Assessing the effects of forest management techniques on sequestering carbon in northern woodlots

Karen Paquin

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Signed by the final examining committee:

Dr. Alan Nash ______________________________ Chair

Dr. David Greene ________________________ Examiner

Dr. Navin Ramankutty ___________________ Examiner

Dr. Damon Matthews ___________________ Supervisor

Dr. Jochen Jaeger _______________________ Supervisor

Approved by Dr. Pascale Biron _______________________________
Chair of Department or Graduate Program Director

April 26, 2011 Dean Brian Lewis _______________________________
Dean of Faculty

Abstract

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Canadian woodlots can play an important role in mitigating climate change through increased carbon sequestration. I conducted a survey of private woodlot owners in Ontario to address three questions related to forest carbon storage and forest management techniques (FMT). The survey responses showed that the largest portion of woodlot owners in this study (46%) is not actively engaged in forest management on their properties, opting for natural succession. Using the data from the survey, I completed four sets of simulations with the CBM-CFS3 model. The simulation results indicated that current carbon storage on the woodlots is 240,753 tons and, if all the landowners let their forests grow without management (natural succession), in 300 years, carbon storage will increase to 501,236 tons. The FMT that stored the greatest amount of carbon over the long-term was a 10% commercial thinning (665,007 tons). Adding a 60-year rotation interval to the 10% commercial thinning increased carbon storage even more (791,027 tons). Conversely, clearcuts and wildfires had devastating effects on carbon storage. After a clearcut or wildfire, transitioning to a red pine forest recovered more lost carbon than any FMT or natural succession. All of these are long-term perspectives, but in the short-term, natural succession may be the best method for storing carbon. However, what made this investigation most interesting was the complexities of the woodlots themselves, their stand make-up, ownership and uses. The diversity of these woodlots may offer a path of least resistance to increasing carbon storage on them.

Dedication

This thesis is dedicated to the three Geography professors who influenced and inspired my love for this discipline more than any others:

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Dr. Glen MacDonald

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Introduction

Charles Keeling, a scientist who worked at the Mauna Loa Observatory in Hawaii, began recording atmospheric CO_2 in 1958. Within two years, he recognized seasonal variations in carbon dioxide levels and, a year later, produced data that demonstrated steadily rising atmospheric carbon dioxide levels (Pales and Keeling 1965). This now famous diagram, known as the "Keeling Curve" (Figure 1), represents the longest continuous record of atmospheric CO_2 and demonstrates clearly its increasing concentration in the atmosphere. In fact, atmospheric CO_2 rose from 315 parts per million (ppm) in 1958 to 380ppm in 2005 (IPCC 2007). There are many examples of the negative impacts of this increase and its effect on increasing global temperatures that are clearly recognizable around the world, including global recession of glaciers (Chaujar 2009, and Ziaja 2005), bleaching coral reefs (Wild et al. 2011), rising sea level (IPCC 2007) and changes in weather patterns (Lamb 1995).

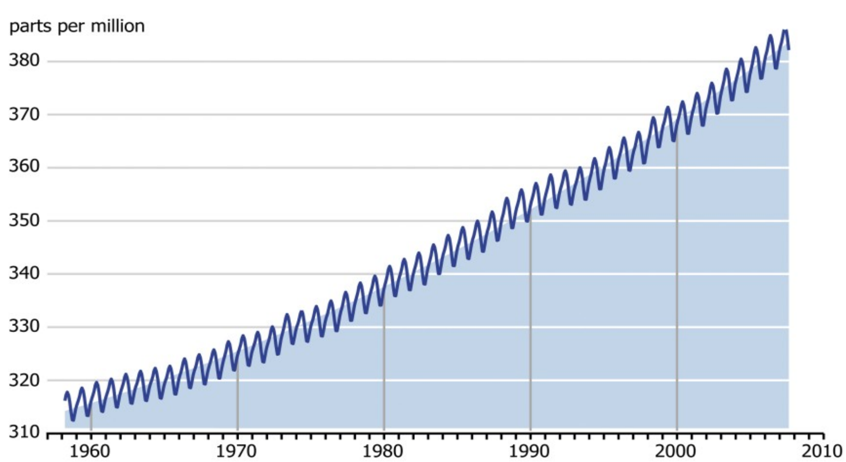


Figure 1. Keeling curve showing monthly CO_2 concentrations through 2007. (Used with permission. Scripps Institution of Oceanography, UC San Diego.)

The fourth IPCC (Intergovernmental Panel on Climate Change) report (2007), the latest in a series of assessments of the most recent scientific, technical and socio-economic knowledge of climate change, looked at the potential impacts of climate change as well as mitigation and adaptation options. Fifteen years after the United Nations Framework Convention on Climate Change (UNFCCC) concluded that precautionary steps should be taken to mitigate the effects of anthropogenic greenhouse gas emissions (Guy and Levine 2001), the fourth IPCC report stated that "warming of the climate system is unequivocal".

The Kyoto Protocol, which came into force in 2005 with the first implementation period beginning three years later, is the only international agreement that addresses both the release and uptake of carbon in a worldwide effort to mitigate anthropogenic emissions (Kurz and Apps 2006) that cause the increased levels of CO_2 and other greenhouse gases in the atmosphere. This document requires international carbon accounting (Kurz et al. 2009) by participating nations. Numerous sections of the Kyoto Protocol describe the obligations for these countries, which range from creating and implementing policy measures to establishing programs to mitigate all aspects of climate change. Article 7 section 3 defines the reporting requirements:

> "Each party shall submit the information required under paragraph 1 above annually, beginning with the first inventory due under the Convention for the first year of the commitment period after this Protocol has entered into force for that Party." (Kyoto Protocol 1998)

Forests are one of the most controversial topics within the Kyoto Protocol and within the realm of climate mitigation, especially when it comes to carbon accounting. As early as 1997, Ravindranath and Bhat (1997) explained that reporting and verification of carbon would be essential, but difficult. The third IPCC working group included a chapter dedicated to forestry (Nabuurs et al. 2007) in the fourth IPCC report. This chapter highlighted the mitigation potential of forest-related carbon sequestration. Although stating that reducing deforestation would produce greater results than afforestation (since deforestation is the single most important source of non-fossil fuel carbon emissions), Nabuurs et al. (2007) listed the other potential ways in which forestry can help to mitigate climate change. These methods involved extending carbon retention in harvested wood products and producing biomass for bio-energy. Sustainable forest management strategies that maintain or increase carbon in forests and provide “annual sustained yield timber, fiber or energy” were also listed as the way to “generate the largest, sustained mitigation benefit” from forests. Despite these recommendations, many challenges related to the inclusion of forests in the Kyoto Protocol exist. These concerns range from questioning their ability to sequester carbon for long periods of time (Bayon et al. 2007 and Wilman and Mahendrarajah 2002) and the potential for the carbon to be released through forest fires, insect infestations and land use changes, to issues of defining exactly what constitutes a forest and which forestry practices are sustainable. How exactly to measure carbon sequestration is another hotly debated issue (Bayon et al. 2007 and Wilman and Mahendrarajah 2002). Complexities also exist when attempting to establish how to manage forests and how much of them can be managed (Canadell and Raupach 2008). Forest-related activities account for 17.4% of total carbon emissions globally (IPCC 2007), but forests also store large reservoirs of carbon (Canadell and Raupach 2008), amounting to 45% of terrestrial carbon in all (Bonan 2008). Additionally, the ways in which forests are managed can have a dramatic effect on carbon storage (Carlson et al. 2010), forming the basis for the argument that “forests can be managed to mitigate climate change,” (Bonan 2008). All of these aspects necessitate the inclusion of forests in the Kyoto Protocol carbon accounting requirements.

Canada, as a signatory and ratifying country of the Kyoto Protocol, committed originally to a carbon dioxide reduction of 6% (240 megatons (MT)) below 1990 levels by 2012 (Amano and Sedjo 2006). According to Amano and Sedjo (2006), Canada planned to sequester 20 MT or 8% of the total 6% through "forestry from business as usual activities" during the first Kyoto Protocol implementation period from 2008-2012. In 2006, however, Canada reneged on its overall Kyoto commitment claiming economic reasons and lack of action by the previous government to implement plans toward reaching that goal and has, instead, established a much weaker national target of an absolute 20% reduction in greenhouse gases, relative to 2006 levels, by 2020 (Environment Canada 2008).

Despite this backwards step by the Canadian national government, some Canadian provinces are taking steps to implement and meet stronger goals. For example, Ontario plans to be a leader in the nation and among world leaders in achieving emission reductions (Ontario Ministry of the Environment 2007). The province has set short, medium and long-term goals of carbon emission reductions below 1990 levels of 6% by 2014, 15% by 2020, and 80% by 2050.

The role that forests will play in the new national plan as well as the provincial ones is not as clearly defined as the overall targets. However, what is clear is that Canada's forests, which constitute 10% of global forest cover (Chen et al. 2000), and land use changes will play a major role in determining carbon accounting tallies. Therefore, as governments across Canada begin to develop post- Kyoto Protocol legislation, forest management techniques (FMT) are sure to be considered (Carlson et al. 2010). Kurz and Apps (2006) state that, to fulfill its obligations to the international community on reporting its greenhouse gas sources and sinks, Canada developed a National Forest Carbon Monitoring, Accounting and Reporting System. This system utilizes "forest-inventory data, growth and yield information, and statistics on natural disturbances, management actions and land-use change to estimate forest carbon stocks, changes in carbon stocks, and emissions of non-CO_2 greenhouse gases," using the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS) (Kurz et al. 2009).

In Ontario, a large portion of forested land is in the boreal forests, just south of the Hudson Bay Lowlands, where 20% of provincial forests are located. Another 20% can be found in the Great Lakes/St. Lawrence region. In southern Ontario, where the land has largely been cleared from its pre-European settlement maximum of 80% forested, only small deciduous forest woodlots remain, making up a fraction of the province's total forested area. Of all of Ontario's forested area, 7% of the forested land is held in private ownership – woodlots. Despite their typically small size relative to public forests, woodlots represent a diverse part of Canada's forests (Wyatt and Bourgoin 2010) with equally varied usage (Beckley 1998). Moreover, Canada's woodlots contribute to the country's economic, social and environmental health (Dansereau and deMarsh 2003).

A woodlot is defined as a segment of a wood or forest capable only of small-scale production of forest products or recreational use. It is at this local level where there is a knowledge gap and more research is needed (Seppälä 2009). Wyatt and Bourgoin (2010) agree, stating that the management of Canadian woodlots has "attracted relatively little academic attention" compared to public forests. More specifically, Seppälä's knowledge gap refers to a lack of understanding, by both landowners and researchers, regarding the role of forests in storing carbon and the potential for forest carbon credits. Land owners need to better understand how their land management decisions will affect not only carbon storage in their forests, but national carbon accounting and the global climate system. From the perspective of researchers, being able to convey mechanisms for achieving climate mitigation, through forest management activities and incentives to both landowners and policy makers, is critical.

Most of the research related to forest carbon sequestration has been focused at national or international levels. According to Canadell and Raupach (2008), four major forest strategies exist to mitigate carbon emissions. They are to: increase forest cover through reforestation; increase the "carbon density of existing forests at both stand and landscape scales"; expand forest product use that sustainably replaces the emission of CO_2 from fossil fuels; and implement measures leading to Reduced Emissions from Deforestation and Degradation (REDD).

The main focus of the COP 15 meeting in Copenhagen in December 2009 was on the latter of these (REDD) (Grainger et al. 2010). In contrast, my research is focused at the local level, utilizing the second strategy listed by Canadell and Raupach (2009) – increasing the carbon density in existing forest stands. In doing so, I hope to help fill the knowledge gap identified by Seppälä (2009) by contributing knowledge of stand-level carbon dynamics in Ontario woodlots. To that end, I address the following three questions in this study:

a) What are the current forest management techniques on Ontario woodlots?

b) What are current levels of carbon sequestration in Ontario woodlots?

c) What adjustments to current forest management techniques would allow for increased carbon sequestration in Ontario woodlots?

To answer these questions, I utilized an inductive approach that incorporated a two-tiered research design. The first step involved the distribution of a questionnaire to a targeted audience of woodlot owners in Ontario, Canada. I used the survey for two main purposes – to address my first research question and gather data for use in model simulations to address my second and third questions. To complete the second step, data from the survey was cleaned and processed for simulations using the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3).

This work focused on private landowners for a few reasons. First, it helped to clarify, to land owners and land managers, the role that forests can play in mitigating climate change. Their forest management decisions affect directly the carbon balance and simulating different potential forest management scenarios has the potential to show them what those decisions mean in terms of carbon storage. Likewise, Carlson et al. (2010) point out that determining which forest management scenarios will maintain the role of Canada's forests in addressing climate change and policies related to it is critical. Second, according to researchers at Natural Resources Canada, data on woodlots and their potential contribution to forest carbon balance is limited. This project increases the known data through the survey. Although this work may be applicable at larger scales and on public lands, that is beyond the scope of the work I carried out for this project.

The benefits of this research are many and may have an impact at numerous levels. Because this work looks specifically at local conditions, it begins to fill the knowledge gap identified by Seppälä (2009) (as explained above) with information that may be utilized on larger spatial scales. On a local level, this study determines the carbon storage of these properties and the way future actions on them will affect that storage going forward. In addition, landowners can use the results of this study to realize the carbon storage and future potential carbon storage on their properties. From a regional perspective, the results of this study can be shared with other woodlot owners in assessing and taking steps to manage carbon storage on their properties. Moreover, this study clarifies for landowners what information is required so that they can estimate carbon storage on their land. At the regional and national levels, the findings of this project provide results that could have policy implications related to landowner benefits for managing carbon on the woodlots, because it offers a more concrete understanding of the carbon that could likely be stored in the woodlots.

Contemporary Woodlots in Southern Ontario: Knowledge Gaps and Available Data

This study uses private forests that are woodlots in the southern part of the province of Ontario, Canada. A woodlot is a small, privately-owned, forested area that can be used for many purposes, including small-scale harvesting, recreational activities, habitat protection, or maple syrup production. These properties, though relatively small, may contain more than a single stand of trees and be of differing sizes. While some woodlots comprise only a single stand, others have many stands. A woodlot owner may identify a stand based on a variety of aspects, ranging from stand age to tree species composition or to the purpose (e.g. recreation use or habitat protection). Essentially, a stand is identified by a feature or features that distinguish it from adjacent areas. This definition differs from that of an industrial forest stand in that industrial forest stands tend to be recognized from adjacent stands by virtue of their homogeneity (Spies 1997). In woodlots, though they are distinguishable from neighboring stands, their stand structure is likely to be more diverse. According to McElhinny et al. (2005), stand structure constitutes the complexity of the stand make up.

In September 2009, I conducted a survey of woodlot owners in Ontario with the intent of gathering data to assess carbon storage and forest management techniques (FMT) on these small, privately owned properties. The direct goal was to answer my first research question. The indirect goal was to gather data to answer my two remaining research questions, which would be addressed through multiple series of forest model simulations that considered a variety of FMTs, different tree species, rotation intervals and natural disasters (wildfire).

By establishing current FMTs and carbon storage levels on these properties, I hoped to identify next steps that land owners could take toward increasing the potential carbon stored on their properties, while also creating an understanding of the situation for policy makers that would allow them to offer support to landowners wanting to increase carbon sequestration. What I found from the survey responses was that, in many regards, this assumption placed the cart in front of the horse. For example, while land owners may need to better understand how their FMT decisions will affect not only carbon storage in their forests, but national carbon accounting and the global climate system, there is another knowledge gap that exists, pertaining to their individual properties, which they must fill first. Once that gap is filled, Seppälä's carbon-based knowledge gap can be addressed. My survey responses confirm what Seppälä observed, but go beyond the scope of carbon storage in these privately owned forests to more fundamental knowledge gaps.

In "A Silvicultural Guide to Managing Southern Ontario Forests" (Bland and Strobl 2000), the fourth chapter lays out basic knowledge of site (stand) conditions that landowners should know. These are physical setting aspects, including broad topics such as climate and physiography. They also include soil characteristics, potential site productivity, natural disturbances, hydrology and nutrient cycling, stand structure and species composition. Supporting this, McElhinny et al. (2005) offer an approach to defining stand structure with an eye towards ecosystem components and not solely based on species composition. All of these aspects of site conditions are the majority of the type of information I requested in the survey I composed. However, the survey responses revealed a lack of knowledge around many of these aspects. While there is a link between this and the larger understanding of climate change and carbon accounting, there is another issue that arises, which demonstrates clearly that the assumptions made about basic forest knowledge that woodlot owners need and that which they actually possess diverge dramatically.

