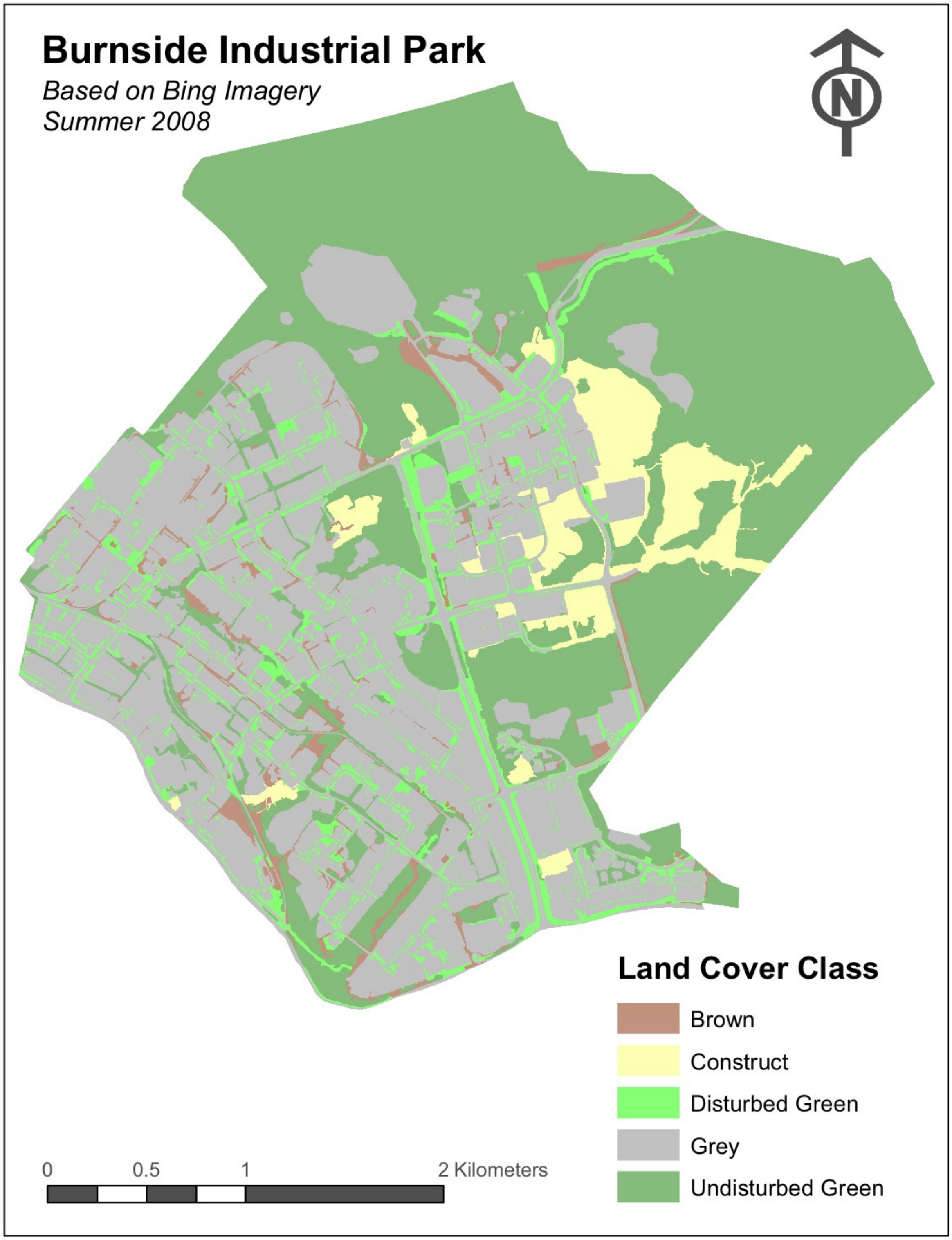


Table 2: Summary of land cover classification results derived from land cover map

Land cover class	Total polygons (#)	Smallest polygon (ha)	Largest polygon (ha)	Average (ha)	Sum (ha)	Percent total coverage (%)
Grey	24	0.002	510	22.0	526	41.5
Brown	181	0.001	1.8	0.18	32	2.5
Construct	16	0.2	43.5	4.6	73.0	5.8
Disturbed Green	1159	0.0005	4.2	0.076	87.6	6.9
Undisturbed Green	121	0.01	217	4.5	550	43.4

Table 3: Summary land ownership within BIP

Land ownership	Total polygons (#)	Smallest polygon (ha)	Largest polygon (ha)	Average (ha)	Sum (ha)	Percent total coverage (%)
HRM	192	0.0005	173	3.3	643	50.7
Provincial	11	0.06	27.0	4.9	54.2	4.3
Federal	22	0.06	6.5	0.6	13.7	1.1
Private	671	0.0000001	9.8	0.8	557	43.9

Table 4: Summary of urban forest development scenarios

Scenario	Description	Addition to 2010 population
1	Maintenance of 2010 population (4, 785)	4,785 + 0
2	Maintenance of population + 50% of all vacancies	4,785 + 44,108
3	Maintenance of population + 100% of all vacancies	4,785 + 82,215

Figure 3: Converting dbh class to represent age structure of the 2010 BIP urban forest.