Therefore, what I demonstrate through my survey results is that, although they satisfy my first research question, the answers provided by the woodlot owners bring to light another matter which may be of greater significance to understanding the potential of woodlot owners to eventually increase carbon storage on their properties, but also to simply better understand what is happening on their properties. Therefore, I have created two sub-questions in light of this initial observation. They are:

1) How much do southern Ontario woodlot owners know about the basic forestry assumptions regarding stand structure on their properties?

2) How does what they know compare to their industrial forestry counterparts?

Forest Management Techniques (FMT): Effects on Carbon Storage on Ontario Woodlots

In Canada, where forests comprise 10% of global forest cover (Chen et al. 2000) and roughly half of Canada's land cover, FMTs become incredibly important with regard to a forest's ability to store carbon or increase carbon storage. This is evidenced by the fact that Canada planned to sequester 20 MT or 8% of the total 6% through "forestry from business as usual activities" during the first Kyoto Protocol implementation period from 2008-2012 (Amano and Sedjo 2006). Although woodlots play an important role in the Canadian economy with total annual revenues estimated to be $1.5 billion Canadian (Dansereau and deMarsh 2003), their role in sequestering carbon is largely unknown. However, researchers have identified FMTs as a significant way for woodlot owners to increase carbon storage on their properties (Carlson et al. 2010, Colombo et al. 2007, and Nabuurs et al. 2007). In fact, Colombo et al. (2007) state that, in Ontario, forest management practices that increase stand growth also offer chances to increase carbon storage.

This part of the study investigated that unknown capacity to increase carbon sequestered in forests through a survey of actual woodlot owners in Ontario. Utilizing the responses gathered from a survey I conducted fall 2009, I addressed three research questions (listed above). The first question was answered directly by responses to the survey. Additional survey data was compiled and used to generate data for running a series of simulations using the CBM-CFS3 model, the same model used by Environment Canada in their Kyoto Protocol carbon accounting. The model simulations included a natural succession scenario that allowed me to estimate how much carbon is currently stored in these woodlots and how much would accumulate if no further FMTs were implemented. This scenario provided me with a baseline from which I ran a selected set of scenarios that forecasted future potential carbon sequestration based on a variety of different potential FMTs to see how each one affected the overall amount of carbon stored on these properties. By comparing the results from these scenarios, I was able to discern which FMTs provided the greatest levels of carbon sequestration. This process addressed my two final research questions.

Chapter 1

Literature Review

Seppälä (2009) identified a knowledge gap at the local level (small, privately owned properties) where more research is needed. Wyatt and Bourgoin (2010) concurred. Most of the work related to forest carbon sequestration occurs on national or international levels where large land areas are covered in the research. These areas range from entire countries (Akelsson et al. 2005, Chen et al. 2000) to entire world regions, such as the Arctic (Dong et al. 2003). Even work done at regional and local levels consider carbon budgets only over short periods (3-5 years) in large areas (Turner et al. 2004, Barr et al. 2002), though some have looked at soil carbon (Blanco-Canqui and Lal 2008, Coleman et al. 2004) and other research centered on the performance of a single tree species (Wise and Cacho 2005). Still other research, while considering land use changes, focused on economic incentives for landowners (Nghiem 2009, Shabman et al. 2002;).

My current research focuses on forest carbon assessment and FMTs for increasing carbon storage at the individual stand level on privately owned woodlots. The literature for this area of research has a broad range that covers the immediate interests of carbon storage by forests from regional to national and international levels and ancillary work that touches on policy actions related to mitigation. What I present here is a short review of a few key papers from these two areas – carbon storage and policy. The first section of this chapter, "Assessing Carbon Storage", shows three examples of carbon storage assessments in Canada. In the second section, "Policy Effects on Carbon Storage", policy-related commentary from a variety of papers will be discussed along with the ways the proposed research could impact Canada's carbon accounting. Because my study looks at forest management techniques on woodlots, I end with a section called "Management on Woodlots" that reviews two papers, one that offers forest management actions designed to reduce negative impacts to Canadian forests and increase carbon storage, and one which highlights the importance of managing woodlots.

Assessing Carbon Storage

Chen et al. (2000) simulated four different forest management strategies for increasing carbon storage in Canadian forests using InTec – the Integrated Terrestrial Ecosystem C-budget model. The simulations related to afforestation (planting forests in areas that were not formerly forested), reforestation (replanting areas that were formerly forested), nitrogen fertilization and the substitution of fossil fuel with wood, all of which were run under different climatic and disturbance scenarios for 100 years and then compared to "other proposed GHG reduction programs in Canada".

The InTEC model described by Chen et al. (2000) is regional in scale with the ability to calculate a given region's annual carbon balance by summing three carbon pools – biomass, soil, and forest products. The model is photosynthesis-based, making it useful for modeling ecosystem dynamics (Kurz et al. 2009). Chen et al. (2000) used this model to assess the response of carbon offset potential by the forests to a variety of scenarios and situations. The researchers built on the original InTEC model so that they could include simulations of carbon cycling of forest products in the form of "landfills, recycling of lumber and pulp products, and use of wood products as a substitute for fossil fuels".

In laying out the four management situations, Chen et al. (2000) explained how they reached their baseline for each management technique. For afforestation, they used 7.2 Mha of marginal agricultural land as identified by Nagle in 1990. The reforestation area was identified as the total area disturbed through natural disturbance and harvesting the previous year. For nitrogen fertilization, the researchers determined a rate whereby no nitrogen saturation would occur. From reviewing other research, Chen et al. accepted a critical load amount of 10-19kg N $ha^{-1}y^{-1}$ and an average atmospheric deposition level of 2.5 kg N $ha^{-1}y^{-1}$ and claimed those numbers indicated that an appropriate maximum nitrogen fertilization rate would be ~7.5 kg N $ha^{-1}y^{-1}$. To "be conservative" they then used two-thirds of that number. Despite the way they reached their decision on what level of nitrogen fertilization to use, their reasoning behind why they chose to apply it to only 30% of Canada's forests seemed to be more well-reasoned. To set the baseline number used for forest harvest rates they selected a maximum allowable harvesting increase of 20%, because harvest rates had been 20-30% below allowable harvesting amounts and they wanted to ensure the long-term sustainability of the forests. Finally, they used a "business as usual" scenario from the IPCC IS92A to set the upper bound of future climate and, for the lower bound, used "climate data extrapolated using linear relationships derived from the historical period 1895-1996". For bounding their disturbance scenarios, they chose an average rate from pre-industrial times to 1996 on the lower end and doubled it for the upper.

Despite the challenges in explaining clearly their methods, Chen et al. presented their results with good explanation as to why they were reached. For example, with respect to the baseline simulation, they provided time frames during which Canadian forests historically were either a small source (1895-1905), a large sink (1930-1970) or a small sink (1980-1996) and the reason for each – fires and insect infestations, forest regrowth in formerly disturbed areas, and a net balance between negative effects of disturbances and positive effects of non-disturbance factors respectively. They also indicated that under low disturbance the forests would become a larger sink and a small source under high disturbance. Their primary result from these simulations was that considerable uncertainty is associated with any projection of the future carbon balance of Canadian forests.

Unlike Chen et al. (2000), who were looking at ways to increase carbon storage, Kurz and Apps (1995) simulated six scenarios of potential future carbon budgets – the exchange of carbon between forests and the atmosphere – for the Canadian boreal forest. Each scenario by Kurz and Apps was based on assumptions about natural disturbances, reforestation rates of disturbed land and converting non-stocked land to productive stands. They excluded from their study ecological and economic aspects for each scenario.

To accomplish this investigation, Kurz and Apps used an earlier version of the model used in the current study (CBM-CFS3). This model differs from the In-TEC model used by Chen et al. in that it is based on growth and yield curve data commonly used by operational foresters for timber supply analysis and forest management planning (Kurz et al. 2009). More explanation of the model is given in the methods section of this paper. The data required for Kurz and Apps' forecasting included the age-class distribution of the forest, along with the growth and yield curves. The primary reason for exploring these different scenarios was built on the carbon budgets that would result from forest management policies based on natural disturbance rates, replanting rates (disturbed areas), and increasing productive land area. They also listed a number of assumptions regarding constant disturbance rates, harvesting practices, and insect infestations. Their scenarios were run from 1990-2040, with a retrospective model run from 1920-1989.

What the authors found through the retrospective analysis was that "changes in the area annually disturbed greatly influence biomass and soil carbon dynamics", which translates into similar net carbon exchanges with the atmosphere; and disturbance regime changes shifted the age-class structure of the forests and forest age. The results of the future-looking scenarios were presented in a simple table that showed whether the change in ecosystem carbon was positive or negative for each scenario. Selective conversion (of non-stocked to stocked stands) showed the greatest increase in ecosystem carbon with a total of 9.2 Pg C, while high fire, not surprisingly, came in last with -1.4 Pg C. Although the results showed an upper bound, Kurz and Apps pointed out that it would require long-term investments of time and money, actual net uptake of carbon will be smaller for a number of reasons associated with model assumptions or lack of consideration of certain real world aspects such as afforestation occurring on marginal agricultural land. There is little in the Canadian boreal forest.

The work by Kurz and Apps (1995) is just one example of the forest-related research that can be carried out using the CBM-CFS3 model. As will be discussed in the "Policy effects on Carbon Storage" section, the Canadian Forest Service (2007) used this model to conduct a detailed analysis of its forests to determine how to incorporate them into its Kyoto Protocol carbon accounting requirements. The CBM-CFS3 has also been used to look at insect infestations (Kurz et al. 2008a), wildfires (Balshi et al. 2007), how increased productivity from climate change may offset the negative effects of wildfires

(Kurz et al. 2007), risks from natural disturbances (Kurz et al. 2008b), the effects of harvesting intensity on carbon stocks (Taylor et al. 2008), and estimating the offset of afforestation on private land in Canada (White and Kurz 2005). Li et al. (2003) used the CBM-CFS2 (an earlier version of the CBM-CFS3) model to look at and update 635 pairs of equations associated with belowground biomass net primary production in the model.

Taylor et al. (2008) ran two scenarios to compare the effects of a partial cut and a clear cut on carbon stocks in twenty-four red spruce stands in the Acadian forest in Nova Scotia, Canada. The simulations were run for 240 years, but as with all projections, the assumptions are valid for only 3-4 decades (Werner Kurz, personal communication, April 24, 2009). Despite decreasing reliability with time in the simulations, due to the potential for environmental changes to occur (e.g., wildfire or ice storm, climatic warming), simulations are run for several hundred years to make projections about both short and long term potentials. The methods for this paper were similar to the methods for my study, although their work was done in a public forest. Because they conducted their research at stand level, their data requirements were the same as those that I gathered. The data they needed included age class, disturbance types, growth and yield, and information on disturbances both natural and anthropogenic (management techniques). For their growth and yield curves, the researchers used data from “revised normal yield tables for Nova Scotia” (Taylor et al. (2008). I used a similar approach in my work; I used the provincial average growth and yield curves available through Ontario Ministry of Natural Resources in Peterborough, Ontario. The curves are the result of the Benchmark Yield Curve Project (explained below), which updates Ontario’s yield curves from curves that were devised in the 1950s.

Taylor et al. (2008) found that the forests became a carbon source for twenty years after the initial clear cut, which is the way both sets of stands (i.e., partial cut and clear cut) originated. In year 80 of the simulations, the stands in both scenarios were largely identical in the amount of carbon they were storing. At that point, the FMTs were applied and the scenarios split. By the end of the 240-year simulation, the partial cut scenario became a sink, while the clear cut remained a source, not quite reaching the level of carbon sequestration it attained prior to the FMT.

Policy Effects on Carbon Storage

Policy will play a pivotal role in establishing and supporting efforts to reduce greenhouse gas emissions around the world. With respect to forestry, it has the potential to offset 15% of those global CO_2 emissions (Nabuurs et al. 2007). One important outcome of the Kyoto Protocol was the recognition of forestry-related activities as valid options for reducing CO_2 in the atmosphere (Moura-Costa 2001). According to Moura-Costa (2001), to influence the creation of policy, initiatives to invest in forestry-based sequestration keep developing. In fact, Okuga and Birol (1994) claimed that forests are more important than the oceans in sequestering carbon, because they can be affected by policy. Bonan (2008) echoed this sentiment, stating that land-use policies can be crafted as the climatic benefits of forests become better understood.

What is clear from this list of statements is that policies related to forest carbon are a critical component of addressing global climate change, but they are still fraught with the controversies and challenges mentioned at the onset of this paper. Policies will have to deal with a myriad of issues to be able to support "…well-directed carbon sequestration projects, along with the provision of sustainably produced timber, fiber, and energy [which] will yield numerous benefits" (Canadell and Raupach 2008). Benefits include providing additional income for rural development, prospects for conservation and other environmental services, and support for indigenous communities. One example of the importance of this came from Gutierrez (2007), who found that small-scale forest farmers in Costa Rica are excluded from the market for carbon services. Moreover, the partnership between climate protection and ancillary benefits, such as sustainable forestry and landowner compensation for it, will determine ultimately how much carbon is sequestered (Canadell and Raupach 2008) around the world. As Canadell and Raupach (2008) pointed out, well-directed carbon sequestration projects would yield multiple benefits.

Current climate change negotiations related specifically to forests center around the role of mitigation activities in developing countries, namely reducing emissions from deforestation and forest degradation (REDD) and sustainable management of forests and enhancement of forest carbon stocks (RECOFTC 2010). Overall mitigation activities within the global forest sector to aid in stabilizing atmospheric greenhouse gas concentrations was deemed to be an essential part of the ongoing negotiations as was putting a fair price on carbon from both market-based incentives and government subsidy perspectives. Equally important, was the ability for participating Parties to take national circumstances and existing policies into account. This latter point is especially important in Canada, where a detailed analysis of its forests using the CBM-CFS3 model showed a greater than nine in ten chance of Canadian forests being a net carbon source during the 2008–2012 Kyoto Protocol implementation period (Canadian Forest Service 2007).

Wildfires and insect infestations were the primary drivers of reduced carbon storage, given that harvests do not fluctuate much through time. Due to the high likelihood that Canadian forests will be carbon sources rather than carbon sinks, the Canadian government opted not to include forest management in Canada's Kyoto accounting. Despite this decision, the carbon impacts of deforestation and afforestation must still be included in the reports.

Furthermore, as the Canadian Forest Service (2007) pointed out, the exclusion of forests from the Kyoto accounting does not mean that Canada will not consider ways to reduce emissions or increase carbon storage in its forests. The right combination of FMTs has the ability to reduce the overall source amount through increases in net carbon storage in both above and below ground carbon pools. Forest management activities, as demonstrated by Taylor et al. (2008), impact the amount of carbon stored in forests.

Management on Woodlots

This is where a set of "Recommended Management Actions" created by Carlson et al. (2010) comes into play. These actions were designed especially for Canada, as the outcomes of a workshop where forest, peatland and climate experts were convened (in 2007) to identify FMTs that would support these ecosystems within climate regulations (Carlson et al. 2010). The result was eleven different management actions that addressed climate change, while incorporating conservation and wood products. Their list offered seven main ways to minimize negative impacts on Canadian forests and peatlands. Their first recommended action was to reduce deforestation and increase afforestation. In fact, Ontario has committed to planting trees on 25,000 hectares in the southern part of the province by 2020 (Government of Canada 2007). It is part of the provincial “Action Plan on Climate Change”. With respect to forest management techniques, Carlson et al.(2010) proposed enhancing carbon storage in three ways – reducing soil disturbance and maintaining woody debris, incorporating silviculture practices geared toward making stands more productive and making regeneration faster, and extending rotation periods. Other recommendations made by the researchers, included logging avoidance, minimizing peat soil extraction and soil disturbance, reducing emissions from forest sector activities, and reducing the impact of climate change-induced natural disturbances such as fires and insect infestations. However, they noted that balanced and regional perspectives must be taken into consideration to ultimately reach the optimal results. Still, this paper is an example of efforts that begin to bridge carbon storage and policy while addressing forest management.

The Ontario Woodlot Association (OWA) (2009) stressed the importance of implementing good forestry practices. OWA points out that good forestry practices add volume to forests at a faster rate than non-managed forests. One woodlot owner’s forest has increased fourfold over the past thirty years due to the regular thinnings he did on his property. Removal of diseased or infested trees was also pointed to as an important way to maintain the health of a woodlot. OWA included a brief discussion about the ways in which sustainable forestry practices that remove poorly performing or poor quality trees allow the remaining trees to grow faster and do a better job of storing carbon. They concluded by talking about the role that firewood can play as an energy source to reduce fossil fuel usage. They claim that, “burning wood from sustainably managed forests is considered carbon neutral.”

Chapter 2

Methods

This chapter is divided into three sections. The first section describes the location, within Ontario, where data for the study was collected from private woodlot owners. The second section discusses the specific methods used in creating, disseminating and cleaning the responses from the survey. In the final section, I describe the methods for the CBM-CFS3 model simulations.