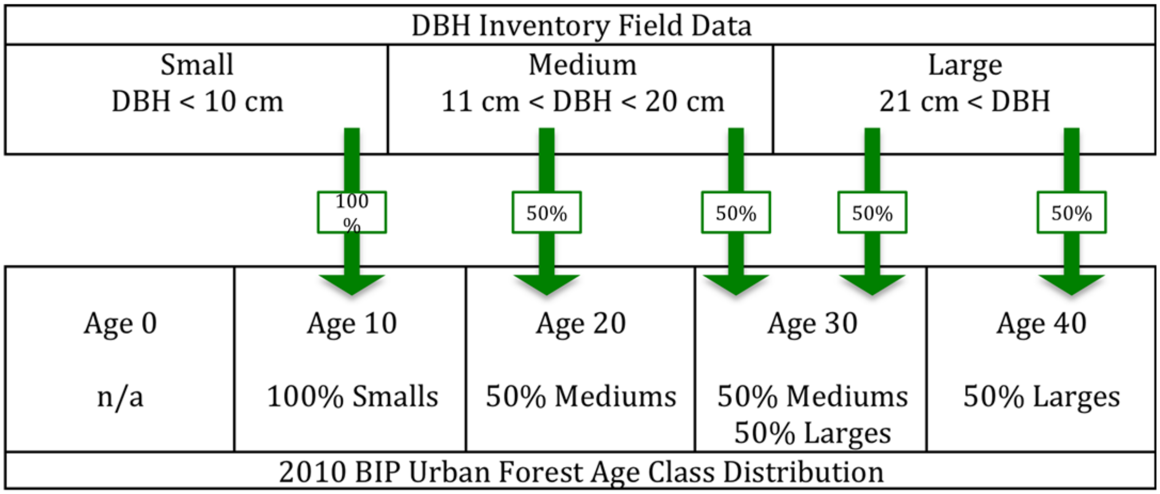


Table 5: Inventory data for species identification and dbh estimation within the 2010 (i.e. current) Burnside Industrial Park urban forest (within Disturbed Green land cover class only; proportional estimate not applied)

	Botanical name	**dbh class**			**Sum of trees inventoried, by species**
		Small dbh<10cm	Medium 11cm<dbh<20cm	Large 21cm<dbh	
1	*Acer campestre*	8	0	0	8
2	*Acer platanoides*	9	28	91	128
3	*Acer rubrum*	11	9	13	33
4	*Acer saccharinum*	3	3	4	10
5	*Acer saccharum*	11	4	0	15
6	*Aesculus hippocastanum*	0	0	1	1
7	*Amelanchier canadensis*	13	3	0	16
8	*Betula papyrifera*	0	0	0	0
9	*Betula pendula*	5	18	25	48
10	*Fagus grandifolia*	1	0	0	1
11	*Fagus sylvatica*	0	1	2	3
12	*Fraxinus nigra*	5	0	3	8
13	*Gleditsia triacanthos*	5	0	3	8
14	*Juniperus scopulorum*	3	0	0	3
15	*Malus spp.*	5	1	1	7
16	*Picea abies*	0	0	5	5
17	*Picea pungens*	0	0	0	0
18	*Picea rubens*	0	0	8	8
19	*Pinus banksiana*	0	0	2	2
20	*Pinus sylvestris*	0	5	0	5
21	*Populus tremuloides*	0	3	6	9
22	*Pyrus calleryana*	0	0	0	0
23	*Quercus rubra*	0	1	7	8

Table 5, continued (2 of 2)

	Botanical name	dbh class			Sum of trees inventoried, by species
		Small dbh<10cm	Medium 11cm<dbh<20cm	Large 21cm<dbh	
24	*Salix nigra*	0	0	0	0
25	*Sorbus aucuparia*	0	1	2	3
26	*Syringa reticulata*	2	6	3	11
27	*Thuja occidentalis*	8	1	5	14
28	*Tilia americana*	0	0	1	1
29	*Ulmus americana*	6	8	0	14
30	*Zelkova serrata*	13	0	0	13
			Sum of trees inventoried		**417**

Table 6: Estimated species composition and dbh distribution of 2010 Burnside Industrial Park urban forest (proportional estimate applied)

	Botanical name	**dbh class**			**Sum of each species**
		Small dbh<10cm	Medium 11cm<dbh<20cm	Large 21cm<dbh	
1	*Acer campestre*	92	0	0	92
2	*Acer platanoides*	103	321	1044	1469
3	*Acer rubrum*	126	103	149	379
4	*Acer saccharinum*	34	34	46	115
5	*Acer saccharum*	126	46	0	172
6	*Aesculus hippocastanum*	0	0	11	11
7	*Amelanchier canadensis*	149	34	0	184
8	*Betula papyrifera*	57	207	287	551
9	*Betula pendula*	11	0	0	11
10	*Fagus grandifolia*	0	11	23	34
11	*Fagus sylvatica*	57	0	34	92
12	*Fraxinus nigra*	57	0	34	92
13	*Gleditsia triacanthos*	34	0	0	34
14	*Juniperus scopulorum*	57	11	11	80
15	*Malus spp.*	0	0	57	57
16	*Picea abies*	0	0	92	92
17	*Picea pungens*	0	0	23	23
18	*Picea rubens*	0	57	0	57
19	*Pinus banksiana*	0	34	69	103
20	*Pinus sylvestris*	0	11	80	92
21	*Populus tremuloides*	0	11	23	34
22	*Pyrus calleryana*	23	69	34	126
23	*Quercus rubra*	92	11	57	161
24	*Salix nigra*	0	0	11	11

Table 6, continued (2 of 2)

	Botanical name	**dbh class**			**Sum of each species**
		Small dbh<10cm	Medium 11cm<dbh<20cm	Large 21cm<dbh	
25	*Sorbus aucuparia*	69	92	0	161
26	*Syringa reticulata*	149	0	0	149
27	*Thuja occidentalis*	34	57	0	92
28	*Tilia americana*	34	69	149	252
29	*Ulmus americana*	0	0	11	11
30	*Zelkova serrata*	46	0	0	46
			Sum of trees inventoried		**417**

Table 7: Summary of operational assumptions and parameters of the Burnside Industrial Park urban forest carbon model (1 of 4)

Characteristic	Unit	Value	Rationale and/or method
Area available for tree planting (Disturbed Green land cover only)	ha	87	Classified land cover of BIP via digitization of aerial photograph. Original estimate was 87.6 ha; rounded down to 87 to preserve a conservative estimate.
Current tree density estimate	trees/ha	55	Field inventory: Counted 355 trees within 6.5 ha of Disturbed Green polygons. *Calculation:* Current urban tree density = total trees/total area; 355 trees/6.5 ha = 55 trees/ha
2010 BIP urban forest total population estimate	total trees	4,785	Proportional estimate based on estimated current tree density. *Calculation:* Estimated density * available planting area; 55 trees/ha * 87 ha = 4,785 trees
Desired tree density	trees/ha	1,000	Walsh/Duinker decision; allocates each tree approximately three square metres for growth
Desired tree population	total trees	87,000	*Calculation:* Desired density * available planting area; 1000 trees/ha * 87 ha = 87,000 trees
Current vacant planting spots	total spots	82,215	*Calculation:* Desired population – current population estimate; 87,000 – 4,785 = 82,215
Trees inventoried for dbh and species composition of 2010 urban forest	total trees	417	Recorded species and dbh category (small, medium, or large) of 417 trees within 124 ha (approximately 10% of BIP) of Disturbed Green polygons.
Scenario 1	total trees	-	Maintain 2010 urban forest population of 4,785 by replacing mortalities.
Scenario 2	total trees	41,108	Maintain 2010 population and introduce 50% of all identified vacant planting spots. ✓ All natalities are introduced in year 2020 as “Age 0” trees ✓ Evenly distributed natalities among desirable species list

			(See Table 12) *Calculation:* 0.5[current vacancies(82215)]

Table 7, continued (2 of 4)

Characteristic	Unit	Value	Rationale and/or method
Scenario 3	total trees	82,215	Maintain 2010 population and introduce 50% of all identified vacant planting spots. ✓ All trees introduced in year 2020 in “Age 0” category ✓ Evenly distributed natalities among desirable species list (See Table 12) *Calculation:* Equal to current vacancies (82215)
All scenarios are initiated using the 2010 BIP urban forest conditions	density, population, area	-	From a practical standpoint, all scenarios of urban forest development commence with the same initial urban forest structure.
Newly planted trees have “zero biomass”	kg or t	0	Walsh/Duinker decision
All natalities are initiated within “Age 0” category	age (years)	0	Walsh/Duinker decision
All newly planted trees are evenly distributed among desirable species	species	-	Desirable species are all native to the Acadian forest region; fifteen species were selected (see Table 12)
All mortalities are replaced	species	-	The sum total of decadal mortalities are divied evenly among the fifteen desirable species (see Table 12), and are introduced into the model as “Age 0”.
Model operates in ten year time steps	years	-	Appropriate and commonly used time-step for aging forests within a carbon model
Trees in model exist only in ages of multiples of ten	years	-	Practicality; simplicity for comprehension; in conjunction with ten-year time steps of simulated forest growth within the model.
All trees are assumed to be in “good” condition; implications of climate change, competition, and other environmental factors omitted from model	-	-	The goal of this model is to provide a simplified initial estimate of C sequestration and storage potentials within the identified urban forest development scenarios. Endless factors influencing this potential could be incorporated, but have been omitted for the

			purpose of achieving the objectives of this research.
Within the 2010 (i.e. initial) urban forest, no tree is greater than forty years old	years (age)	0, 10, 20, 30, or 40	Development of BIP began approximately 40 years ago, is therefore assumed that no trees older than forty years are found within the Disturbed Green (i.e. developed) portion of BIP.

Table 7, continued (3 of 4)

Characteristic	Unit	Value	Rationale and/or method
Carbon release via decomposition is not accounted for	-	-	The goal of this model is to provide a simplified initial estimate of C sequestration and storage potentials within the identified urban forest development scenarios. Endless factors influencing this potential could be incorporated, and as such, C implications related to decomposition of urban tree mortalities are omitted from this model. Additionally, it C stored as biomass is not immediately re-released into the atmosphere as CO_2, as decomposition is a biological process that occurs over time.
Area available for tree planting within BIP remains static through time	ha	87	There are multiple many variables and uncertainties associated with future development scenarios of the BIP landscape, therefore the model assumes land composition of BIP remains static through time.
Biomass calculations account for above-ground biomass, including foliage	kg or t	-	Approximately 20% of a tree's biomass is below ground. Omitting below-ground dry weight biomass estimates from C sequestration and storage potentials helps ensure a conservative per-tree biomass (and therefore C) estimate.
Tree growth rate	cm/decade	various	Derived from literature and Rostami's (2011) database; Walsh/Duinker executive decision was applied when other venues yielded no results. See Table 9.
Tree longevity	years	various	Derived from literature and Rostami's (2011) database; Walsh/Duinker decision was applied when other venues yielded no results. When range was given within the chosen source, the average of high and low values was used. See Table 8.
Species-specific biomass equations	allometric	various	All equations are derived from rural forest based data because of

	biomass equations		the lack of research and availability of biomass equations specific for urban trees (see McHale et al., 2009 for further discussion of biomass equation issues). See Table 11.