Site Location

The research area for this project is in Ontario, Canada. The province of Ontario covers 107.6 million hectares; 66% or 71.3 million hectares of which are forested. Its forests are broken down into four main geographical areas (Table 1). According to Ontario's Ministry of Natural Resources (OMNR), 7.6 million hectares are privately owned. That is to say that 11% of forested land in the province is held by private landowners. The 1.8 million hectares of private forests in southern Ontario represent 3% of Ontario's forests.

Region	Forested Area (%)
Hudson Bay Lowlands	20
Boreal Forest	59
Great Lakes-St. Lawrence Forest	20
Deciduous Forest	1

Table 1. Geographical distribution of forested lands in Ontario, Canada, showing forested area within each region.

As indicated on the OMNR website:

http://www.mnr.gov.on.ca/en/Business/Forests/2ColumnSubPage/STEL02_166334.html)

"About half of the privately owned forests are in the southern part of Ontario. In the southwestern part of the province there is less than 5% forest cover and nearly all of these remnant woodlands are privately owned and have a special ecological significance." It is from the southern portion of the province that I received all of my survey responses (Figure 2.) In southern Ontario, forest composition, productivity, and natural distribution results from the effects of past glaciations on the landscape (Bland and Strobl 2000), which created a diversity of deposits. Additionally, Bland and Strobl (2000) explain that the underlying geology also affects these aspects of a forest. For example, limestone bedrock provides for higher productivity and species diversity than granite or gneiss.

Figure 2. Map of southern Ontario counties. Numbers indicate survey responses from each county (i.e., 7 from Hastings). Nine landowners put Canada as their county, so they are not included in this map, but their woodlots are included in the study if they met all other required criteria. (Provided courtesy of DeMartino Mapping Services ©2011. www.demartinomapping.com)

Surveying the woodlot owners

Content. The questionnaire contained mainly closed-questions, which asked for information regarding data commonly used in wood-supply planning. A completed draft was reviewed by three forest managers and their terminology suggestions and corrections were incorporated into the final questionnaire. The original draft included a question asking for growth and yield curves for each property, but it was removed because each of the forest managers indicated that it was information that woodlot owners simply didn't have. Instead, they recommended gathering information that would allow me to create or acquire growth and yield curves. Therefore, forest inventory information, such as species, forest type, area, site class, age; and information about past and planned management activities, like harvesting and planting were all addressed in the survey. The questions were designed to obtain the criteria necessary to complete the environmental modeling of the stands using the CBM-CFS3, a forest carbon model. Through the online survey, landowners were asked if they had specific information about each required piece of criteria (e.g., "Do you have information on the specific site index or site class for compartment1?). If they answered "no", they were re-directed to a question that allowed them to choose from a range of options (Table 3). The hard copy of the survey addressed the questions similarly (Appendix A), where the landowners could write in the information or choose between the same range of options offered online.

Dissemination. Hard copies of the survey and cover letter (Appendix A) were sent out to the 1100 members of the Ontario Woodlot Association as an insert in their quarterly newsletter in fall 2009. A link to the online version of the survey, supported by Survey Monkey, was also included on the hard copy. This link took landowners to the Ontario Woodlot Association homepage, where there was a direct link to the survey on the Survey Monkey website. The Ontario Woodlot Association Executive Director, also emailed the questionnaire as a fillable PDF to the members on the organization's listserv.

Responses received. I received 86 responses. Fifty-seven woodlot owners replied electronically, using the online survey. Twenty-nine replied by mail using the hard copy. I entered the surveys that were received by mail into the online survey so as to keep all surveys in the same format. Survey results were compiled on the Survey Monkey website and exported into a single Microsoft Excel spreadsheet. From there, the data was cleaned. In all, 63 properties totaling 135 stands were accepted for the modeling component of the project.

Data cleaning. To clean the data, I went through the information provided for each stand on each woodlot. Of the 86 surveys received, 23 properties were removed from the process due to lack of required information or incomplete surveys. One respondent found the questions confusing and was not able to complete the survey with enough detail to include his/her property. Missing information that resulted in immediate removal from the study was for the categories: tree species, stand size, age of species and percentage of stand occupied by a species. Within these categories, answers such as "old" or "100+" for species age were not specific enough, thus the stand would be removed. However, when an age range was given, I selected the 75th percentile as a representative age for the stand. The only exception to this was in the case that a planting was the most recent forest management technique used on the stand; in this instance, I used the 25th percentile of the given age range, as more trees were likely to be younger by virtue of the planting.

Answers missing from certain categories did not result in the immediate removal of a stand from the study. For example, soil type could be missing as long as there were other combinations of components, such as soil moisture and depth, which were answered. Aside from soil type these "combination" categories included soil moisture and depth, site class or index (stand productivity), and basal area (stand stocking density). In some instances, the stand developmental stage could be surmised based on other information provided by the landowner in the questions where they were given the opportunity to provide additional notes of interest about a given stand.

Section 1 of the questionnaire asked basic descriptive questions, the first of which was: In what county is your woodlot located? Nine landowners misread the question as country and wrote in Canada. However, if the rest of their survey contained the required information, the woodlot was included in the survey results.

Two key areas where the data underwent significant cleaning were stand age and stand area. In the case of the former, most stands contained multiple species of different ages. However, the CBM-CFS3 forest model used for the carbon storage tests on this data allows for only one stand age. Therefore, I used a weighted average, based on the area occupied by each species, to establish a single age for the stand.

To obtain the growth and yield curve data required by the CBM-CFS3 model, I had to provide the Ontario Ministry of Natural Resources (OMNR) with stand information whereby the stand area was made up of 100% forest. This was the second area of significant cleaning. A number of obstacles within the survey response information had to be corrected for me to provide the OMNR with the correct data. Some respondents listed multiple species as a single species, while other percentages occupied by listed species did not add up to 100% for the stand. This resulted in the resizing of some stands and the creation of additional "stands" to accommodate all the species listed so as to include as much area as possible. In one instance, a landowner noted a four acre pond on the stand, so the stand area was reduced by 4 acres to remove the pond and create a 100% forested area.

To determine the actual percentage of a stand occupied by a given species, the species' original percentage occupied was multiplied by the total original acreage listed for the stand. This gave the actual acreage occupied by the species. The actual total acreage for each species was added together to obtain the actual acreage that equaled 100% forest for the stand (Table 2). Then, the actual acreage for each species was divided by the new actual stand acreage to get the actual area percentage for each species.

	Original		Resized
Species	% Area	Acres	% Area
White Ash	15	2.25	28
Sugar Maple	10	1.5	19
Beech	10	1.5	19
Pignut Hickory	10	1.5	19
Red Oak	8	1.2	15

Table 2. Example, using stand 36A data, of resizing woodlot stand from 15 acres to 7.9 acres.

It should also be noted that, when multiple species were listed as a single species, the percentage was split evenly between them (i.e., 4 species occupying 12% = each species listed individually occupying 3%).

Lastly, there was some data cleaning involved in the FMTs. This was done for two main reasons. First, information from more than one answer had to be used to determine the actual technique used. For example, when asked what the most recent FMT that was used on a given stand was, the woodlot owner might have said a clearcut. Then, when given the option to include additional information about the stand, the percentage of the clearcut – 40% – was written in; in such a case, I changed the FMT to "40% clearcut"

Information from multiple questions was also used to determine, for example, the type of thinning done – commercial or pre-commercial. Second, as much as possible, I wanted the data to be in the same language. That is to say if a landowner wrote “20% harvest” or “20% logging” as a FMT, this was changed to “20% commercial thinning”. In all, nine FMTs were altered in this way, less than 7% of all stands.

Preparing data for OMNR. To create the table needed by the OMNR to provide me with growth and yield data for the model simulations, specific information on productivity, stocking density, moisture regime, and soil depth was required. An example of the information submitted to OMNR is shown in Appendix B. With regard to site class and stocking density, most respondents did not have this knowledge of their woodlot stands. Therefore, if they did not know the information, they were given the option of answering more general questions on broad scales (see Appendix A – Compartment/Stand section). Values were assigned to these attributes based on conversations with my OMNR representative (Table 3). Where the landowner did not know the site class, the site class value was determined by averaging the values for soil moisture and soil depth.

Topic	Measurements		
Productivity/quality (site class)	productive	fair	poor
	1	2	3
Density/stocking (basal area)	dense	medium	thin
	1.0	0.8	0.6
Moisture regime	wet	moist	dry
	1	2	3
Soil depth	deep	modest	shallow
	1	2	3

Table 3. Values assigned in the survey to aspects of the stands for determining growth and yield data.

Finally, the spreadsheet was emailed to the OMNR and run through their database to acquire growth and yield data for each stand.

Simulating carbon storage on the woodlots

OMNR database. Because I had no growth and yield data for individual stands, I acquired the Ontario provincial average growth and yield curves that are available through Ontario Ministry of Natural Resources (OMNR) in Peterborough, Ontario. In 1999, the Canadian Ecology Centre-Forestry Research Partnership was formed to improve Ontario's yield estimates (Stinson et al. unpublished). The partnership developed the Benchmark Yield Curve Project. This was done to align with Ontario's forest management plans, which rely on yield curves for wood supply calculations and growth projections (Sharma et al. 2008). The result is a database of several thousand actual forest plots. The plots are permanent sample plots and they are measured on a 5-year re-measurement cycle (Sharma et al. 2008).

The forest type that most closely matched my data sets was selected for each stand, then adjusted based on that stand's species proportion, site class and stocking density. This process allowed me to obtain the most accurate growth and yield curves available for each stand. As Stinson et al. (unpublished) claim, inaccuracies arise when mixedwoods are treated as a homogenous forest type from a yield perspective. By utilizing data from the Benchmark Yield Curve Project rather than more generic curves, my results were more reflective of the actual stands. Only field measurements of these stands would make the results more accurate. Finally, to have the yield data from OMNR align with the CBM-CFS3 model parameters, I interpolated the values for the 10-year age intervals 10, 20, 30, etc. format utilized by the CBM-CFS3 from of the OMNR yield data, which ran in 10-year intervals of 5, 15, 25, etc. This allowed me to incorporate that information easily into the import file.

I used the same process to generate growth and yield curves for six individual tree species, which I used in some of the clearcut and wildfire simulations. I wanted to create an average stand for each of the six species, rather than a high or low quality stand, but the OMNR had only high and low quality categories. Therefore, I took the mean of the high and low quality stand curves to represent an average quality curve. Once that curve was established for each of the six individual species, I interpolated the data the same way I did for the curves for my actual data.

CBM-CFS3 model and FMTs. The forest carbon model used in this project is the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3), which is an empirical yield curve driven model. As Kurz et al. (2009) explained, forest carbon dynamics models are divided into two categories – empirical yield curve driven and photosynthesis growth driven. Chen et al. (2000) used a photosynthesis growth driven model called InTEC. Kurz and Apps (1995) used an earlier version of the empirical yield curve driven model that was used in this study.

The CBM-CFS3 was developed by research scientists at Natural Resources Canada and is used for forest carbon accounting. The model is a Windows-based software modeling framework that can be utilized at multiple levels, from stand to landscape-level forests. It is also the central model of the Government of Canada's National Forest Carbon Monitoring, Accounting and Reporting System (NFCMARS). CBM-CFS3 calculates forest carbon stocks and stock changes in multiple ways. It monitors past forest management practices and projects how those practices will behave in the future. The model creates, simulates and compares a variety of forest management scenarios to assess the impacts those practices will have on carbon sequestration. It is compliant with requirements under the Kyoto Protocol and with the Good Practice Guidance for Land Use, Land-Use Change and Forestry (2003) report published by the Intergovernmental Panel on Climate Change (IPCC).

The CBM-CFS3 contains two main carbon pools – biomass and DOM (dead organic matter). Carbon can be transferred between these two carbon pools when an FMT is applied: carbon stored in the biomass carbon pools (of which there are 10) is decreased and transferred, in part, to the DOM pools (of which there are 11) (Kurz et al. 2009). However, the CBM-CFS3 also tracks changes on an annual basis and not only when a disturbance occurs. As Kurz et al. (2009) explain, annual changes in the carbon stocks from growth, decay and other variables are simulated in the model. In the dead organic matter (DOM) pools, standing dead trees are represented above-ground, while organic and mineral soil horizons are found in the below-ground DOM pools. The biomass pools have pools both above and below ground too. Above ground pools include foliage, merchantable stemwood for both hard and softwood, and branches and snags. Below-ground biomass pools are represented by coarse and fine root for hardwood and softwood. Additionally, the pools are further broken down into very fast, fast, medium, and slow decay rates. The CBM-CFS3 also includes a pool for carbon released to the atmosphere and one to the forestry sector in the form of harvested timber.

The CBM-CFS3 model includes two potential tools for simulating data – the Stand Level Project Creator (SLPC) and the CBM Standard Import Tool (CBM-SIT). I used the former for some preliminary simulations to assist with determining which FMTs would constitute my selected scenarios for use on my actual data. The SLPC is a seven-step process that requires manual input of stand information into the CBM-CFS3, whereas the

CBM-SIT utilizes a set of spreadsheets that are imported as a single Microsoft Excel workbook. However, both require the same data inputs.

For a series of preliminary simulations, I used a standard set of growth and yield curves, known as the Plonski curves. These curves were developed by Walter Plonski in the 1950s and, until recently, served as the “basis for most wood supply calculations and growth projections in Ontario” (Sharma et al. 2008). I selected the Plonski curve for six different tree species – trembling aspen, white pine, red pine, tolerant hardwoods, spruce, and white birch – and applied several disturbance types to each, which in the CBM-CFS3, are synonymous with FMTs. That is to say that, in the CBM-CFS3 model, the term “disturbance type” is used to represent both natural disturbances and FMTs. The FMTs I selected are options that are readily available within the CBM-CFS3. Based on my preliminary simulations, I developed four sets of FMT scenarios (Table 4) to apply to my full set of stands. In the first and second sets, I applied the selected FMTs at year 25 of the simulation only, while in the third and fourth sets of FMTs, which pertained to rotational intervals, I implemented the FMTs at a given recurring interval during each simulation (e.g., 40-year intervals over the 300-year simulation).

Once the simulation scenarios were selected, I created a series of worksheets, within a single Microsoft Excel workbook, that are required for the import process in the CBM-CFS3 (Table 5). With regard to establishing stands and their carbon levels, the CBM-CFS3 requires information about the historic and most recent FMTs used on the woodlots, the growth and yield curve data, and stand size and age. All of this information must be included in the worksheets before they can be imported into the model. I made the worksheets using my actual survey data and the growth and yield curve data from OMNR. I imported the workbook into the model as a single project using the CBM Standard Import Tool. For each simulation, I changed the name of the workbook to reflect the FMT to be simulated and re-imported the workbook under the name of the FMT. Finally, I exported the results for each simulation back into Excel for analysis.

Set 1 – FMTs	
Natural Succession (Baseline)	50% commercial thinning
10% commercial thinning	Clearcut harvesting with salvage
25% commercial thinning	Clearcut harvesting without salvage

Set 2 – Clearcuts (CCWS and CCWOS) with Transition to a New Species	
Trembling aspen	Tolerant hardwoods
White pine	Spruce
Red pine	White birch

Set 3 – Rotation Intervals	
10% commercial thinning 25-year	10% commercial thinning 60-year
10% commercial thinning 40-year	25% commercial thinning 60-year
10% commercial thinning 50-year	50% commercial thinning 60-year

Set 4 – Wildfire at 150 years (NS, RI and RP)	
10% commercial thinning 25-year	10% commercial thinning 60-year
10% commercial thinning 40-year	25% commercial thinning 60-year
10% commercial thinning 50-year	

Table 4. The four sets of simulation scenarios applied to the full set of stands from the survey. Set 1 is forest management techniques (FMT) only, applied at year 25 of the simulations. Set 2 is two types of clearcuts one with salvage(CCWS) and one without salvage(CCWOS), also applied at year 25. Each clear cut was run once for each transition species listed (and for natural succession in set 1). Set three includes rotation intervals of 25, 40, 50, and 60 years for a 10% commercial thinning and 60 year intervals for the 25% and 50 % commercial thinnings. Set 4 is for wildfires that occur at year 150 for each of the rotation interval scenarios from set 3, excluding the 50% commercial thinning. They are run once allowing the stand to regenerate via natural succession (NS), re-establishing the rotation intervals (RI) and a second time transitioning to a red pine (RP) forest.

The CBM-CFS3 that I used has many strengths, which I highlighted in the literature review section to show the wide variety of studies that are possible with it. Nonetheless, it comes with a list of known issues as well. These issues deal with some dead organic matter pools (DOM), some volume to biomass conversions, and general functionality related to projects with multiple ecological zones, imported files, and a stand replacing disturbance bug (Kull et al. 2007). While I encountered some obstacles in this project, it does not appear as though any of these known issues with the model affected my results. However, this project used the CBM-CFS3 model defaults for carbon pools and turnover rates.