Table 7, continued (4 of 4)

Characteristic	Unit	Value	Rationale and/or method
Tree mortality	trees/ decade	various	Trees are killed off at three different rates through out their lives. All trees experience a mortality rate of 0.9 per decade from ages 0 -20. Trees older than 20 years experience a mortality rate of 0.95 per decade until the last 1/3 of life. During the last 1/3 of life, the mortality rate becomes species-specific, and is directly dependant on a given tree's overall longevity, and uses the following calculation: *[# remaining trees – (10[# remaining trees/1/3 lifespan])].* Total decadal mortalities of all species are summed and divided by fifteen to inform replacement natalities. See Table 14.
Tree naitality (i.e. new tree planting)	trees/ decade	various	All natalities are selected from the list of desirable species (see Table 12); no preference is given to any one species. Naitality estimates (generated via mortalities or scenario trees) are rounded down to the nearest integer.

Table 8: Species-specific longevity; desirable species indicated by green font

	Botanical name	**Longevity**	**Reference**
1	*Acer campestre*	75	Consultation
2	*Acer platanoides*	75	Leopold, 2005
3	*Acer rubrum*	100	Farrar, 1995
4	*Acer saccharinum*	130	Farrar, 1995
5	*Acer saccharum*	200	Farrar, 1995
6	*Aesculus hippocastanum*	100	Farrar, 1995
7	*Amelanchier canadensis*	150	Hightshoe 1988
8	*Betula alleghaniensis*	150	Farrar, 1995
9	*Betula papyrifera*	120	Farrar, 1995
10	*Betula pendula*	75	Consultation
11	*Fagus grandifolia*	200	Farrar, 1995
12	*Fagus sylvatica*	200	Consultation
13	*Fraxinus nigra*	150	USDA, 2010
14	*Gleditsia triacanthos*	125	Hightshoe 1988
15	*Juniperus scopulorum*	300	Burns and Honkala, 1990
16	*Malus spp.*	62.5	Hightshoe 1988
17	*Ostrya virginiana*	150	Hightshoe 1988
18	*Picea abies*	400	USDA, 2010
19	*Picea pungens*	600	Farrar, 1995
20	*Picea rubens*	300	Farrar, 1995
21	*Pinus banksiana*	300	Burns and Honkala, 1990
22	*Pinus strobus*	200	Farrar, 1995
23	*Pinus sylvestris*	150	Burns and Honkala, 1990
24	*Populus grandidentata*	60	Farrar, 1995
25	*Populus tremuloides*	80	Farrar, 1995
26	*Pyrus calleryana*	75	City of Marion, 2008
27	*Quercus rubra*	150	Farrar, 1995
28	*Salix nigra*	70	Farrar, 1995
29	*Sorbus aucuparia*	40	Consultation
30	*Syringa reticulata*	75	Consultation
31	*Thuja occidentalis*	700	Farrar, 1995
32	*Tilia americana*	200	Farrar, 1995
33	*Tsuga canadensis*	600	Farrar, 1995
34	*Ulmus americana*	200	Farrar, 1995
35	*Zelkova serrata*	75	City of Marion, 2008

Table 9 (1 of 2): Species-specific growth rate categories and associated values; desirable species indicated by green font

	Botanical name	**Growth rate category**	**Reference**	**Growth rate values (cm/decade)**			
				Initial value	**First 1/3 life**	**Second 1/3 life**	**Third 1/3 life**
1	*Acer campestre*	l	OSU, 2002	7.5	7.5	3.75	1.875
2	*Acer platanoides*	m	Stoecklein, 2001	10	10	5	2.5
3	*Acer rubrum*	m	Consultation	10	10	5	2.5
4	*Acer saccharinum*	h	Stoecklein, 2001	15	15	7.5	3.75
5	*Acer saccharum*	l	Consultation	7.5	7.5	3.75	1.875
6	*Aesculus hippocastanum*	m	Stoecklein, 2001	10	10	5	2.5
7	*Amelanchier canadensis*	m	Evans, 2005	10	10	5	2.5
8	*Betula alleghaniensis*	h	Stoecklein, 2001	15	15	7.5	3.75
9	*Betula papyrifera*	h	Stoecklein, 2001	15	15	7.5	3.75
10	*Betula pendula*	h	Evans, 2005	15	15	7.5	3.75
11	*Fagus grandifolia*	l	Stoecklein, 2001	7.5	7.5	3.75	1.875
12	*Fagus sylvatica*	l	Stoecklein, 2001	7.5	7.5	3.75	1.875
13	*Fraxinus nigra*	m	USDA, 2010	10	10	5	2.5
14	*Gleditsia triacanthos*	h	Farrar, 2005	15	15	7.5	3.75
15	*Juniperus scopulorum*	h	Consultation	15	15	7.5	3.75
16	*Malus spp.*	m	Evans, 2005	10	10	5	2.5
17	*Ostrya virginiana*	l	Stoecklein, 2001	7.5	7.5	3.75	1.875
18	*Picea abies*	h	Consultation	15	15	7.5	3.75
19	*Picea pungens*	h	Consultation	15	15	7.5	3.75
20	*Picea rubens*	h	Consultation	15	15	7.5	3.75
21	*Pinus banksiana*	h	Consultation	15	15	7.5	3.75
22	*Pinus strobus*	h	Consultation	15	15	7.5	3.75
23	*Pinus sylvestris*	h	Consultation	15	15	7.5	3.75
24	*Populus grandidentata*	h	Consultation	15	15	7.5	3.75
25	*Populus tremuloides*	h	Consultation	15	15	7.5	3.75
26	*Pyrus calleryana*	h	Evans, 2005	15	15	7.5	3.75
27	*Quercus rubra*	h	Stoecklein, 2001	15	15	7.5	3.75
28	*Salix nigra*	h	Farrar, 2005	15	15	7.5	3.75