Worksheet	How it's used
Age Classes	Defines the age intervals in the growth and yield curves
Disturbance Types	Lists all disturbance types used in the simulation – historic, most recent, and future scenarios
Classifiers and Values	Features that describe the forest type for each stand
Inventory	Contains the information about the make-up of the forest – age, area, species, historic and most recent FMTs
Yields	Growth and yield curve data
Transition Rules	Tells the model what the forest looks like after a disturbance is applied (applies transition species, if desired)
Disturbance Events	The planned disturbances on a stand, when they should occur, how often, and the overall simulation length

Table 5. Worksheets required by the CBM Standard Import Tool in the CBM-CFS3 and how they are used by the model. The worksheets form a single workbook that is imported into the model for simulations.

Chapter 3

Results

This section is divided into two parts. The first part explains the results from the survey, which addresses my first research question as well as the two sub-questions I created based on the observations I made while cleaning the survey responses. In the second part, I present the results of the simulations I did on the CBM-CFS3 model that deal with my second and third questions.

What the survey revealed

The Ontario Woodlot Association has approximately 1100 members, 86 of whom responded to the survey. This represents nearly 8% (7.8%) of the Association's membership. After cleaning the survey responses and removing those respondents whose information was incomplete, the final number was 63 woodlot owners or close to 6% (5.7%) and 135 stands. The total area covered by these stands is 1,386 hectares, with an average stand size of 10.3 hectares.

The information supplied by the surveyed woodlot owners provided insight into my first research question: What are the current management techniques on Ontario woodlots?

On forty-six (34%) of the 135 stands used in the study, natural succession was the most recent FMT applied. That number jumps to 91 stands (67%) when looking at the historical management technique on these stands. The historical FMT is the forest management technique that had been traditionally applied to a given stand. The most recent FMT refers to the technique that occurred last on the stand. Eight respondents did not know the historical techniques, but of those 8, the most recent technique was a planting or afforestation on six of them and natural succession on the remaining two. Figure 3a-b summarizes both the most recent FMT as well as the historical FMT. A complete list of both disturbance types can be found in Appendix C. The second most common recent FMT used was a planting. Clear cuts and 10% thinning came in third, with a long list of additional techniques occurring 1-3 times each – 24 instances of an FMT occur once; nine occur twice and three occur three times.

The remaining results pertain specifically to the answers (submitted by the woodlot owners) related to the information deemed necessary (for them) to know about their woodlots for basic management purposes. I did this investigation to begin to resolve two sub-questions:

> How much do southern Ontario woodlot owners know about the basic forestry assumptions regarding stand structure on their properties?
>
> Why do the woodlot owners know what they know about their properties?

To answer the first question, my findings indicate that the vast majority of landowners lack this specific basic knowledge of their properties. First, as noted in chapter 3, the forest managers, who reviewed my original survey draft, suggested that I remove the growth and yield curve question because woodlot owners wouldn't have it. The second area where owners seem to not have the required information on their properties includes productivity, stocking density, moisture regimes and soil depth.

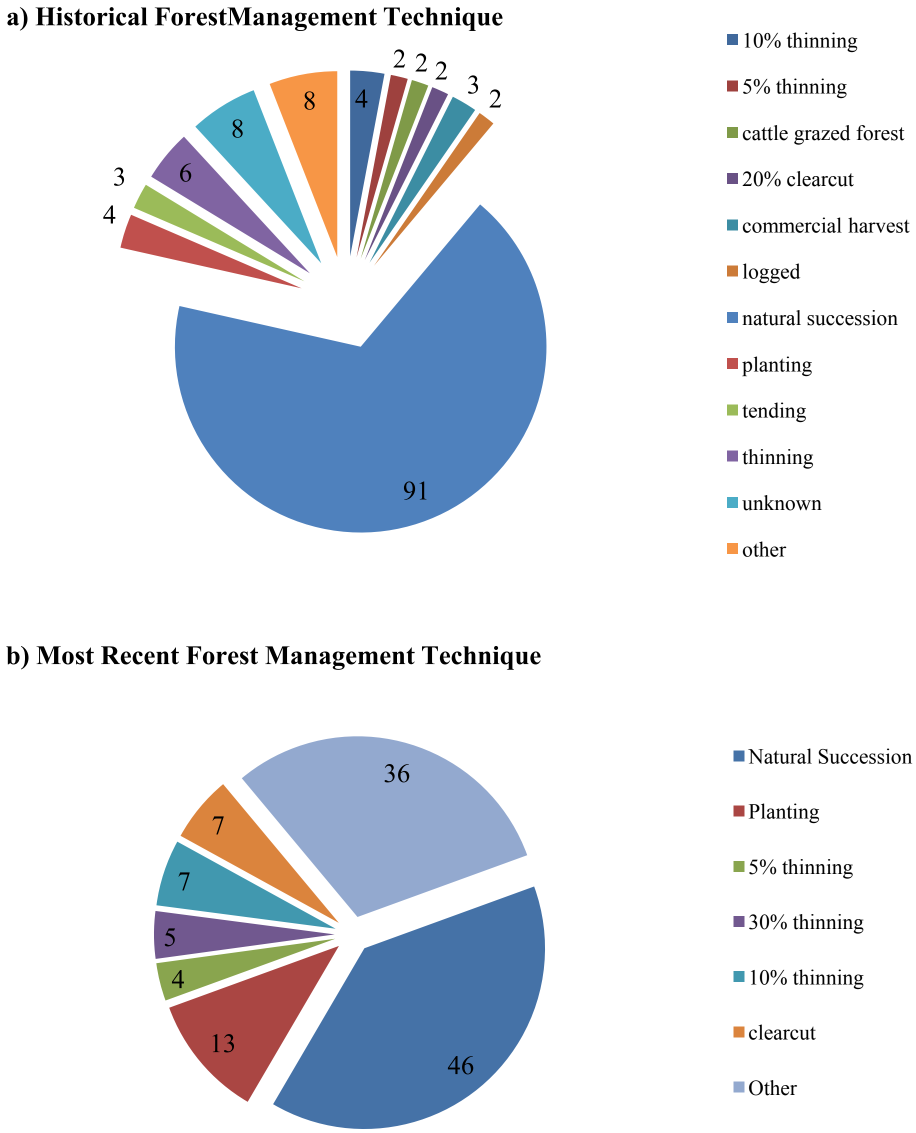


Figure 3a-b. Historical (a) and most recent (b) FMTs used on woodlot stands based on survey results. In the historical data (a), "other" represents a single occurrence of an FMT. For example, there were eight techniques that occurred once. Natural succession dominates the historical FMTs and remains a majority in the most recent FMTs applied to the stands. In the most recent FMTs, "other" represents the occurrence of 24 FMTs that occur once, 8 that occur twice and 3 that occur 3 times. Numbers on chart represent percentages.

This set of answers refers to responses given regarding the first stand on woodlot properties. The reason for this is because all woodlot owners had at least one stand on their property, but 16 (18%) of the 89 respondents did not have a second. Therefore, for the first stand, given the question about site class or site index, 89% of woodlot owners knew neither and responded, instead, using the broad scale option of productive, fair or poor (Table 3). For soil depth, 73.6% did not know. Sixty landowners (70%) didn't know the moisture regime for their stand.

In the discussion that follows in the next chapter, I speculate as to the answer to my second sub-question. However, the short answer as to why woodlot owners know what they know is indicated in the literature and has to do with woodlot demographics such as uses for the properties.

What the CBM-CFS3 simulations indicate

The results presented in this section focus on my second and third research questions. The second question was how much carbon is currently being stored in Ontario woodlots right now. Presently, according to the CBM-CFS3 model, the woodlots represented in my survey are storing 240,753 tons of carbon (Figure 4). The area covered by the woodlots in this study represents <1% (0.074%) of the forested area in southern Ontario; similarly, the carbon stored in the woodlots represented in my study hold 0.077% of the total carbon storage estimated by the OMNR (Colombo et al. 2007). Assuming that the woodlots used here are a representative sample of southern Ontario woodlots and given a total of 1.8 million hectares of privately owned forests in southern Ontario, I can extrapolate, from my results, a total of 313 million tons of carbon in southern Ontario private forests. This amount is comparable to the official provincial predictions for 2010 of 334.8 million tons of carbon (Colombo et al. 2007).

Based on this simulation result, in 300 years, if the landowners let their forests grow without management (natural succession only), the woodlots' carbon storage will increase to 501,236 tons of carbon. That's an increase of 48% (260,483 tons of carbon) during that time period simply by letting nature take its course. This natural succession scenario (Figure 4) serves as the baseline for measuring the effectiveness of the other forest management scenarios in storing carbon.

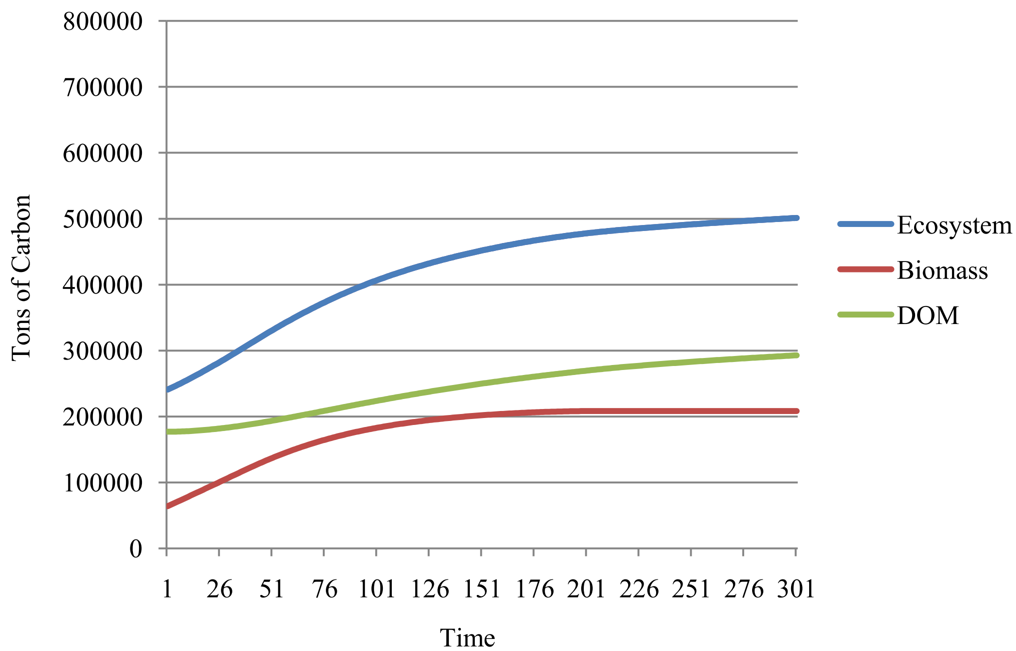


Figure 4. Total carbon stored in the woodlots from the survey at present and over 300 year period if no FMT is applied. (Natural succession) For the total ecosystem, the starting amount is 240,753 tons of carbon. End amount is 501,236 tons of carbon. DOM = dead organic matter. The total ecosystem carbon stored serves as the baseline for this study.

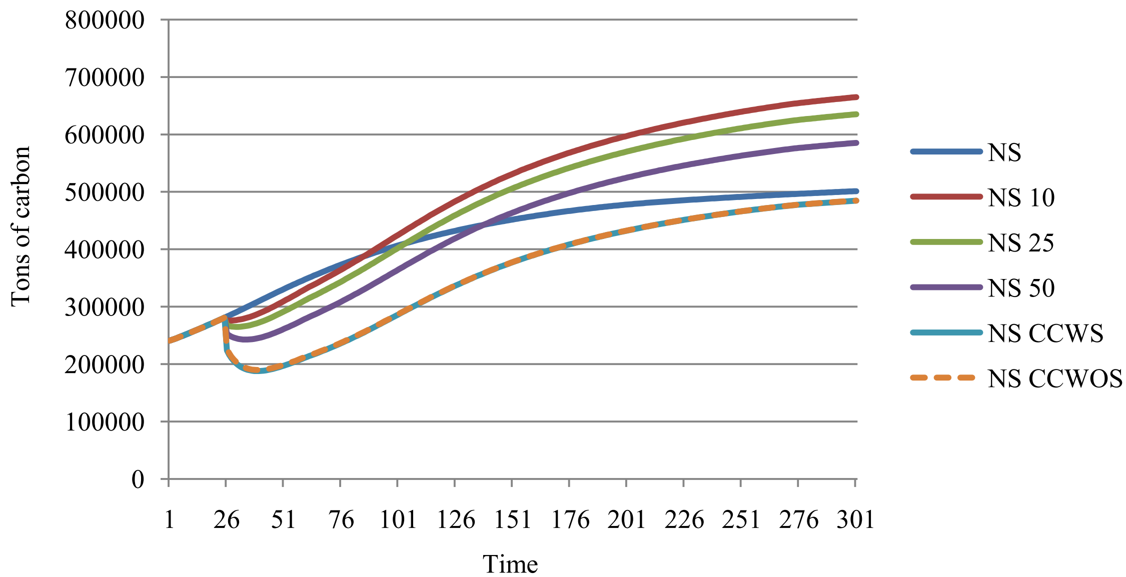
Figure 4 shows the total carbon storage for the entire ecosystem, which in this case represents the woodlot stands, and biomass and DOM, which represent the two major carbon pools used by the model. At the beginning of the simulation, 73% of the carbon was stored in the DOM, with only 27% in the biomass. Under natural succession, however, vegetation biomass increased to 42% of the total carbon with DOM dropping to 58%.

After I established the natural succession baseline, I ran the first set of simulations (Table 4) to determine which of the selected FMTs offered the greatest carbon storage potential. Of the five FMT options, the 10% commercial thinning scenario (NS10) stored the most carbon over time (Figure 5a-c). In this scenario, the initial carbon lost to the thinning was regained in nine years and, within 60 years of the thinning, the NS10 scenario carbon storage surpassed the natural succession baseline. By year 300 of the simulation, the NS10 scenario stored 163,771 tons of carbon more than the natural succession baseline, a 33% increase over the baseline. Carbon storage in the 25% and 50% commercial thinning scenarios also surpassed the natural succession baseline. However, by the end of the 300-year simulations, their increased carbon levels were less (27% and 17% over the natural succession baseline) than those obtained in the NS10 scenario. Additionally, the 25% and 50% commercial thinnings took longer than NS10 to recover the carbon lost during the thinning process. They did not regain the carbon lost by the FMT application until 20 and 36 years, respectively, after the FMT was applied. The carbon stored in the 25% commercial thinning scenario surpassed the baseline 79 years after the FMT was applied; for the carbon stored in the 50% commercial thinning scenario, it took 113 years after the FMT was applied to surpass the carbon stored by the unmanaged (natural succession) forest.

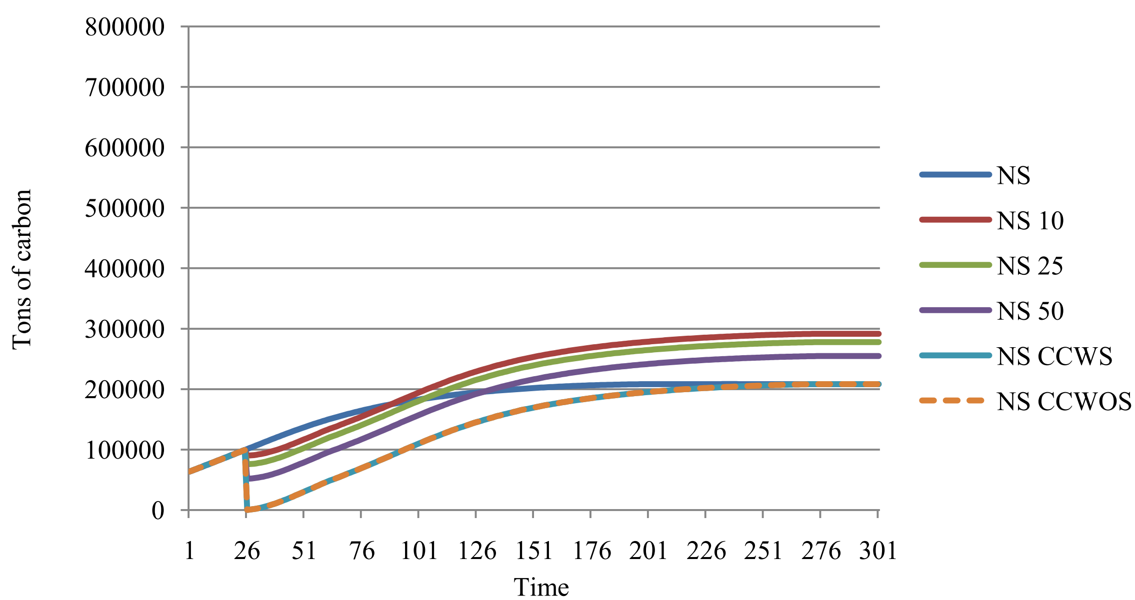
In addition to the commercial thinning scenarios, this first set of simulations included two clearcut scenarios, one with salvage and one without salvage. The difference that this created between the results of the two clearcut scenarios was minimal, an average of >1 ton of carbon/year/hectare, and the difference decreased through time (Figure 6a-b). Moreover, these scenarios did not improve carbon storage on the surveyed woodlots.

However, the clearcut scenarios provided a good opportunity to look at the capacity of different tree species to store carbon. In the second set of scenarios (Table 4), I investigated the potential for this aspect of forest management – transitioning to different tree species – to increase carbon storage in woodlots.

a) Total Ecosystem



b) Biomass



c) DOM

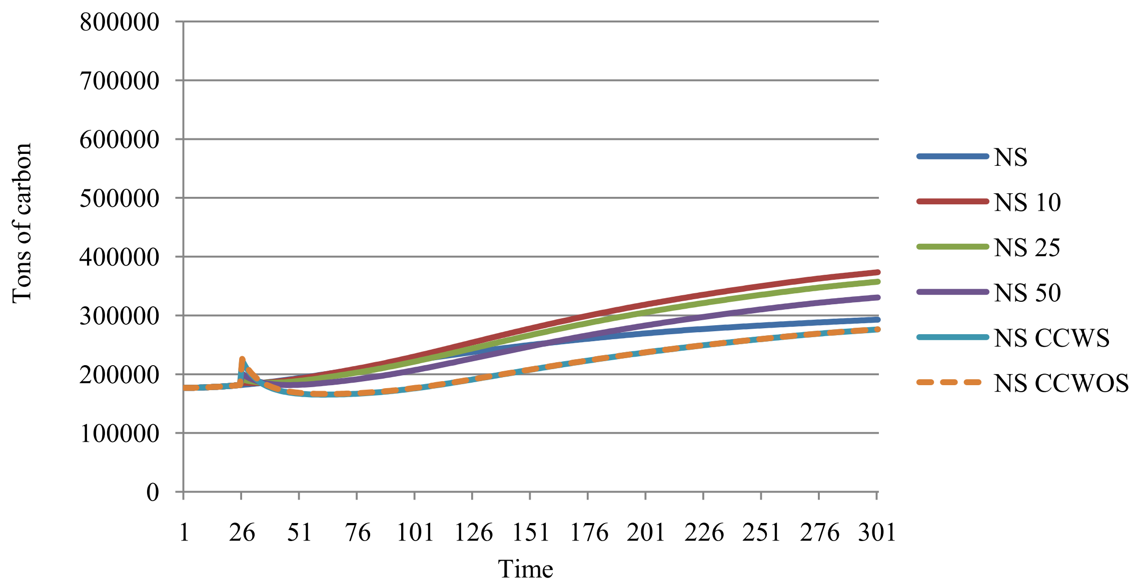


Figure 5a-c. Model simulation results for set 1 FMTs. This set shows carbon stored in a) total ecosystem, b) biomass, and c) DOM (dead organic matter). This figure also shows how carbon moves from one pool to another when and FMT is applied to a stand. NS=natural succession; NS 10=10% commercial thinning; NS 25=25% commercial thinning; NS 50=50% commercial thinning; NS CCWS=clearcut with salvage; NS CCWOS=clearcut without salvage.

For the second set of simulations, I began with my full data set and ran clearcuts with and without salvage followed by a transition to each of six different tree species (Table 4). I applied the clearcuts in year 25, then changed the forest type to a single species which then grew for the remaining 275 years of the simulation. No other FMTs were applied. The results indicated that transitioning to red pine after a clearcut leads to the highest carbon accumulation over time (Figure 6a). Red pine was the only species, of the six selected, that surpassed the natural succession baseline by 40,240 tons of carbon at the end of the simulation. Even then, it took 202 years after the clearcut FMT was applied. By the end of the simulations, all species regained the carbon lost due to the clearcut with a range of 52-213 years to do it. The tolerant hardwoods fared the worst, taking until year 238 (213 years) of the simulation to recover the lost carbon.

As I've shown (Figure 6a-b), the difference in carbon storage between these two clearcut FMTs is negligible. Therefore, only the results of the clearcuts without salvage are shown here (Figure 7).

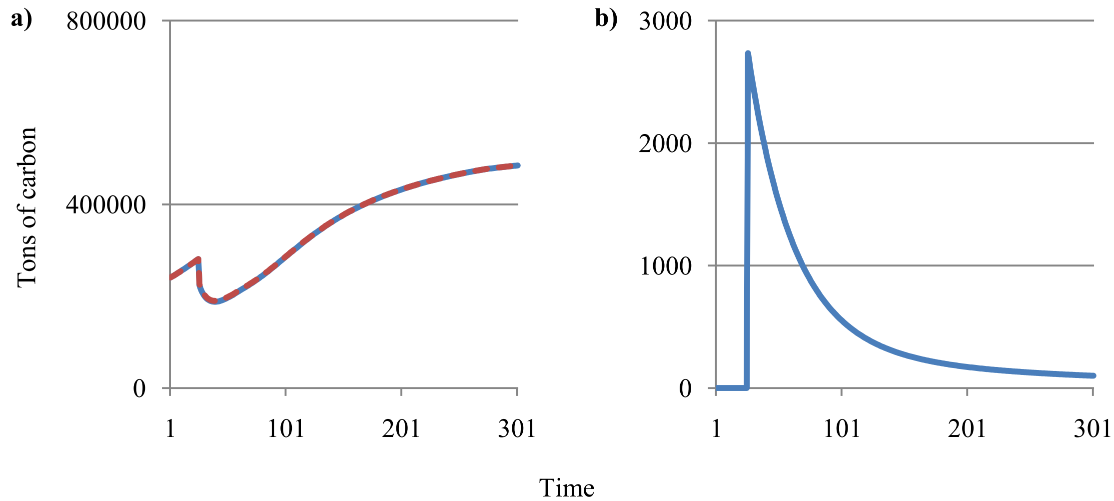


Figure 6a-b. Figure 6a shows the total ecosystem results of the simulations for clear cut with salvage (solid blue line) and clear cut without salvage (red dotted line) where the stands were allowed to regenerate naturally. Figure 6b shows the slight difference in the amount of carbon stored between the two simulations. The simulation without salvage stores only slightly more carbon after the FMT is applied in year 25.

In the third set of FMT scenarios (Table 4), I looked at the effects of rotation intervals and FMT intensity on carbon storage on the woodlots. A rotation interval is the time between subsequent applications of a given FMT on a stand. For example, a 10% commercial thinning with a 25-year rotation interval means that the 10% commercial thinning is applied to the stand every 25 years. This series of simulations included three FMTs applied with four different rotation intervals. Figure 8 shows the results.

Based on the results from the first and second sets of simulations, all four rotation intervals – 25, 40, 50 and 60-year – were applied to the 10% commercial thinning. For the 60-year interval, I also included scenarios with the 25% and 50% commercial thinning FMTs. No clearcut simulations were included, because the clearcuts did not surpass the baseline in storing carbon in the first or second sets of simulations.

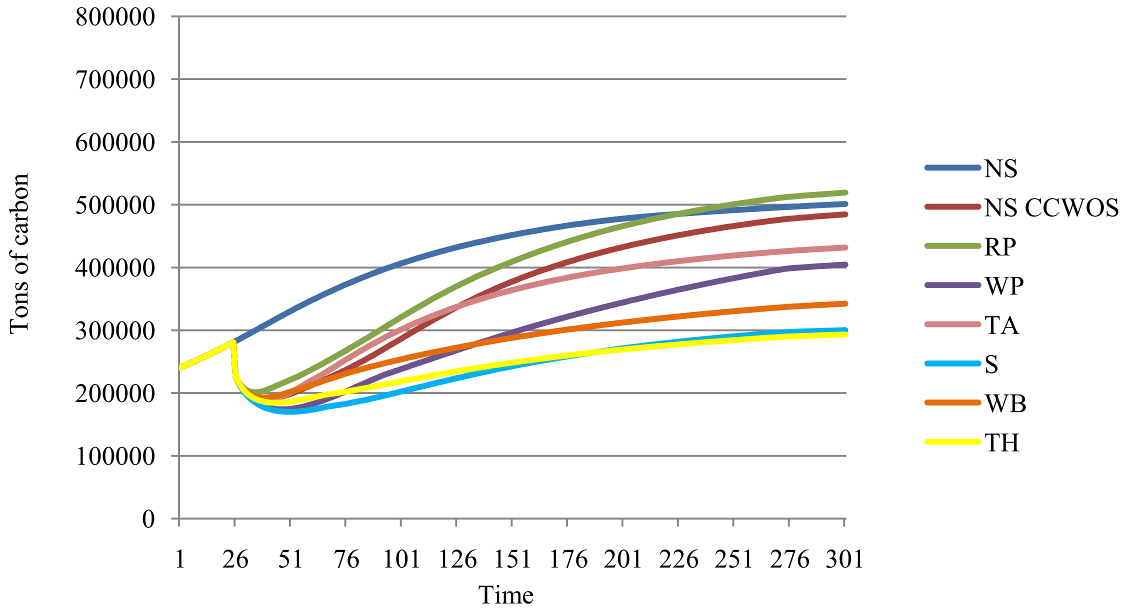


Figure 7. Simulation results showing the effects on carbon storage from transitioning from my original data set to six different species after applying clearcut FMTs at year 25. NS=natural succession – no FMT applied; NS CCWOS=natural succession after clearcut without salvage; RP=red pine after CCWOS; WP=white pine after CCWOS; TA=trembling aspen after CCWOS; S=spruce after CCWOS; WB=white birch after CCWOS; TH=tolerant hardwoods after CCWOS.

The results of these simulations showed increased carbon storage with longer rotation intervals (Figure 8). Conversely, increased FMT intensity, that is thinning larger portions of the stands, resulted in lower carbon storage levels overall. The 50% commercial thinning at 60-year intervals (50-60) scenario, while showing a gradual increase in carbon storage, remained approximately 100,000 tons of carbon below the natural succession baseline by the end of the simulation. This scenario took longer than any of the rotation interval scenarios to recapture the carbon lost to the first 50% commercial thinning that was applied to it, 48 years. The 25% commercial thinning with the 60-year rotation interval (25-60) recovered its lost carbon in 25 years after the FMT application and stored 21% more carbon than the natural succession baseline by the end of the simulation.

However, that amount was still significantly below the carbon storage of the 10% commercial thinning with the 60-year rotation interval (10-60), which had sequestered 60% more carbon than the natural succession baseline by the end of the simulation.

The 10-60 sequestered more carbon over the 300-year simulation than any other FMT. By the end of the simulation, it stored 791,026 tons of carbon. The 10-60 scenario also stored more carbon than the 10% commercial thinning from set 1, where the FMT was applied at year 25 followed by no further disturbance (Figure 5a). That scenario's (the NS10) carbon storage level was only 33% above the baseline by the end of the simulation.

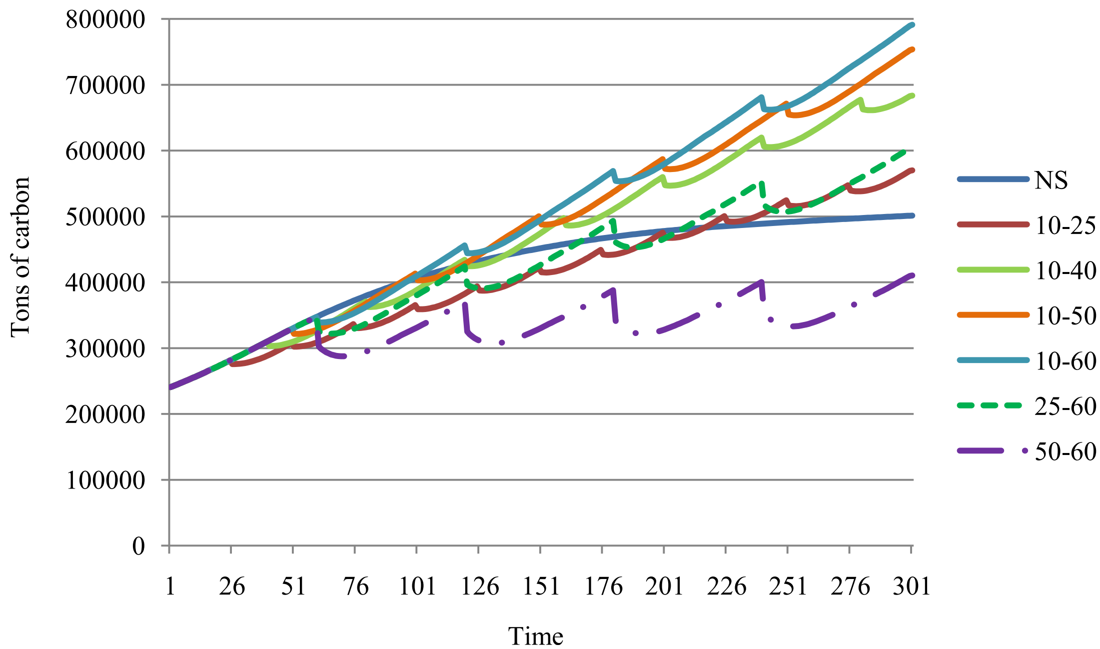


Figure 8. Simulation results showing rotation interval effects in six scenarios against the baseline natural succession (NS) scenario. In the legend, the first number indicates the commercial thinning percentage (10, 25, 50). The second number represents the rotation interval in years (25, 40, 50, 60). For example, the 10% commercial thinning FMT using a 60-year rotation interval stores the most carbon in this set of simulations. The 25% and 50% commercial thinning are depicted with dashed lines.

These results also demonstrated a trend relating to the rotation interval. In general, longer rotation intervals resulted in greater long term carbon storage.

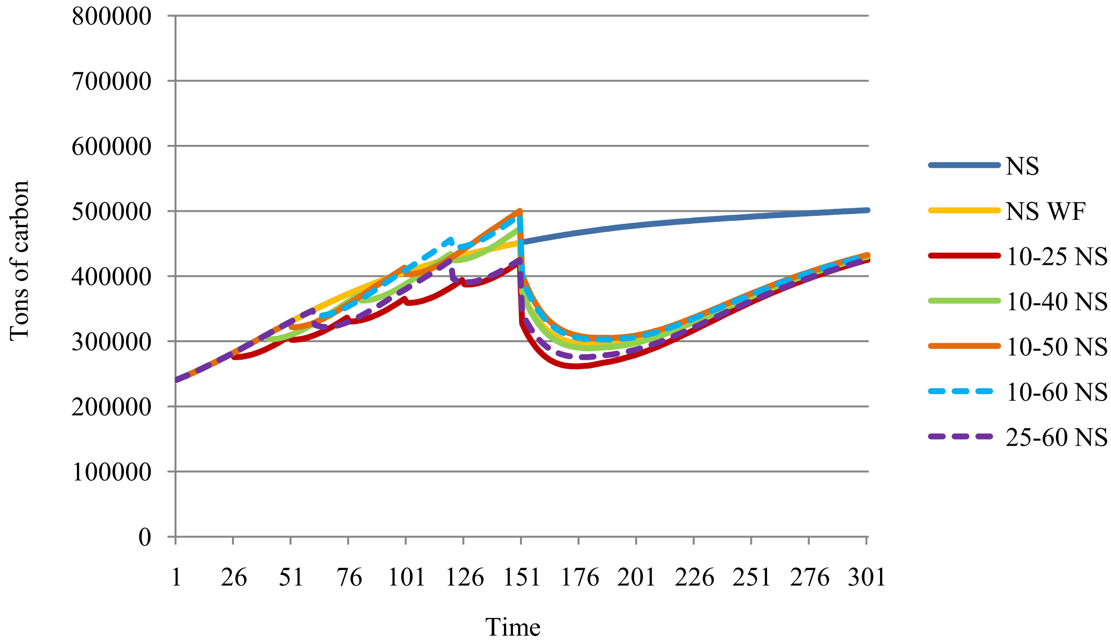
An additional perspective to consider in looking at these simulation results is the short term timeline. To this point of the study, the focus has been on long term carbon storage potential – by the end of the 300-year simulation, a 10% commercial thinning stored more carbon than any other scenario, especially with the longer rotation intervals of 50 to 60 years. However, carbon storage in the decades immediately following the initial FMT does not follow the same pattern. For example, at year 75 of the rotation interval scenarios (Figure 8), the natural succession baseline stores more carbon than any of the FMT scenarios. It takes until between years 85 and 90 for the longer rotation interval scenarios to begin to store more carbon than natural succession. Therefore, in the short term, even a 10% commercial thinning may be no more beneficial in terms of increasing carbon storage than the natural succession baseline scenario in the short term, unless the natural succession baseline is not the only measuring point for carbon storage.