Table 9, continued (2 of 2)

	Botanical name	**Growth rate category**	**Reference**	**Growth rate values (cm/decade)**			
				Initial value	**First 1/3 life**	**Second 1/3 life**	**Third 1/3 life**
29	*Sorbus aucuparia*	m	Evans, 2005	10	10	5	2.5
29	*Sorbus aucuparia*	m	Evans, 2005	10	10	5	2.5
30	*Syringa reticulata*	m	Evans, 2005	10	10	5	2.5
31	*Thuja occidentalis*	h	Consultation	15	15	7.5	3.75
32	*Tilia americana*	m	Consultation	10	10	5	2.5
33	*Tsuga canadensis*	h	Consultation	15	15	7.5	3.75
34	*Ulmus americana*	m	Stoecklein, 2001	10	10	5	2.5
35	*Zelkova serrata*	m	Evans, 2005	10	10	5	2.5

Table 10 (1 of 2): dbh look-up table; desirable species indicated by green font

	Botanical name	**Age 0**	**Age 10**	**Age 20**	**Age 30**	**Age 40**	**Age 50**	**Age 60**	**Age 70**	**Age 80**
1	*Acer campestre*	0	7.50	15.00	22.50	26.25	30.00	31.88	33.75	0.00
2	*Acer platanoides*	0	10.00	20.00	30.00	35.00	40.00	42.50	45.00	0.00
3	*Acer rubrum*	0	10.00	20.00	30.00	35.00	40.00	45.00	47.50	50.00
4	*Acer saccharinum*	0	15.00	30.00	45.00	60.00	67.50	75.00	82.50	90.00
5	*Acer saccharum*	0	7.50	15.00	22.50	30.00	37.50	45.00	52.50	56.25
6	*Aesculus hippocastanum*	0	10.00	20.00	30.00	35.00	40.00	45.00	50.00	52.50
7	*Amelanchier canadensis*	0	10.00	20.00	30.00	40.00	50.00	55.00	60.00	65.00
8	*Betula alleghaniensis*	0	15.00	30.00	45.00	60.00	75.00	82.50	90.00	97.50
9	*Betula papyrifera*	0	15.00	30.00	45.00	60.00	67.50	75.00	82.50	90.00
10	*Betula pendula*	0	15.00	30.00	45.00	52.50	60.00	63.75	67.50	0.00
11	*Fagus grandifolia*	0	7.50	15.00	22.50	30.00	37.50	45.00	52.50	56.25
12	*Fagus sylvatica*	0	7.50	15.00	22.50	30.00	37.50	45.00	52.50	56.25
13	*Fraxinus nigra*	0	10.00	20.00	30.00	40.00	45.00	50.00	55.00	60.00
14	*Gleditsia triacanthos*	0	15.00	30.00	45.00	60.00	67.50	75.00	82.50	90.00
15	*Juniperus scopulorum*	0	15.00	30.00	45.00	60.00	75.00	90.00	105.00	120.00
16	*Malus spp.*	0	10.00	20.00	25.00	30.00	32.50	35.00	0.00	0.00
17	*Ostrya virginiana*	0	7.50	15.00	22.50	30.00	37.50	41.25	45.00	48.75
18	*Picea abies*	0	15.00	30.00	45.00	60.00	75.00	90.00	97.50	105.00
19	*Picea pungens*	0	15.00	30.00	45.00	60.00	75.00	90.00	105.00	120.00
20	*Picea rubens*	0	15.00	30.00	45.00	60.00	75.00	90.00	105.00	120.00
21	*Pinus banksiana*	0	15.00	30.00	45.00	60.00	75.00	90.00	105.00	120.00
22	*Pinus strobus*	0	15.00	30.00	45.00	60.00	75.00	90.00	105.00	112.50
23	*Pinus sylvestris*	0	15.00	30.00	45.00	60.00	75.00	82.50	90.00	97.50
24	*Populus grandidentata*	0	15.00	30.00	37.50	45.00	48.75	0.00	0.00	0.00
25	*Populus tremuloides*	0	15.00	30.00	45.00	52.50	60.00	63.75	67.50	0.00