Against the natural succession baseline, many of the scenarios did not fare well, especially in the short term. Removing that comparison and looking only at carbon recovery times improved the appearance of more of the FMTs. This perspective used the carbon level of the stand right before the FMT was applied as the measuring point as opposed to measuring what carbon storage would have been if the FMT had not been applied (natural succession baseline). From this view, recovery times were shorter, because the scenarios had to recover lost carbon only and not surpass the baseline. Once carbon lost to the FMT application was recovered, carbon that accumulated beyond that level can be considered an increase or additional carbon. For example, most of the rotation interval scenarios recovered the carbon lost to the initial FMT application within 11 years. Only the 50% commercial thinning with the 60-year rotation interval took a longer time to recover, 48 years. The carbon it stored beyond that year could be viewed as an increase.

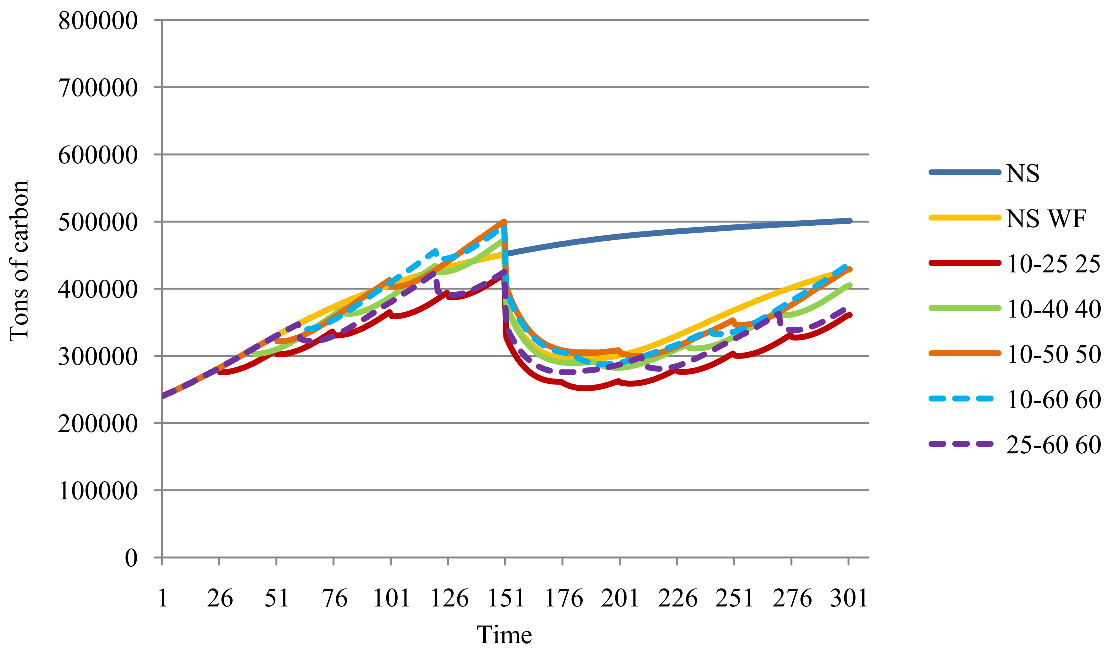
Considering short term carbon storage is an important aspect of forest management planning, partly because of the possibility of changing natural disturbance regimes in the context of long term climate change. Until now, the simulations have not included the possibility of natural disturbances. Barring any natural disturbances, most of the FMTs have shown positive increases in carbon storage over the long term. The exceptions have been the clearcuts and the 50% commercial thinning with the 60-year interval. When a natural disturbance is added to these scenarios, long term projections change dramatically. That is why, to begin to understand the potential impacts natural disturbances have on forest carbon storage, I re-ran the rotation interval scenarios and added a wildfire at year 150, halfway through the simulation timeframe, in three different situations (Figure 9a-c) – wildfire followed by natural succession regeneration, wildfire followed by rotation interval resumption, and wildfire followed by a transition to red pine. These simulations are listed as set 4 in Table 4.

The results show that a wildfire decreased carbon storage dramatically. The three scenarios in the natural succession rotation interval set (Figure 9a) that had passed the natural succession baseline in amount of carbon stored prior to the wildfire – the 10% commercial thinning with 40, 50 and 60-year rotation intervals – in the absence of a natural disturbance, do not do so in the presence of a wildfire (Figure 9a).

a) Wildfire followed by natural succession



b) Wildfire followed by continued thinning with rotation intervals



c) Wildfire followed by transition to red pine

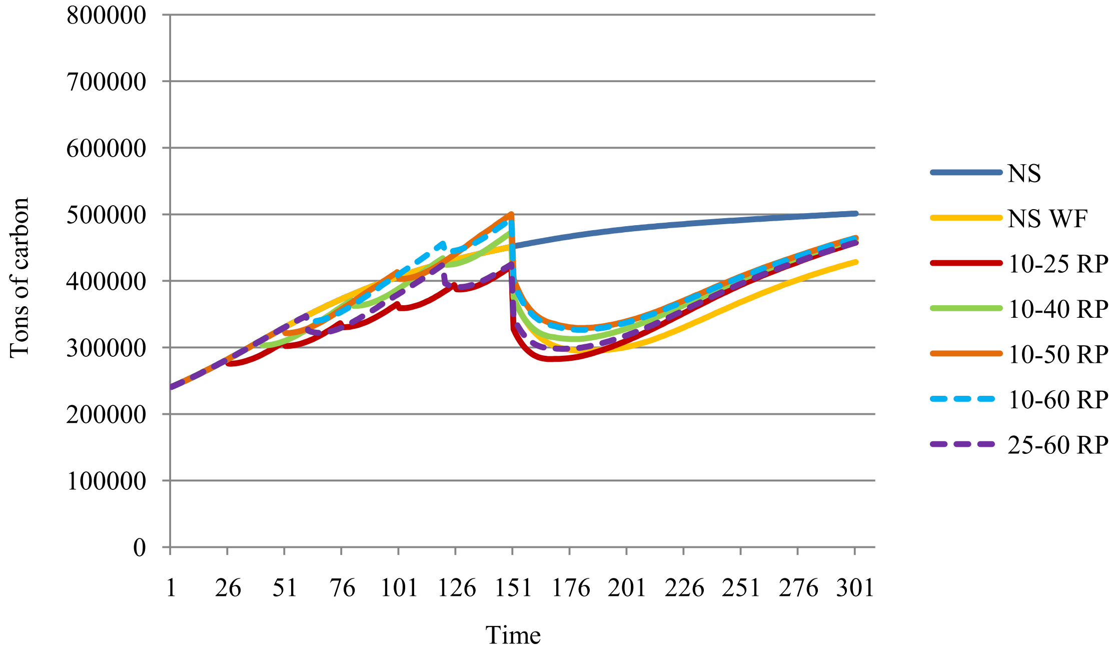


Figure 9a-c. Simulation results showing the effect of wildfire on the rotation interval scenarios. Following the wildfire in year 150, three different scenarios are examined: a) natural succession, b) resumption of the thinnings with the rotation intervals, and c) replacing the former forest type with red pine. In the RI scenarios, the 40 and 60-year intervals are adjusted to address the wildfire, so that the RIs resume 40 and 60 years after the fire. In the legend, the first number indicates the commercial thinning percentage (10 and 25). The second number represents the rotation interval in years (25, 40, 50, 60) and the third numbers or letters represent the FMT implemented following the fire. For example, 25 60 RP=a 25% commercial thinning every 60 years and replacing the stand with red pine after the fire. NS WF=the wildfire applied to the natural succession baseline.

In addition, the two scenarios that appeared to store the least amount of carbon in the long term – the 10% commercial thinning with a 25-year rotation interval and the 25% commercial thinning with a 60-year interval – had recovered the carbon lost by the wildfire by the end of the simulation. In Figure 9b, where the rotation intervals were resumed after the wildfire occurred, the results demonstrated the same trend as prior to the wildfire, with the 10% commercial thinning with a 60-year rotation interval capturing the most carbon by the end of the simulation, but still not recovering all the carbon lost by the wildfire. The same held true for the 10% commercial thinning with a 25-year interval simulation in Figure 9b. However, in Figure 9a, where no FMT was applied after the fire, the 10% commercial thinning with a 25-year interval had recovered the carbon lost by the wildfire and was storing additional carbon.

In Figure 9c, I present the results of simulations where I replaced the existing stand with a single species, red pine, after the wildfire. The results matched those in the natural succession simulations (Figure 9a), but switching to red pine after the wildfire increased carbon levels in all five scenarios. By the end of the simulation, the 10% commercial thinning with the 60- year interval that switched to red pine after the wildfire stored 7% more carbon than the case of the wildfire followed by natural succession. Due to constraints in the model, I could not continue the rotation intervals for the scenarios with a new species following the wildfire, because the FMTs were already assigned to the original forest type and could not be assigned to more than one in a given simulation. Comparing the results from Figure 9a and 9b, continuing with the FMT rotation intervals was less effective than allowing the forests to regenerate naturally in the short term and in the long term the longer rotations were just beginning to store more carbon by the end of the simulations. Based on this, I infer that the trend would be the same if applied to the red pine scenarios.

Chapter 4

Discussion

In this chapter, I discuss the results of the two aspects of this study – What the surveys revealed and what the model suggests is the most effective approach to forest carbon storage based on the data from my survey results. I bring together these two aspects in a third section – How to support carbon storage in woodlots – which is a brief examination of the economics and policy aspects related to forest carbon storage.

Interpreting the surveys

The survey respondents represent 6% of the Ontario Woodlot Association (OWA) membership and, based on descriptions in the literature (Dansereau and deMarsh 2003 and Beckley 1998) and the surveys responses, the woodlots appear to fairly represent an average woodlot in southern Ontario based on woodlot size, diversity of management on the properties, and property uses. According to Dansereau and deMarsh (2003), the average woodlot size in Ontario is 28 hectares. The average woodlot size in my study is 22 hectares. The slightly smaller size of the woodlots in my study is due, in part, to two things. Some of the stands in my study were re-sized (as mentioned above) to make the stand 100% forest for acquiring the growth and yield curves, thus removing ponds and other non-forest features. Additionally, not all stands on every property were used. Some had incomplete data, while others were not forested. For example, one woodlot stand was "muck/wetland, not treed". That 12.14 hectare stand was removed from this project. Beckley (1998) stated that, "Management or lack thereof, is more diverse on small, private holdings. This is reflective of the diversity of values held by woodlot owners." The results of my survey demonstrate a similar diversity as evidenced by Figure 3a-b. For example, the "other" category in the Most Recent FMT applied to the stands included 24 FMTs, each of which was applied to a different stand. Another nine FMTs occurred on two stands each. Finally, the uses for woodlots include things like recreational trails, harvesting, maple syrup production, and cutting firewood (Beckley 1998). All of these activities are represented on the woodlots in my survey. Therefore, I believe that the woodlots in my study are fairly representative of woodlots in southern Ontario.

The survey I conducted of the OWA members addressed my first research question. However, in the process, another aspect regarding basic assumptions about forest knowledge revealed itself. I discovered that the woodlot owners that responded to the survey did not possess the basic knowledge about their properties that is required by the CBM-CFS3 model. Much of this information was also required to determine growth and yield curves from the Benchmark Yield Curve Project used by OMNR. In considering this deficiency of knowledge, another question surfaced regarding why they don't know it. The answers to this question closed the loop on this investigation and began to clarify the reason for the knowledge gap.

One of the most interesting aspects of this part of the study, and an interesting example of the knowledge gap, relates to growth and yield data. Not only is this a primary requirement for the CBM-CFS3 model in order to run any simulations (Kull et al. 2007), but forest management plans in Ontario require it as well (Sharma et al. 2008). These two examples demonstrate the seeming importance of this knowledge. Yet, separately all three forest managers that reviewed my survey draft removed the growth and yield curve question from the questionnaire and assured me that this was information that woodlot owners simply did not possess.

A summary paper written by Buckley (1998) compares four different types of forest management – industrial, co-managed, community, and small private (woodlots). In this paper, Buckley defines each of these forest types from multiple perspectives, and industrial forest managers and private woodlot owners stand in stark contrast to each other in every way he mentions (e.g., goals for the land and forest management practices). The differing definitions between a woodlot stand and an industrial forest stand, noted earlier (page 8), also give an indication of the differences between woodlots and industrial forests. These diverging descriptions begin to explain the disparity in the information provided by the woodlot owners in my survey.

The main reason industrial firms own or manage forest land is “for the production of fibre resources” (Buckley 1998). However, woodlot owners do not seem to posses the industrial mindset, even though, as Buckley points out, the industrial mindset was the dominant forest management approach throughout Canada in the 20th century. Despite that fact, woodlots have existed noticeably on the Canadian landscape since European settlement (Dansereau and daMarsh 2003). To counter the industrial forestry mindset, in PEI, Nadeau et al. (2005) found that small woodlot owners own their woodlots for simple reasons such as it is part of their farm or they inherited the property. Moreover, their survey results indicated that woodlot owners, who had not harvested timber from their properties in the past ten years, had no intention of doing so in the future. Likewise, Dansereau and deMarsh (2003) claimed that woodlot owners own their properties for very different reasons than industrial forestry firms. While certain aspects of income are involved in some of these reasons (Buckley 1998), one overarching theme relates to good stewardship of the land. This, of course, results in clean water through natural filtering processes, protection of wildlife and its habitat (Dansereau and deMarsh 2003), but it also includes human activities like hunting, berry picking, and making maple syrup (Buckley 1998). Responses to my survey included comments such as, "entire property is used for recreation", "this part of the property could have benefited with more tending on the trails and pruning", "management is for wildlife habitat". "Only logging is of dead trees for firewood within 50 ft of cabin", and "overall management objective is wildlife/water fowl management." These responses and the findings of other researchers speak directly to the reasons why woodlot owners do not possess the same type of knowledge about their properties as their industrial forestry firm counterparts. It is simply not as relevant to the daily managing of their properties.

Given these diverse interests in land use, it becomes obvious that the management interests of woodlot owners do not, in general, align with their industrial counterparts either. Dansereau and deMarsh (2003) shed more light into the reasons for this by looking at the professional composition of woodlot owners. In Québec, only 6% of woodlot owners surveyed are forestry professionals. Blue collar workers and retired people make up the majority of woodlot owners in that province. Some of the comments from the respondents of my survey align well with this description as well. For instance, one woman commented that, "My husband had deteriorating health during the past ten years and has now passed on. Help was scarce. It was unwise to go into the forest alone." In conversations I had with woodlot owners at the Ontario Woodlot Association

Annual General Meeting and Woodlot Conference in 2009, I drew similar conclusions. Most of those in attendance were retired or recently bought their woodlot for their future retirement.

As stated earlier (page 9), there is a basic assumption about what woodlot owners should know about their properties (Bland and Strobl 2000). In fact, Bland and Strobl (2000) state that there are “important abiotic factors and some of these aspects of forests and species ecology that managers and landowners should understand in order to develop suitable silvicultural prescriptions.” As was visible in the responses I received to my survey, this is the knowledge gap that exists and which has caused the gap to which Seppälä (2009) referred to with regard to carbon storage. While it may benefit landowners to know this information, the acquisition of it does not appear to be of primary interest to them.

In summary, in order for woodlot owners to understand how their FMTs affect carbon storage on their properties, there is a certain amount of knowledge they should have about their woodlots that enables them to create suitable land management plans (Bland and Strobl 2000). However, many woodlot owners do not fit into these industrial stipulations around forestry knowledge. This is due to two main reasons. First, their goals for their woodlots equate rarely to the goals of industrial forestry firms, who manage their land primarily for wood fibre production. Woodlot owners’ reasons are far more diverse and sometimes quite simple. Second, the make-up of woodlot owners is different from that of industrial foresters. Only a small portion of these private land owners are professional foresters. In fact, who woodlot owners are is as diverse as their reasons for owning their properties in the first place. Given these divergent qualities, it is easy to see why the knowledge gap exists, when the required forestry knowledge is directed toward the comprehension of industrial foresters and not to the opposite end of the spectrum with the small private land owner.

The most effective approaches to forest carbon storage

The results of the CBM-CFS3 modeling offered insight into a variety of FMTs for managing carbon on woodlots. In this section, I discuss the results of my simulations, according to the sets laid out in Table 4, and consider them in both short and long term perspectives. I also compare my finding to those of other studies.

Set 1 – Forest Management Techniques (FMT). The first set of simulations I ran, which followed each FMT with regeneration through natural succession, showed that a 10% commercial thinning offered the greatest capacity for increasing carbon sequestration on the woodlots. This result was over the duration of the 300-year simulations.

Harmon et al. (2009) investigated the effects of two FMTs – partial cuts of 33% and clearcuts – on Douglas fir and western hemlock forests in western Canada using the STANDCARB 2.0 model, which is a small-scale model designed to work specifically at stand level. When they ran their version of a natural succession scenario, which they called a "no major disturbance" simulation, the carbon storage continued to increase gradually for 200-300 years. This aligns with my findings (Figure 4). With regard to their 33% partial cutting runs, their results, again, are comparable to mine. The partial cuts stored more carbon than the clearcut scenarios. Essentially, they found that the smaller the harvest, the greater amount of carbon that was stored. My study results are comparable, where the conclusion that a small commercial thinning (10%) exceeded every other FMT in increasing carbon storage in the stands. My findings also showed that increasing the percentage of area being thinned, decreased the amount of carbon stored (Figure 5a). Interestingly, within their study, Harmon et al. (2009) looked at aggregated versus dispersed 33% partial cuts. Although there was a major impact on species composition as a result of these cutting styles, they found little difference between these styles and carbon storage.

Further support for my findings derives from Taylor et al. (2008), who, like Harmon et al., investigated the effects of clear cut harvesting versus 33% partial cutting. Their study focused on red spruce stands in Nova Scotia. Their simulations ran for 240 years and showed a carbon storage increase in the partial cut scenario but a decline in the clearcutting scenario. These results line up with my own findings and demonstrate the same trend as Harmon et al. (2009), with less cutting resulting in greater amounts of stored carbon.

My survey responses, with regard to FMTs, suggest that large scale harvesting (cuts) is not a common practice on small woodlots. Therefore, aside from the clearcutting scenarios, I did not use any large scale harvesting scenarios in my simulations. Others found similar results with regard to FMTs used on woodlots (Dansereau and deMarsh 2003). On woodlots, where harvesting is not a primary focus of the forest management planning, long term planning may be more applicable than on industrial forest land where harvesting is of primary concern. A long term perspective, though it decreases in reliability through the simulation (page 18), allows for more varied forest management planning and forest policy considerations. Perhaps this is why neither Harmon et al.

(2009) nor Taylor et al. (2008) considered the shorter term view. However, it is important to look at the same simulations over different time frames. Model reliability decreases with time in the simulations. Additionally, short term views of the same information may reveal different outcomes to the same scenario.

For example, looking at the same set of simulations (set 1) over two shorter time frames (50 and 100 years) revealed some different results. Fifty years following the FMT, the natural succession baseline continued to store more carbon than any FMT. Therefore, if short term carbon storage is the goal of the landowner, applying no FMT addresses the goal the best. After another 50 years, the 10% commercial thinning had surpassed the natural succession baseline and was sequestering more carbon. Similarly, four years later, 79 years after being applied, the 25% commercial thinning had increased its carbon storage over that of the baseline. These results allude to the issue addressed in set 3 of my simulations – rotation intervals – which are discussed in their own section.

The two final scenarios in set 1 of my study were clear-cutting with and without salvage. Neither one offered carbon benefits over the natural succession baseline in either the short or long term views of the simulation results. Harmon et al. (2009) and Taylor et al. (2008) drew similar conclusions in their work, where their results demonstrated significant declines in carbon storage after they applied clearcuts to their stands. However, applying a clear cut scenario to the stands allowed for the opportunity to see how different species might assist with increasing carbon storage on woodlots.

Set 2 – Clearcuts with Transition to New Species. In set 2, I used the clearcut scenarios to look at the ability of different tree species, to store carbon and to see how long it would take for a stand to recover the carbon lost during a clearcut FMT. Taylor et al. (2008) applied a similar disturbance to their study, originating all stands from a clearcut scenario. As noted, the clearcut scenarios had devastating effects on carbon storage and recovering the carbon lost by this FMT took a century or more.

Among the six species I selected for the simulations, red pine stored the most carbon over time. Red pine is fast-growing and long-lived, but prefers dry sandy soils (North Central Research Station Red Pine Management Guide). These aspects may be why red pine out-performed other species in my study in sequestering carbon. It is why red pine was chosen as one of the primary species for Ontario's "50 million tree planting program" (Parker et al. 2009). According to Parker et al. (2009), red pine establishes well in marginal areas and has a high growth rate. Other species, such as trembling aspen are fast growing and short-lived, while others like white pine are slower growing with longer life spans.

With regard to species, Liski et al. (2001), working in Finland, found analogous results, noting that tree species create variations in carbon storage, especially when partnered with different FMTs. Their studies showed that over longer rotation lengths Scots pine stored the most carbon, while Norway spruce stored more over short rotation lengths.

More recently, Hennigar et al. (2008) established a hypothetical 30,000 ha forest using species that are common to eastern Canada and divided it into 3 separate areas. Each area contained different species types; area one was softwoods dominated by spruce and balsam fir; area two was mixed woods and consisted of yellow birch, sugar maple, beech, trembling aspen, red maple and white birch; and the final area was hardwoods made up of spruce and tolerant hardwoods. The hardwoods stored the most carbon by the end of their simulations, which they claimed was a result of wood density.

My results point clearly to clearcutting, either with or without salvage, as not beneficial when considering carbon storage. While each species becomes a carbon sink by the end of the simulation, only red pine, which recaptured the lost carbon in year 77, acquired more carbon by the end of the simulation than the natural succession baseline. The other species took longer to recover the lost carbon from the clear-cutting scenarios (trembling aspen in year 89, natural succession in year 98, white pine in year 136, spruce in year 223, white birch in year 139, tolerant hardwoods in year 238), more than a century in most cases. Given the time frames required to recapture lost carbon in these scenarios (more than 75 years in the best circumstance), the short term perspective reinforces the fact that clearcuts do not aid in increasing carbon on woodlots.

Through a different process that examined carbon pools within different forest types, Liao et al. (2010) drew comparable conclusions. Their study revealed that replacing natural forests with plantations, which is essentially what my CCWS and CCWOS scenarios that transition to a single species do, did not increase carbon storage. The carbon levels in the plantations used in their project held far less carbon in their ecosystem pools than natural forests, a difference between them of 79 Mg C ha^{-1}. Their results were consistent based on multiple factors, including stand age, coniferous versus deciduous, native versus exotic species planted in the plantations, historical FMTs, and geographic regions. With the exception of the transition to red pine scenarios, my results were the same.

Set 3 – Rotation Intervals. The simulations I ran in the first two sets of scenarios applied a variety of FMTs 25 years into each simulation, because my goal was to establish likely "best practices" for managing woodlots to increase carbon, more specifically, to determine which FMT would accomplish this. However, I realized I needed to take another step, because a number of studies (Gonzalez-Benecke et al. 2010, Harmon et al. 2009, and Hennigar et al. 2008,) utilized rotation intervals as a major component of their FMT scenarios. For example, Liski et al. (2001) found that Scots pine stored the most carbon with a longer rotation, while Norway spruce stored more in shorter rotations.

Harmon et al. (2009) ran simulations for partial cuttings for eleven different rotation intervals. Over all, their study indicated that forest carbon can be increased by increasing rotation intervals or reducing the percentage of trees harvested. By completing a rigorous comparison between rotation intervals and harvest levels, Harmon et al. identified optimal rotation intervals for each level of harvesting they attempted (20%, 40%, 60%, 80% 100%). This process showed that, with smaller harvests, rotation intervals can be shorter, but rotation intervals had to be increased with larger harvests. They claimed that a 20% harvested system stored 5.5 to 6 times more carbon than that of the 100% harvested system. This was true for all rotation intervals (20, 40, 60, 80, 100, 120, 140, 160, 180, 200, and 250 years), but the highest levels of carbon storage with the smaller cuts were not obtained with the longest rotation intervals. When Hennigar et al. (2008) attempted to maximize forest carbon storage, their rotation interval increased from 60 to 155 years. In my study, results indicated a similar trend toward extending rotation intervals to increase carbon.

Gonzalez-Benecke et al. (2010) noted increases when they extended their rotation intervals from 22 to 35 years. Simulating slash pine forests in northern Florida, they found that the greatest carbon storage occurred with two 33% commercial thinnings, one at 14 and 22 years with a harvest at 35 years. Their results also showed that the effect of thinning on carbon storage was linked to the intensity of the FMT and its timing. However, their investigation also considers “ex situ wood product pools”, which is carbon stored in harvested wood, a feature that is beyond the scope of my research.

The results of my rotation intervals simulations are comparable to these other studies. The longest rotation intervals applied in a 10% commercial thinning simulation stored the most carbon by the end of the simulation. In the case of the 60-year interval, nearly 300,000 more tons of carbon were stored than in the natural succession baseline. The 50-year rotation interval applied to the 10% commercial thinning stored 252,407 tons of carbon more than the baseline, just 37,383 tons less than the 60-year interval scenario. The 40-year rotation also applied to the 10% commercial thinning stored 182,274 tons of carbon more than the baseline. At the opposite end of carbon storage, the 50% commercial thinning with a 60-year interval applied stored 90,896 tons less than the natural succession baseline and 380,687 tons of carbon less than the same rotation interval (60-years) applied to a 10% commercial thinning. This demonstrates clearly the findings of Gonzalez-Benecke et al. (2010) linking decreased carbon storage to intensified FMTs. However, my results show that the negative effect of intensified FMTs can be reduced with a longer rotation interval. For example, when I applied a 60- year rotation interval to a 25% commercial thinning, its carbon storage surpassed a 10%

commercial thinning with a 25-year rotation interval in year 263 of the 300-year simulation.

The short term view of the rotation interval scenarios, again, produce different results. Until year 92, when the 50-year rotation interval applied to the 10% commercial thinning exceeds the natural succession baseline in carbon storage, the baseline is the best FMT at storing carbon. Eight years later, it is surpassed by the 60-year rotation interval applied to the 10% commercial thinning, but that's only because the 50-year interval scenario gets thinned at year 100.

Set 4 – Wildfires at 150 years. Prior to this final set of simulations, natural disturbances were not considered. Natural disturbances are a part of forest cycles. In southern Ontario, those disturbances are more likely to be weather related, such as downed trees from ice-storms, or insect infestations (e.g. gypsy moth, spruce budworm) (http://www.mnr.gov.on.ca/en/Business/Forests/2ColumnSubPage/STEL02_166999.html). However, Ontario's fire season is expected to increase by as much as 25 days as a result of climate warming (Wotton and Flannigan 1993). According to Colombo (2008), fire risk will increase due to higher summer temperatures and increased evaporation that will dry out forest soils and dead and downed trees. Therefore, understanding the effects of a wildfire on stored forest carbon is important, especially as introducing a wildfire disturbance into my simulations changed long term projections dramatically.

Working in the southwestern United States, Sorensen et al. (2011) looked not only at the effects of wildfires on carbon stores, but also on the ways in which pre- and post-fire treatments (thinnings and prescribed burnings) affected carbon storage. Thinnings, though they do not reduce the likelihood of a fire, they did reduce high-intensity fire risks by removing fuel sources. By extending fire occurrence to a 100-year interval, Sorensen et al. (2011) allowed carbon storage to increase. However, they point out that this result was probably an artificially high number since 100 years without a fire in the area (northern Arizona) is unlikely. There 50-year fire interval scenario, which is more reasonable for the dry areas of the southwestern US, lost more carbon earlier and did not regain lost carbon at the same levels as the 100-year interval scenario.

Hurteau and North (2010) took a similar approach in the southern Sierra Nevada in California, where they focused on reducing the risk of wildfire through a variety of thinnings. Their results showed greater carbon recapture after the wildfire by the stands that had undergone thinning, whereas those that had been treated with burns prior to the fire recovered less carbon in the same time frame. However, they also point out the importance of determining the timeframe necessary for the burned forests to recover the lost carbon.

My study approached the wildfire scenarios from a different perspective, though with the same ultimate goal as Hurteau and North (2010), to determine how long it took the forest to recover the carbon lost to the fire. Rather than looking solely at thinning, I considered three different approaches – natural succession regeneration, rotation intervals applied to thinning, and transitioning to a different species. Although steps can be taken to reduce the impact of wildfires (Sorensen et al. 2011, Hurteau and North 2010), recovering the lost carbon was of greater interest in keeping with the goals of this research – to increase carbon storage on woodlots. My results indicate that, after a wildfire, the most carbon is recaptured by transitioning to red pine after a wildfire. The red pine scenarios surpass all others, despite the thinning FMT that was applied prior to the wildfire. A 10% commercial thinning with a 50-year rotation interval transitioning to red pine after the wildfire stores more carbon than any other scenario. It is followed by a 10% commercial thinning with a 60-year rotation interval transitioning to red pine. The highest carbon stored in a non-red pine scenario is a 10% commercial thinning with a 60-year rotation interval that continues after the wildfire. It is followed by the 10% commercial thinning with a 50-year interval and natural succession regeneration after the fire.

How to support carbon storage in woodlots

This study would not be complete without discussing the ways in which my results and those of other similar research provide important information to both policy makers and landowners in deciding how to increase carbon storage on woodlots. In fact, many of the papers cited herein include information on policy and/or landowner incentives (RECOFTC 2010, Canadell and Raupach 2008, Taylor et al. 2008, Nabuurs et al. 2007, Shabman et al. 2002, Moura-Costa 2001, Okugu and Birol 1994). These two components are important pieces in the puzzle, because they encourage landowners to take steps to increase carbon storage to mitigate the effects of climate change.

Shabman et al. (2002) and Nghiem (2009) highlighted the importance of making carbon sequestration in forests economically viable. Similarly, Olschewski and Benítez (2005) look at minimum compensations in Ecuador that would make reforestation a viable competitor to agricultural land uses. Their investigation showed that natural succession after harvest would be an acceptable alternative to replanting, because of the lower cost. Replanting increases costs by about 36% over natural succession. For Canadian woodlot owners, the economics of carbon storage may not be the primary reason they would participate in sequestering carbon on their land. Although Park and Wilson (2007) promote the idea of reforestation in the form of plantations in Canada and note that "managed forests may also qualify for carbon credits", the complexities around woodlot uses and other variables make the likelihood of woodlot owners participating in incentive programs uncertain. Wyatt and Bourgoin (2010) conducted interviews with woodlot owners, woodlot association and timber industry representatives in New Brunswick and Québec, and reviewed documents to determine why certifying small, private forests is not keeping up with certifications on public land and industrial forest land. These certifications are an important tool related to sustainable forest management and are becoming more vital to meeting market demands for sustainably produced timber (Wyatt and Bourgoin 2010). Such a program could easily be transferred to incentive programs for carbon sequestration. Wyatt and Bourgoin (2010) uncovered a situation that links somewhat readily to what I found through my woodlot owner surveys. Canadian woodlot owners are wary of government regulations; they want certification processes to be simple and at no or low cost; provincial governments don't support woodlot certification, but do support woodlot management; and in areas where certification programs are voluntary, owners who choose to become certified are already good land managers.

The last point is the key link to the results of my survey. Simply looking at the current FMTs employed on these woodlots, 34% of woodlot owners are using natural succession as their FMT, another 12% are using FMTs that affect less than 10% of their stand area and a majority of those FMTs being carried out are simply to get firewood or to maintain trails. As stated by Dansereau and deMarsh (2003), only 6% of woodlot owners in

Québec are professional foresters. The majority are blue collar workers and retired people. The survey responses I received and my personal experience at the Ontario Woodlot Association Annual General Meeting and Woodlot Conference in 2009 suggest those characteristics are applicable in Ontario as well. The question becomes: if woodlot owners are suspect of government policies and not interested in obtaining sustainability certification for their harvested products, what would interest them in following a similar path to certification to receive credits for carbon sequestration?

Where do we go from here?

Through this discussion, I have highlighted some important realizations in the results of my study and other related research. Multiple studies have shown that smaller harvests over longer rotation intervals allow more carbon to be stored than more intense harvests or shorter rotation intervals. The devastating effects of clear-cutting on forest carbon storage have also been demonstrated repeatedly. To understand the ability of forests to store carbon in response to natural disturbances is another key component of determining the best ways to increase forest carbon storage. While some researchers focused on fire mitigation efforts to reduce carbon loss when fires occur (Sorensen et al. 2011, Hurteau and North 2010), there was another aspect that I considered, that of determining the best way to recapture the carbon lost because of a fire.

Although some potentially divergent information may exist in these studies, there is one important point to make in that regard. Multiple processes and aspects can play a role in sustaining carbon accumulation in trees (Ciais et al. 2008). Bland and Strobl (2000) list many aspects that affect stand structure and productivity, including bedrock, hydrology, and climate. Species variety also adds to the stand conditions (Jacob et al. 2010). Jacob et al. (2010) looked at stand productivity and, another significant variable in determining carbon storage in their study, stand age. Jacob et al. (2010) state that understanding these different parameters is imperative for developing accurate carbon sequestration strategies. Hennigar et al. (2008) included simulations to look at initial age class structure to understand the effects on forest carbon storage. Gonzalez-Benecke et al. (2010) cite stand productivity as a key factor aiding forest carbon storage in slash pine stands. As was seen in my project, although the growth and yield curves played a major role in determining forest carbon storage in the CBM-CFS3, other input components (e.g., historical and most recent FMTs, species composition, and stand age) influenced forest carbon storage too. Parameters such as historical and most recent disturbance help to construct current conditions on the stands. Stand age also impacts carbon stores. These different variables all point to the complexity of establishing accurate carbon storage numbers and developing the best FMTs to maximize it.