Table 10, continued (2 of 2)

	Botanical name	**Age 0**	**Age 10**	**Age 20**	**Age 30**	**Age 40**	**Age 50**	**Age 60**	**Age 70**	**Age 80**
26	*Pyrus calleryana*	0	15.00	30.00	45.00	52.50	60.00	63.75	67.50	0.00
27	*Quercus rubra*	0	15.00	30.00	45.00	60.00	75.00	82.50	90.00	97.50
28	*Salix nigra*	0	15.00	30.00	37.50	45.00	52.50	56.25	0.00	0.00
29	*Sorbus aucuparia*	0	10.00	15.00	20.00	0.00	0.00	0.00	0.00	0.00
30	*Syringa reticulata*	0	10.00	20.00	30.00	35.00	40.00	45.00	50.00	0.00
31	*Thuja occidentalis*	0	15.00	30.00	45.00	60.00	75.00	90.00	105.00	120.00
32	*Tilia americana*	0	10.00	20.00	30.00	40.00	50.00	60.00	70.00	75.00
33	*Tsuga canadensis*	0	15.00	30.00	45.00	60.00	75.00	90.00	105.00	120.00
34	*Ulmus americana*	0	10.00	20.00	30.00	40.00	50.00	60.00	70.00	75.00
35	*Zelkova serrata*	0	10.00	20.00	30.00	35.00	40.00	42.50	45.00	0.00
27	*Quercus rubra*	0	15.00	30.00	45.00	60.00	75.00	82.50	90.00	97.50
28	*Salix nigra*	0	15.00	30.00	37.50	45.00	52.50	56.25	0.00	0.00
29	*Sorbus aucuparia*	0	10.00	15.00	20.00	0.00	0.00	0.00	0.00	0.00
30	*Syringa reticulata*	0	10.00	20.00	30.00	35.00	40.00	45.00	50.00	0.00
31	*Thuja occidentalis*	0	15.00	30.00	45.00	60.00	75.00	90.00	105.00	120.00
32	*Tilia americana*	0	10.00	20.00	30.00	40.00	50.00	60.00	70.00	75.00
33	*Tsuga canadensis*	0	15.00	30.00	45.00	60.00	75.00	90.00	105.00	120.00
34	*Ulmus americana*	0	10.00	20.00	30.00	40.00	50.00	60.00	70.00	75.00
35	*Zelkova serrata*	0	10.00	20.00	30.00	35.00	40.00	42.50	45.00	0.00

Table 11: Biomass equations; desirable species indicated by green font (1 of 3)

Botanical name	Original biomass equation	a	b	Study location	dbh range (cm)	Reference
Acer campestre	ln W = a + b ln D	-1.9702	2.3405	n/a	n/a	*Acer rubrum*
Acer platanoides	ln W = a + b ln D	-1.9702	2.3405	n/a	n/a	*Acer rubrum*
Acer rubrum	ln W = a + b ln D	-1.9702	2.3405	Nova Scotia	1.3 - 32.3	Duinker, 1981
Acer saccharinum	bm = Exp(a + b ln dbh)	-1.9123	2.3651	General: USA	>2.5 to 66	Jenkins et al., 2003; 2004 (soft maple/birch)
Acer saccharum	ln W = a + b ln D	-1.876	2.3924	Nova Scotia	1.2 - 33.5	Duinker, 1981
Aesculus hippocastanum	bm = Exp(a + b ln dbh)	-2.48	2.4835	General: USA	>2.5 to 56	Jenkins et al., 2003; 2004, (mixed hardwood)
Amelanchier canadensis	bm = Exp(a + b ln dbh)	-2.48	2.4835	General: USA	>2.5 to 56	Jenkins et al., 2003; 2004 (mixed hardwood)
Betula alleghaniensis	ln W = a + b ln D	-2.1306	2.451	Nova Scotia	2.6 - 29.0	Duinker, 1981
Betula papyrifera	ln W = a + b ln D	-2.0045	2.3634	Nova Scotia	1.1 - 31.4	Duinker, 1981
Betula pendula	ln W = a + b ln D	-2.0045	2.3634	n/a	n/a	*Betula papyrifera*
Fagus grandifolia	$M=aD^b$	0.1958	2.2538	New Brunswick	2 to 29	Ter-Mikaelian and Korzukhin, 1997
Fagus sylvatica	$M=aD^b$	0.1958	2.2538	n/a	n/a	*Fagus grandifolia*
Fraxinus nigra	$M=aD^b$	0.1634	2.348	Upper Great Lakes	4 to 32	Ter-Mikaelian and Korzukhin, 1997
Gleditsia triacanthos	bm = Exp(a + b ln dbh)	-2.48	2.4835	General: USA	>2.5 to 56	Jenkins et al., 2003; 2004 (mixed hardwood)
Juniperus scopulorum	bm = Exp(a + b ln dbh)	-0.7152	1.7029	General: USA	>2.5 to 78	Jenkins et al., 2003; 2004 (woodland)

Table 11, continued (2 of 3)