More research needs to be done to address the complexities of forests, forest carbon pools and increasing carbon stored in forests. The studies I cited here, including my own research, provide good insight into the some of the potential ways to address these issues and they line up opportunities for further investigation into them. This research project took a step in that direction by looking at current FMTs implemented on and carbon storage in Ontario woodlots along with potential FMTs that could expand stored carbon on the woodlots in a number of situations (e.g., increasing or incorporating rotation intervals, and recapturing forest carbon after a natural disturbance).

Chapter 5

Conclusion

Carbon sequestration in forests offers Canadian woodlot owners a chance to assist with climate change mitigation efforts (Carlson et al. 2010). In fact, they can play an important role in mitigating the effects of climate change through forest carbon sequestration. By the year 2014, Ontario plans to reduce its carbon emission levels by 6% under 1990 levels, which were 177 million tons of CO_2e (gogreenontario.ca 2007). With a "business as usual" prediction of emission levels of 227 million tons of CO_2e in 2014, achieving this 6% goal requires a CO_2e reduction of 61 million tons from the "business as usual scenario". Toward that goal, over the next four years, woodlots in southern Ontario will store approximately 4.8 million tons of CO_2 of carbon each year, for a total of 19.26 million tons of CO_2.

Yet, woodlots have been neglected by academics relative to attention paid to public and industrial forests. This is a primary area where research can be conducted. For example, my research focused on woodlots, but the other papers cited in this study with respect to forest carbon were carried out in large stands at industrial forestry levels (e.g., Sorensen et al. 2011) and in hypothetical forest stands (e.g., Hennigar et al. 2008). Understanding how the diversity found in woodlots (in size, species composition, ownership, property goals and uses) affects the ability of woodlots to increase stored forest carbon would assist with establishing effective ways to incorporate forest carbon storage into forest planning efforts and policies and incentive programs for landowners. First and foremost, woodlot owners need to understand their properties in terms of how to best manage them, including how to increase stored carbon. More work by researchers at the level of my study would offer the most benefit in this regard. A key aspect of studies conducted here should involve field study to acquire data that is as accurate as possible, including data regarding owner knowledge of their properties.

Second, there are many FMT scenarios that warrant investigation. Simulating individual FMTs, such as in the first set of scenarios in my study, provided good insight into which FMTs would increase carbon stored in forests the most. The leading FMT utilized on the woodlots in this study is natural succession. Essentially 34% of the woodlot owners are doing nothing with their stands. The current carbon sequestered on these properties is estimated, by the CBM-CFS3 based on my woodlot survey data, to be 240,753 tons. The FMT that offers the greatest long-term increase carbon storage is a 10% commercial thinning. Other FMTs increased carbon levels on the woodlots, though to a lesser degree. Clearcuts, with or without salvage did not show any carbon sequestration benefits. The thinning options within the CBM-CFS3 pertained to commercial and pre-commercial. However, other thinning types exist, such a crown thinning, which is a pruning method, which are not an option in the CBM-CFS3.

Third, more studies that look at individual tree species' ability to store carbon would provide landowners with options when considering what trees to plant. For example, in my study, red pine fared better than the other five species I selected. However, red pine is a shade intolerant species and may not do as well on a north-facing slope where red spruce, a shade tolerant species, might store more carbon.

Fourth, rotation intervals can also affect carbon storage positively in the long-term. In my study and others referenced here (e.g., Harmon et al. 2009, Taylor et al. 2008), longer rotation intervals were more effective at storing carbon than shorter ones over the long term. Sixty-year intervals proved to store the most carbon in the long term. In the short-term, natural succession appeared to store more carbon than any of the FMTs I applied, despite and rotation interval. This is an area where much more individualized work could be done, because a single rotation interval will not be applicable to all stands. For example, Liski et al. (2001) showed that carbon storage varied with species and rotation intervals. Some researchers incorporated rotation intervals with harvests (Taylor et al. 2008), demonstrating different goals for forest stands, beyond carbon storage.

Fifth, some studies have looked at FMTs as ways to mitigate carbon loss due to wildfires (Sorensen et al. 2011, Hurteau and North 2010). In contrast, my work looked at the potential ways to recapture the carbon lost to the fire the fastest. More work could be conducted on both fronts. In my study, rotation intervals could not be continued after the wildfire occurred when I transitioned the stands to red pine, because the rotation intervals were assigned to a different forest type. Given that the red pine scenarios post-wildfire resulted in the fastest recapture of carbon lost to the fire, it would be interesting to see if adding rotation intervals to the red pine stands would increase carbon storage even more, especially since the 10% commercial thinning with a 60-year rotation interval applied offers the greatest carbon storage after the red pine scenarios by the end of the 300-year simulations.

The list for future potential work is exhaustive both within and outside of the topics covered in my study. Outside my study for example, changes in natural disturbance regimes should also be investigated. For example, as temperatures warm insect infestations in areas formerly too cold for the insects to exist are increasing (Kurz et al.

2009). One other area of research must be mentioned that was outside the realm of my research, but which is growing in the area of forest carbon storage. Forest modeling research should look at ways to incorporate carbon storage in wood products (Hennigar et al. 2008, Nabuurs et al. 2007), because this keeps the carbon from being released into the atmosphere (Colombo et al. 2007). It will also become an interesting point of discussion in policy and economic conversations around carbon offsets. There is growing trend to include carbon stored in wood products in carbon sequestration tallies. In Ontario, carbon stored in wood products is included in the provincial carbon stocks projections (Colombo et al. 2007).

As this body of research grows and increases our understanding of forest carbon dynamics and forest management strategies, it will help with the creation of policies and incentive programs to support and compensate the efforts of woodlot owners who are attempting to increase carbon storage on their properties.

Still, the key insights in this process were the complexities of woodlots in their stand-make up, ownership and uses. These are what make woodlots so interesting. They contrast industrial forestry in almost every sense and each one is different from the next. This complexity poses a challenge to both research and the creation of policies and landowner incentives. However, the potential gains with respect to carbon sequestration and improving the sustainability of small scale forestry make the effort worthwhile.

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Appendices

Appendix A – Cover letter and survey

Dear Ontario Woodlot Association Member,

Hello, my name is Karen Paquin and I am completing my Master of Science degree in Geography at Concordia University in Montreal. My research area is climate change, specifically looking at carbon storage in woodlots. To accomplish the goals of my thesis project (see box below), I need your help.

I would greatly appreciate it if you could complete the following short survey about your property. The survey is completely anonymous and the answers that you and other woodlot owners provide will be the primary focus of my work. Please take a few minutes to complete the survey and send it back to me at the address below. (If you cannot answer all the questions, please complete as much as you can). You may also complete the survey online. A link to the online survey is posted on the OWA website at <www.ont-woodlot-assoc.org> or you can access it at <www.surveymonkey.com>.

The survey is arranged in two parts: (1) a short section of general questions at the bottom of this page; and (2) a second set of questions that relate specifically to your woodlot and management activities. For this second group of questions, you will answer the same set of questions for each forest compartment/stand (up to 5) on your property. If you have a management plan for your property that includes detailed forest resource inventory most of the information needed to answer the questionnaire can be found there. Other information needed to complete the survey may be found in the compartment/stand history or report of past activities of your management plan.

All completed surveys should be returned to me by October 2, 2009. If you have any questions about the survey, you may contact me at any time.

Once my research is complete, I will prepare a special report that will be posted on the Ontario Woodlot Association's website so that you may view the results. If you do not have access to the Internet, please contact me directly for a hard copy of the report.

Thank you very much for your time and for helping me with this essential part of my thesis research.

Gratefully,

Karen Paquin
Concordia University
Department of Geography, Planning and Environment
1455 de Maisonneuve West
Montreal, Quebec, Canada H3G 1M8
Tel: (514) 848-2424 x2022
k_paqui@live.concordia.ca

My project goals:

1) to determine current carbon storage (quantify it) on Ontario woodlots

2) to compile a list of FMTs being used on those woodlots

3) to run model simulations to show how different FMTs may increase the amount of carbon stored.

Section 1

1. In what County is your woodlot located?______________________________
2. How many acres is your property?______________________________
3. How many acres of your property are forested?______________________________
4. How many forest compartments/stands do you have on your property?______________
5. Property history. How far back does your forest management information go? (number of years)______________________________

Section 2: Please provide the following information for each forest compartment/stand. (If you have more than 5 compartments/stands, you may combine similar stands or select the most productive):

Compartment/Stand 1

Stand size (in acres)______ Soil type_______________ Origin of trees: __planted __natural

Species, including relative proportion of each and ages (list up to five, starting with major tree species)

Species	Proportion of compartment/stand	Age (in years)

Productivity/quality (specify site class, site index)__________________________Or circle one of these 3 options:
Productive Fair Poor

Density or stocking (basal area)__________________________Or circle one of these 3 options:
Dense Medium Thin

Moisture regime__________________________Or circle one of these 3 options:
Wet Moist Dry

Soil depth (in inches)__________________________Or circle one of these 3 options:
Deep Modest Shallow

Development stage (check one): __Immature __Late successional __Two-canopy (seed cut)
__Mature __Pre-sapling __Sapling __Uneven-aged open canopy

Most recent forest management treatment applied and year of application____________________

After treatment, what percentage of forest remained?______________________________

Other treatments used on this compartment/stand in the past 50 years and dates if available (i.e., commercial harvest, pre-commercial thinning, tending, planting, none, etc.)__________________________

____

Compartment/Stand 2

Stand size (in acres)__________________ Soil type________________________________

Species, including relative proportion of each and ages (list up to five, starting with major tree species)

Species	Proportion of compartment/stand	Age (in years)

Productivity/quality (specify site class, site index)__________________________Or circle one of these 3 options:

Productive Fair Poor

Density or stocking (basal area)____________________________________Or circle one of these 3 options:

Dense Medium Thin

Moisture regime____Or circle one of these 3 options:

Wet Moist Dry

Soil depth (in inches)____Or circle one of these 3 options:

Deep Modest Shallow

Development stage (check one): __Immature __Late successional __Two-canopy (seed cut)
__Mature __Pre-sapling __Sapling __Uneven-aged open canopy

Most recent forest management treatment applied and year of application____________________

After treatment, what percentage of forest remained?______________________________________

Other treatments used on this compartment/stand in the past 50 years and dates if available (i.e., commercial harvest, pre-commercial thinning, tending, planting, none, etc.)____________________________

____

Compartment/Stand 3

Stand size (in acres)__________________ Soil type________________________________

Species, including relative proportion of each and ages (list up to five, starting with major tree species)

Species	Proportion of compartment/stand	Age (in years)

Productivity/quality (specify site class, site index)__________________________Or circle one of these 3

options:		
Productive	Fair	Poor

Density or stocking (basal area)________________________________ Or circle one of these 3 options:		
Dense	Medium	Thin

Moisture regime____ Or circle one of these 3 options:		
Wet	Moist	Dry

Soil depth (in inches)_______________________________________ Or circle one of these 3 options:		
Deep	Modest	Shallow

Development stage (check one): __Immature __Late successional __Two-canopy (seed cut) __Mature __Pre-sapling __Sapling __Uneven-aged open canopy

Most recent forest management treatment applied and year of application____________________

After treatment, what percentage of forest remained?____________________________________

Other treatments used on this compartment/stand in the past 50 years and dates if available (i.e., commercial harvest, pre-commercial thinning, tending, planting, none, etc.)____________________________

____

Thank you very much for completing this survey!! Your time and effort are greatly appreciated.

Appendix B – Table for OMNR to get growth and yield data

STAND ID	Area	Stand Age	Origin	SPP COMP	Site Class	Stocking	Basal Area	Development Stage	Notes
1A	6.07	39	N	MH 53AW 27BW 13CE 7	3	0.8		M	
1B	2.02	39	N	MH 80AW 10CE 10	2	0.8		M	
2A	23.47	73	N	QR 80MA 10BE 5OH 5	1		18.0	M	
3A	9.41	50	N	OH 47CE 20BW 13PW 13PO 7	3	1.0		U	OH = glossy buckthorn
4A	2.09	35	N	MH 80AW 20	1	0.8		S	
4B	4.17	60	N	MH 100	1		14 inches	M	
4C	3.62	35	P	PR 60PW 40	2	0.8		I	
5A	10.76	78	N	MS 38OB 21MH 17BE 12PW 12	2		19.0m2/ha medium	M	medium in my stocking/ density = .8
6A	42.78	72	N	MH 29BF 29AW 21IW 14PO 7	2	0.8		M	
6B	8.98	53	N	AW 33OH 17CH 17PW 17MH 16	3	0.6		I	OH = Sumac
6C	2.42	102	N	CE 20YB 20HE 20AW 20BF 20	2	1.0		M	

Appendix C – FMTs survey responses (not cleaned)

Historic FMT	Most Recent FMT		Historic FMT	Most Recent FMT
natural succession	75% clearcut		natural succession	natural succession
natural succession	clearcut		natural succession	harvest 5%
natural succession	10% thinning		silviculture	planting
thinning	thinning		natural succession	harvest 5%
natural succession	80% thinning		logged	natural succession
tending	tending		natural succession	wildfire
pruning	pruning			afforestation
natural succession	logging		natural succession	clearcut
tending and selective cutting	natural succession		natural succession	planting
natural succession	natural succession		firewood 10%	natural succession
natural succession	natural succession		natural succession	firewood removal
selective thinning	33% thinning		natural succession	firewood removal
natural succession	natural succession		conifer plantation	33% thinning
natural succession	natural succession		natural succession	natural succession
natural succession	natural succession		natural succession	salvage 50%
natural succession	clearcut		natural succession	10% thinning
natural succession	natural succession		5% thinning	5% thinning
thinning and planting	thinning and planting		natural succession	10% thinning
thinning and planting	thinning and planting			afforestation
natural succession	planting		natural succession	natural succession
natural succession	natural succession		natural succession	natural succession
natural succession	natural succession		natural succession	30% thinning
natural succession	natural succession		natural succession	30% thinning
natural succession	natural succession		natural succession	5% thinning
natural succession	natural succession		natural succession	30% thinning
natural succession	25% thinning		natural succession	5% thinning
natural succession	commercial harvest 35%		20% thinning	20% thinning
natural succession	commercial harvest 45%		natural succession	1% thinning
commercial harvest	20% thinning		natural succession	natural succession
commercial harvest	commercial harvest 20%		natural succession	20% thinning
natural succession	clearcut		10% thinning	10% thinning
natural succession	natural succession		10% thinning	10% thinning
natural succession	natural succession		cattle grazed forest	30% shelter cut
natural succession	natural succession		natural succession	natural succession
	planting		clearcut (20%)	clearcut

Historic FMT	Most Recent FMT		Historic FMT	Most Recent FMT
natural succession	1% thinning		clearcut (20%)	30% thinning
natural succession	natural succession		natural succession	commercial harvest 45%
natural succession	logging		natural succession	natural succession
natural succession	2% thinning		natural succession	natural succession
natural succession	60% harvest		natural succession	clearcut
natural succession	50% commercial logging		commercial harvest	tending 5%
	afforestation		natural succession	natural succession
natural succession	clearcut		natural succession	planting
natural succession	natural succession		natural succession	natural succession
natural succession	2% tending		natural succession	natural succession
natural succession	2.5% tending			planting
natural succession	planting			planting
natural succession	2.5% tending		natural succession	natural succession
natural succession	10% commercial harvest		natural succession	natural succession
natural succession	natural succession		natural succession	natural succession
natural succession	planting		thinning	30% thinning
natural succession	natural succession		thinning	pre commercial thinning
natural succession	natural succession		natural succession	natural succession
natural succession	natural succession		natural succession	natural succession
	natural succession		natural succession	natural succession
natural succession	natural succession		thinning	pre commercial thinning
	natural succession		natural succession	diameter limit cut
natural succession	pre commercial thinning		natural succession	diameter limit cut
thinning	2% thinning		planting	pre commercial thinning
thinning	planting		planting	planting
10% thinning	10% thinning		pre commercial thinning	pre commercial thinning
10% thinning	10% thinning		tending	tending
natural succession	clearcut		natural succession	5% thinning
natural succession	15% commercial harvest		logging	natural succession
natural succession	pruning		natural succession	natural succession
natural succession	1% firewood harvest		natural succession	natural succession
cattle grazed forest	natural succession		natural succession	natural succession
			5% thinning	5% thinning