Botanical name	**Original biomass equation**	**a**	**b**	**Study location**	**dbh range (cm)**	**Reference**
Malus spp.	bm = Exp(a + b ln dbh)	-2.48	2.4835	General: USA	>2.5 to 56	Jenkins et al., 2003; 2004 (mixed hardwood)
Ostrya virginiana	bm = Exp(a + b ln dbh)	-2.48	2.4835	General: USA	>2.5 to 56	Jenkins et al., 2003; 2004 (mixed hardwood)
Picea abies	$M=aD^b$	0.2722	2.104	New York	12 to 44	Ter-Mikaelian and Korzukhin, 1997
Picea pungens	ln W = a + b ln D	-1.7957	2.2417	n/a	n/a	*Picea rubens*
Picea rubens	ln W = a + b ln D	-1.7957	2.2417	Nova Scotia	2.5 - 28.3	Duinker, 1981
Pinus banksiana	$M=aD^b$	0.1093	2.3291	Nova Scotia	3 - 33.4	Ter-Mikaelian and Korzukhin, 1997
Pinus strobus	$M=aD^b$	0.1617	2.142	New Brunswick	2 to 37	Ter-Mikaelian and Korzukhin, 1997
Pinus sylvestris	$M=aD^b$	0.1093	2.3291	n/a	n/a	*Pinus banksiana*
Populus grandidentata	ln W = a + b ln D	-2.32	2.3773	Nova Scotia	1.2 - 33.8	Duinker, 1981
Populus tremuloides	ln W = a + b ln D	-2.3778	2.4085	Nova Scotia	0.8 - 26.5	Duinker, 1981
Pyrus calleryana	bm = Exp(a + b ln dbh)	-2.48	2.4835	General: USA	>2.5 to 56	Jenkins et al., 2003; 2004 (mixed hardwood)
Quercus rubra	$M=aD^b$	0.1335	2.422	Upper Great Lakes	5 to 34	Ter-Mikaelian and Korzukhin, 1997
Salix nigra	$M=aD^b$	0.1619	2.0552	Maine	3 to 24	Ter-Mikaelian and Korzukhin, 1997
Sorbus aucuparia	bm = Exp(a + b ln dbh)	-2.48	2.4835	General: USA	>2.5 to 56	Jenkins et al., 2003; 2004 (mixed hardwood)

Table 11, continued (3 of 3)

Botanical name	**Original biomass equation**	**a**	**b**	**Study location**	**dbh range (cm)**	**Reference**
Syringa reticulata	bm = Exp(a + b ln dbh)	-2.48	2.4835	General: USA	>2.5 to 56	Jenkins et al., 2003; 2004 (mixed hardwood)
Thuja occidentalis	$M=aD^b$	0.1148	2.1439	New Brunswick	2 to 30	Ter-Mikaelian and Korzukhin, 1997
Tilia americana	$M=aD^b$	0.0872	2.3539	Upper Great Lakes	4 to 47	Ter-Mikaelian and Korzukhin, 1997
Tsuga canadensis	$M=aD^b$	0.1617	2.1536	New Brunswick	2 to 34	Ter-Mikaelian and Korzukhin, 1997
Ulmus americana	$M=aD^b$	0.0825	2.468	Upper Great Lakes	4 to 29	Ter-Mikaelian and Korzukhin, 1997
Zelkova serrata	bm = Exp(a + b ln dbh)	-2.48	2.4835	General: USA	>2.5 to 56	Jenkins et al., 2003; 2004 (mixed hardwood)
Thuja occidentalis	$M=aD^b$	0.1148	2.1439	New Brunswick	2 to 30	Ter-Mikaelian and Korzukhin, 1997
Tilia americana	$M=aD^b$	0.0872	2.3539	Upper Great Lakes	4 to 47	Ter-Mikaelian and Korzukhin, 1997

Table 12: Desirable species list for all tree natalities

Botanical name	**Common name**
Acer rubrum	Red maple
Acer saccharinum	Silver maple
Acer saccharum	Sugar maple
Betula alleghaniensis	Yellow birch
Betula papyrifera	Paper birch; white birch
Fraxinus nigra	Black ash
Ostrya virginiana	Ironwood; American hop hornbeam
Picea rubens	Red spruce
Pinus strobus	White pine
Populus grandidentata	Largetooth aspen
Populus tremuloides	Trembling aspen
Quercus rubra	Red oak
Tilia americana	American linden; basswood
Tsuga canadensis	Hemlock
Ulmus americana	American elm

Table 13: Calculations used to estimate C sequestration and storage of current and future BIP urban forest structures

Purpose	**Unit**	**Calculation**
Carbon storage per species cohort	kg C/species cohort	$C_{\text{store/species cohort}} = 0.5ab$ *where:* *a* = # trees in species cohort; *b* = above-ground dry weight biomass (kg/tree); 0.5 = conversion factor (above-ground dry weight biomass to C)
Carbon stored by total population	kg C/total population	$C_{\text{store of total population}} = \text{Sum}(C_{\text{stored/species cohort}})$
Net carbon sequestration	kg carbon stored/year	$\dfrac{[(\text{total C stored by year } y \text{ forest}) - (\text{total C stored in year } x \text{ forest})]}{\#\ \text{years}}$

Table 14: Mortality calculations

Tree age	**Mortality loss calculation**
Age 0 -10 (inclusive)	(# cohorts)*0.9
Age >10- less than or equal to 20	(# cohorts)*0.9
Age > 20 – Final 1/3 of life	(# cohorts)*.95
Final 1/3 of life	# remaining trees – (10*(# remaining trees/1/3 lifespan))

Table 15: Summary of ownership within Disturbed Green land cover

Disturbed Green land cover ownership	Area (m^2)	Area (ha)	Percent ownership (%)
HRM	385,000	38.5	44
Private	436,000	43.6	50
Federal	8,700	0.871	1
Provincial	47,000	4.70	5

References

Burns, R.M., Honkala, B.H. (1990). *Silvics of North America*. Washington DC, USA: USDA Forest Service, United States Department of Agriculture.

City of Marion. (2008). A leader in the delivery of the community vision, draft street tree strategy (Reference number GC230908R01). Retrieved from City of Marion: http://marion.dcw.lga.sa.gov.au/webdata/resources/files/GC230908R01_-_Draft_Street_Tree_Strategy.pdf

Duinker, P.N. 1981. *Biomass prediction equations for ten tree species in central Nova Scotia.* (Unpublished master's thesis). Dalhousie University, Canada.

Evans, E. (2005). *North Carolina State University plant fact sheets.* Retrieved from http://www.ces.ncsu.edu/depts/hort/consumer/factsheets/index.html

Farrar, J.L. (1995). *Trees in Canada,* (12th edition). Ottawa, Canada: Canadian Forest Service.

Hightshoe, G.L. (1988). *Native trees, shrubs, and vines for urban and rural America: a planting design manual for environmental designers.* New York, New York: Van Nostrand Reinhold.

Jenkins, J.C., Chojnacky, D.C., Heath, L.S., & Birdsey, R.A. (2003). National-scale biomass estimators for United States tree species. *Forest Science, 49*(1), 12–35.

Jenkins, J.C., Chojnacky, D.C., Heath, L.S., Birdsey, R.A., & Richard, A. (2004). Comprehensive database of diameter-based biomass regressions for North American tree species (General Technical Report NE-319). Retrieved from United States Forest Service: http://www.uvm.edu/~jcjenkin/jenkins%20et%20al.%202004.pdf

Leopold, D.J. (2005). *Native plants of the northeast: A guide for gardening and conservation.* Portland, OR: Timber Press.

McHale, M.R., Burke, I.C., Lefsky, M.A., Peper, P.J., & McPherson, E.G. (2009). Urban forest biomass estimates: Is it important to use allometric relationships developed specifically for urban trees? *Urban Ecosystems, 12,* 95-113.

Ohio State University (OSU). (2002). *PlantFacts*. Retrieved from http://plantfacts.osu.edu/

Plotnik, A. (2000). *The urban tree book: An uncommon field guide for city and town.* New York, USA: Three Rivers Press.

Rostami, M. (2011). *Tree species selection for the Halifax urban forest under a changing climate*. (Unpublished master's thesis). Dalhousie University, Canada.

Stoecklein, M.C. (2001). *The complete plant selection guide for landscape design.* Indiana, USA: Purdue University Press.

Ter-Mikaelian, M.T., Korzukhin, M.D. 1997. Biomass equations for sixty-five North American tree species. *Forest Ecology and Management, 97*, 1-24.

United States Department of Agriculture (USDA). (2010). *Fire effects information system*. Retrieved from http://www.fs.fed.us/database/feis

APPENDIX 2: SUMMARY OF RESULTS GENERATED BY THE BURNSIDE INDUSTRIAL PARK URBAN FOREST CARBON MODEL

Table 1: Summary of total tree population per scenario (total population)

Scenario	Year				
	2010	**2020**	**2030**	**2040**	**2050**
Scenario 1	4,785	4,782	4,787	4,783	4,783
Scenario 2	4,785	45,897	45,900	45,895	45,894
Scenario 3	4,785	86,997	87,000	86,995	86,994

Table 2: Summary of tree densities per scenario (trees/ha)

Scenario	Year				
	2010	**2020**	**2030**	**2040**	**2050**
Scenario 1	55	55	55	55	55
Scenario 2	55	528	528	528	528
Scenario 3	55	1,000	1,000	1,000	1,000

Table 3: Summary of carbon storage estimates per scenario (tC)

Scenario	Year				
	2010	**2020**	**2030**	**2040**	**2050**
Scenario 1	986	1,634	2,281	2,836	3,412
Scenario 2	986	1,634	3,271	7,484	14,892
Scenario 3	986	1,634	4,261	12,130	26,368

Table 4: Summary of carbon storage per hectare per scenario (tC/ha)

Scenario	Year				
	2010	**2020**	**2030**	**2040**	**2050**
Scenario 1	11	19	26	33	39
Scenario 2	11	19	38	86	171
Scenario 3	11	19	49	139	303

Table 5: Summary of total carbon sequestration per scenario (tC/year)

	2010-2020	**2020-2030**	**2030-2040**	**2040-2050**	**Average 2010-2050**
Scenario 1	65	65	56	58	61
Scenario 2	65	164	421	741	348
Scenario 3	65	263	787	1,424	635

Table 6: Summary of carbon sequestration per scenario (tC/year/ha)

	2010-2020	**2020-2030**	**2030-2040**	**2040-2050**	**Average 2010-2050**
Scenario 1	0.7	0.7	0.6	0.7	0.7
Scenario 2	0.7	1.9	4.8	8.5	4.0
Scenario 3	0.7	3.0	9.0	16.4	7.3